2

Bioenergy

Coordinating Lead Authors:

Helena Chum (USA/Brazil), Andre Faaij (The Netherlands), José Moreira (Brazil)

Lead Authors:

Göran Berndes (Sweden), Parveen Dhamija (India), Hongmin Dong (China), Benoît Gabrielle (France), Alison Goss Eng (USA), Wolfgang Lucht (Germany), Maxwell Mapako (South Africa/Zimbabwe), Omar Masera Cerutti (Mexico), Terry McIntyre (Canada), Tomoaki Minowa (Japan), Kim Pingoud (Finland)

Contributing Authors:

Richard Bain (USA), Ranyee Chiang (USA), David Dawe (Thailand, USA), Garvin Heath (USA), Martin Junginger (The Netherlands), Martin Patel (The Netherlands), Joyce Yang (USA), Ethan Warner (USA)

Review Editors:

David Paré (Canada) and Suzana Kahn Ribeiro (Brazil)

This chapter should be cited as:

Chum, H., A. Faaij, J. Moreira, G. Berndes, P. Dhamija, H. Dong, B. Gabrielle, A. Goss Eng, W. Lucht, M. Mapako, O. Masera Cerutti, T. McIntyre, T. Minowa, K. Pingoud, 2011: Bioenergy. In IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation [O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, C. von Stechow (eds)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

2

Bioenergy

Coordinating Lead Authors:
Helena Chum (USA/Brazil), Andre Faaij (The Netherlands), José Moreira (Brazil)

Lead Authors:
Göran Berndes (Sweden), Parveen Dhamija (India), Hongmin Dong (China), Benoît Gabrielle (France), Alison Goss Eng (USA), Wolfgang Lucht (Germany), Maxwell Mapako (South Africa/Zimbabwe), Omar Masera Cerutti (Mexico), Terry McIntyre (Canada), Tomoaki Minowa (Japan), Kim Pingoud (Finland)

Contributing Authors:
Richard Bain (USA), Ranyee Chiang (USA), David Dawe (Thailand, USA), Garvin Heath (USA), Martin Junginger (The Netherlands), Martin Patel (The Netherlands), Joyce Yang (USA), Ethan Warner (USA)

Review Editors:
David Paré (Canada) and Suzana Kahn Ribeiro (Brazil)

This chapter should be cited as:

Chum, H., A. Faaij, J. Moreira, G. Berndes, P. Dhamija, H. Dong, B. Gabrielle, A. Goss Eng, W. Lucht, M. Mapako, O. Masera Cerutti, T. McIntyre, T. Minowa, K. Pingoud, 2011: Bioenergy. In IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation [O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, C. von Stechow (eds)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Table of Contents

Executive Summary

Bioenergy has a significant greenhouse gas (GHG) mitigation potential, provided that the resources are developed sustainably and that efficient bioenergy systems are used. Certain current systems and key future options including perennial cropping systems, use of biomass residues and wastes and advanced conversion systems are able to deliver 80 to 90% emission reductions compared to the fossil energy baseline. However, land use conversion and forest management that lead to a loss of carbon stocks (direct) in addition to indirect land use change (d+iLUC) effects can lessen, and in some cases more than neutralize, the net positive GHG mitigation impacts. Impacts of climate change through temperature increases, rainfall pattern changes and increased frequency of extreme events will influence and interact with biomass resource potential. This interaction is still poorly understood, but it is likely to exhibit strong regional differences. Climate change impacts on biomass feedstock production exist but if global temperature rise is limited to less than 2°C compared with the pre-industrial record, it may pose few constraints. Combining adaptation measures with biomass resource production can offer more sustainable opportunities for bioenergy and perennial cropping systems.

Biomass is a primary source of food, fodder and fibre and as a renewable energy (RE) source provided about 10.2% (50.3 EJ) of global total primary energy supply (TPES) in 2008. Traditional use of wood, straws, charcoal, dung and other manures for cooking, space heating and lighting by generally poorer populations in developing countries accounts for about 30.7 EJ, and another 20 to 40% occurs in unaccounted informal sectors including charcoal production and distribution. TPES from biomass for electricity, heat, combined heat and power (CHP), and transport fuels was 11.3 EJ in 2008 compared to 9.6 EJ in 2005 and the share of modern bioenergy was 22% compared to 20.6%.

From the expert review of available scientific literature, potential deployment levels of biomass for energy by 2050 could be in the range of 100 to 300 EJ. However, there are large uncertainties in this potential such as market and policy conditions, and it strongly depends on the rate of improvement in the production of food and fodder as well as wood and pulp products.

The upper bound of the technical potential of biomass for energy may be as large as 500 EJ/yr by 2050. Reaching a substantial fraction of the technical potential will require sophisticated land and water management, large worldwide plant productivity increases, land optimization and other measures. Realizing this potential will be a major challenge, but it could make a substantial contribution to the world's primary energy supply in 2050. For comparison, the equivalent heat content of the total biomass harvested worldwide for food, fodder and fibre is about 219 EJ/yr today.

A scenario review conducted in Chapter 10 indicates that the contribution of bioenergy in GHG stabilization scenarios of different stringency can be expected to be significantly higher than today. By 2050, in the median case bioenergy contributes 120 to 155 EJ/yr to global primary energy supply, or 150 to 190 EJ/yr for the 75th percentile case, and even up to 265 to 300 EJ/yr in the highest deployment scenarios. This deployment range is roughly in line with the IPCC Special Report on Emission Scenarios (SRES) regionally oriented A2 and B2 and globally oriented A1 and B1 conditions and storylines. Success in implementing sustainability and policy frameworks that ensure good governance of land use and improvements in forestry, agricultural and livestock management could lead to both high (B1) and low (B2) potentials. However, biomass supplies may remain limited to approximately 100 EJ/yr in 2050 if such policy frameworks and enforcing mechanisms are not introduced and if there is strong competition for biomaterials from other (innovative future) sectors. In that environment, further biomass expansion could lead to significant regional conflicts for food supplies, water resources and biodiversity, and could even result in additional GHG emissions, especially due to iLUC and loss of carbon stocks. In another deployment scenario, biomass resources may be constrained to use of residues and organic waste, energy crops cultivated on marginal/degraded and poorly utilized lands, and to supplies in endowed world regions where bioenergy is a cheaper energy option compared to market alternatives (e.g., sugarcane ethanol production in Brazil).

Bioenergy has complex societal and environmental interactions, including climate change feedback, biomass production and land use. The impact of bioenergy on social and environmental issues (e.g., health, poverty, biodiversity) may be positive or negative depending on local conditions and the design and implementation of specific projects. The policy context for bioenergy, and particularly biofuels, has changed rapidly and dramatically in recent years. The food versus fuel debate and growing concerns about other conflicts are driving a strong push for the development and implementation of sustainability criteria and frameworks. Many conflicts can be reduced if not avoided by encouraging synergisms in the management of natural resource, agricultural and livestock sectors as part of good governance of land use that increases rural development and contributes to poverty alleviation and a secure energy supply.

Costs vary by world regions, feedstock types, feedstock supply costs for conversion processes, the scale of bioenergy production and production time during the year. Examples of estimated commercial bioenergy levelized cost ranges are roughly USD_{2005} 2 to 48/GJ for liquid and gaseous biofuels; roughly US $cents_{2005}$ 3.5 to 25/kWh (USD_{2005} 10 to 50/GJ) for electricity or CHP systems larger than about 2 MW (with feedstock costs of USD_{2005} 3/GJ_{feed} and a heat value of USD_{2005} 5/GJ for steam or USD_{2005} 12/GJ for hot water); and roughly USD_{2005} 2 to 77/GJ for domestic or district heating systems with feedstock costs in the range of USD_{2005} 0 to 20/GJ (solid waste to wood pellets). These calculations refer to 2005 to 2008 data and are expressed in USD_{2005} at a 7% discount rate.

Recent analyses of lignocellulosic biofuels indicate potential improvements that enable them to compete at oil prices of USD_{2005} 60 to 70/barrel (USD_{2005} 0.38 to 0.44/litre) assuming no revenue from carbon dioxide (CO_2) mitigation. Scenario analyses indicate that strong short-term research and development (R&D) and market support could allow for commercialization around 2020 depending on oil and carbon pricing. In addition to ethanol and biodiesel, a range of hydrocarbons and chemicals/materials similar to those currently derived from oil could provide biofuels for not only vehicles but also for the aviation and maritime sectors. Biomass is the only renewable resource that can currently provide high energy density liquid fuels. A wider variety of bio-based products can also be produced at biorefineries to enhance the economics of the overall conversion process. Short-term options (some of them already competitive) that can deliver long-term synergies include co-firing, CHP, heat generation and sugarcane-based ethanol and bioelectricity co-production. Development of working bioenergy markets and facilitation of international bioenergy trade can help achieve these synergies.

Further improvements in power generation technologies, supply systems of biomass and production of perennial cropping systems can bring bioenergy costs down. There is clear evidence that technological learning and related cost reductions occur in many biomass technologies with learning rates comparable to other RE technologies. This is true for cropping systems where improvements in agricultural management of annual crops, supply systems and logistics, conversion technologies to produce energy carriers such as heat, electricity and ethanol from sugarcane or maize, and biogas have demonstrated significant cost reductions.

Combining biomass conversion with developing carbon capture and storage (CCS) could lead to long-term substantial removal of GHGs from the atmosphere (also referred to as negative emissions). Advanced biomaterials are promising as well from both an economic and a GHG mitigation perspective, though the relative magnitude of their mitigation potential is not well understood. The potential role of aquatic biomass (algae) is highly uncertain but could reduce land use conflict. More experience, research, development and demonstration (RD&D), and detailed analyses of these options are needed.

Multiple drivers for bioenergy systems and their deployment in sustainable directions are emerging. Examples include rapidly changing policy contexts, recent market-based activities, the increasing support for advanced biorefinery and lignocellulosic biofuel options and, in particular, development of sustainability criteria and frameworks. Sustained cost reductions of key technologies in biomass production and conversion, supply infrastructure development, and integrated systems research can lead to the implementation of strategies that facilitate sustainable land and water use and gain public and political acceptance.

2.1 Introduction

Bioenergy is embedded in complex ways in global biomass systems for food, fodder and fibre production and for forest products; in wastes and residue management; and in the everyday living of the developing countries' poor. Bioenergy includes different sets of technologies for applications in various sectors.

2.1.1 Current pattern of biomass and bioenergy use and trends

Biomass provided about 10.2% (50.3 EJ/yr) of the annual global primary energy supply in 2008, from a wide variety of biomass sources feeding numerous sectors of society (see Table 2.1; IEA, 2010a). The biomass feedstocks used for energy are shown in Figure 2.1 (top), and more than 80% are derived from wood (trees, branches, residues) and shrubs. The remaining bioenergy feedstocks came from the agricultural sector (energy crops, residues and by-products) and from various commercial and post-consumer waste and by-product streams (biomass product recycling and processing or the organic biogenic fraction of municipal solid waste[1] (MSW)).

Biomass is used (see Table 2.1) with varying degrees of energy efficiency in various sectors:

- Low-efficiency *traditional biomass*[2] such as wood, straws, dung and other manures are used for cooking, lighting and space heating, generally by the poorer populations in developing countries. This biomass is mostly combusted, creating serious negative impacts on health and living conditions. Increasingly, charcoal is becoming a secondary energy carrier in rural areas. As an indicator of the magnitude of traditional biomass use, Figure 2.1 (bottom) illustrates that the global primary energy supply from traditional biomass parallels the world's industrial roundwood production.

In the International Energy Agency's (IEA) World Energy Statistics (IEA, 2010a) and World Energy Outlook (WEO: IEA, 2010b) TPES from traditional biomass amounts to 30.7 EJ/yr based on national databases that tend to systematically underestimate fuelwood consumption. Although international forestry and energy data (FAO, 2005) are the main reference sources for policy analyses, they are

Table 2.1 | Examples of traditional and select modern biomass energy flows in 2008 according to the IEA (2010 a,b) and supplemented by Masera et al., 2005, 2006; Drigo et al., 2007, 2009.

Type	Approximate Primary Energy (EJ/yr)	Approximate Average Efficiency (%)	Approximate Secondary Energy (EJ/yr)
Traditional Biomass			
Accounted for in IEA energy statistics	30.7	10–20	3–6
Estimated for informal sectors (e.g., charcoal)	6–12		0.6–2.4
Total Traditional Biomass	37–43		3.6–8.4
Modern Bioenergy			
Electricity and CHP from biomass, MSW, and biogas	4.0	32	1.3
Heat in residential, public/commercial buildings from solid biomass and biogas	4.2	80	3.4
Road transport fuels (ethanol and biodiesel)	3.1	60	1.9
Total Modern Bioenergy	11.3	58	6.6

Notes: According to the IEA (2010a,b), the 2008 TPES from biomass of 50.3 EJ was composed primarily of solid biomass (46.9 EJ); biogenic MSW used for heat and CHP (0.58 EJ); and biogas (secondary energy) for electricity and CHP (0.41 EJ) and heating (0.33 EJ). The contribution of ethanol, biodiesel, and other biofuels (e.g., ethers) used in the transport sector amounted to 1.9 EJ in secondary energy terms. Examples of specific flows: output electricity from biomass was 0.82 EJ (biomass power plants including pulp and paper industry surplus, biogas and MSW) and output heating from CHP was 0.44 EJ. Modern residential heat consumption was calculated by subtracting the IEA estimate of traditional use of biomass (30.7 EJ) from the total residential heat consumption (33.7 EJ).

Some table numbers were taken directly from the IEA global energy statistics, such as secondary biofuels at 1.9 EJ (whereas the derived primary energy input is based on the assumed efficiency of 60% which could be lower) as well as output electricity and heat at 1.3 EJ for all feedstocks. Primary input for MSW and biogas (secondary) and the corresponding output were available and efficiencies are calculated. Solid biomass primary input was calculated from the average efficiency for MSW. Not included in the numbers above are solid biomass (3.4 EJ) used to make charcoal (1.15 EJ) for heating (0.88 EJ, traditional mostly) and industry, such as the iron/steel industry (0.22 EJ), mostly in Brazil. Heat for making charcoal is included in Figure 1.18 in the 5.2 EJ from biomass for electricity, CHP, and heat plants. Not included in Table 2.1 is the industry sector that consumed 7.7 EJ, but the electricity sold by the pulp and paper industry is included.

1 MSW is used throughout the chapter with the same meaning as the term municipal wastes as defined by EUROSTAT.

2 Traditional biomass is defined as biomass consumption in the residential sector in developing countries and refers to the often unsustainable use of wood, charcoal, agricultural residues and animal dung for cooking and heating (IEA, 2010b and Annex I). All other biomass use is defined as modern biomass; this report further differentiates between highly efficient modern bioenergy and industrial bioenergy applications with varying degrees of efficiency (Annex I). The renewability and sustainability of biomass use is primarily discussed in Sections 2.5.4 and 2.5.5, respectively (see also Section 1.2.1 and Annex I).

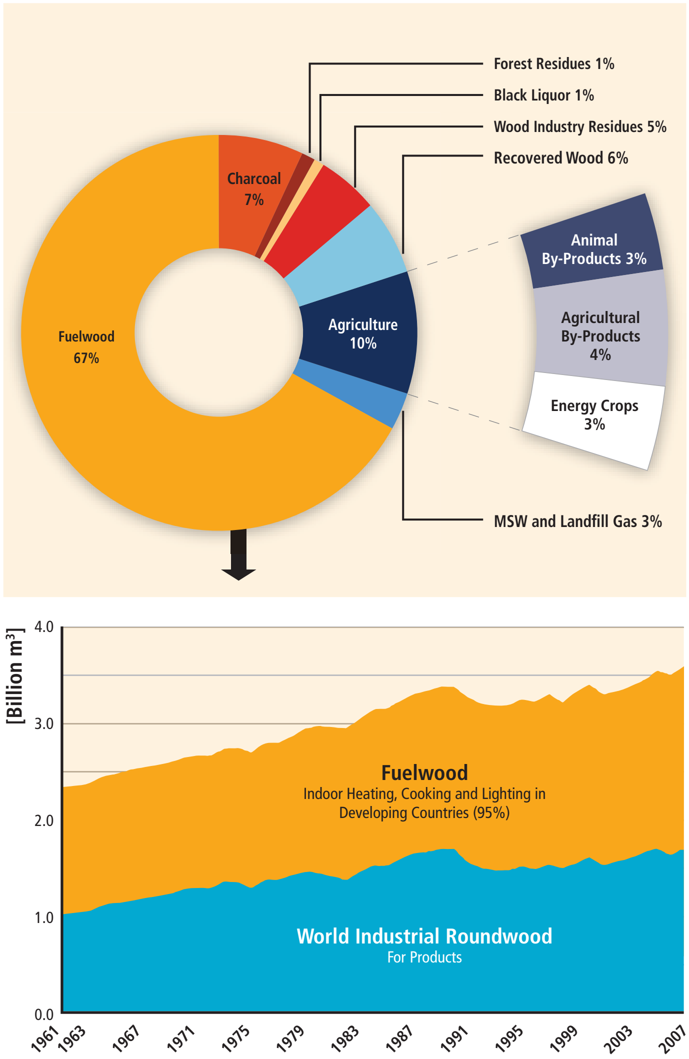


Figure 2.1 | Top: Shares of global primary biomass sources for energy (IPCC, 2007a,d; IEA Bioenergy, 2009); Bottom: Fuelwood used in developing countries parallels world industrial roundwood[1] production levels (UNECE/FAO Timber Database, 2011).

Note: 1. Roundwood products are saw logs and veneer logs for the forest products industry and wood chips that are used for making pulpwood used in paper, newsprint and Kraft paper. In 2009, reflecting the downturn in the economy, there was a decline to 3.25 (total) and 1.25 (industrial) billion m^3; the data can be retrieved from a presentation on Global Forest Resources and Market Developments: timber.unece.org/fileadmin/DAM/other/GlobalResMkts300311.pdf.

often in contradiction when it comes to estimates of biomass consumption for energy, because production and trade of these solid biomass fuels are largely informal.[3] A supplement of 20 to 40% to the global TPES of biomass in Table 2.1 is based on detailed, multi-scale, spatially explicit analyses performed in more than 20 countries (e.g., Masera et al., 2005, 2006; Drigo et al., 2007, 2009). Traditional biomass is discussed in later sections on feedstock logistics and supply (Section 2.3.2.2), improved technologies, practices and barriers (Sections 2.4.2.1 and 2.4.2.2), climate change effects (Section 2.5.4) and socioeconomic aspects (Section 2.5.7).

3 See the Glossary in Annex I for a definition of informal sector/economy.

- High-efficiency *modern bioenergy* uses more convenient solids, liquids and gases as secondary energy carriers to generate heat, electricity, combined heat and power (CHP) and transport fuels for various sectors (Figure 2.2). Many entities in the process industry, municipalities, districts and cooperatives generate these energy products, in some cases for their own use, but also for sale to national and international markets in the increasingly global trade. Liquid biofuels, such as ethanol and biodiesel, are used for global road transport and some industrial uses. Biomass-derived gases, primarily methane from anaerobic digestion of agricultural residues and waste treatment streams, are used to generate electricity, heat or CHP for multiple sectors. The most important contribution to these energy services is, however, based on solids, such as chips, pellets, recovered wood previously used etc. Heating includes space and hot water heating such as in district heating systems. The estimated TPES from modern bioenergy is 11.3 EJ/yr and the secondary energy delivered to end-use consumers is roughly 6.6 EJ/yr (IEA, 2010a,b). Modern bioenergy feedstocks such as short-rotation trees (poplars or willows) and herbaceous plants (*Miscanthus* or switchgrass) are discussed in Sections 2.3.1 and 2.6.1. The discussion of modern bioenergy includes biomass logistics and supply chains (Sections 2.3.2 and 2.6.2); conversion of biomass into secondary carriers or energy through existing (Section 2.3.3) or developing (Section 2.6.3) technologies; integration into bioenergy systems and supply chains (Section 2.3.4); and market and industry development (Section 2.4).

- High energy efficiency biomass conversion is found typically in the *industry* sector (with a total consumption of ~7.7 EJ/yr) associated with the pulp and paper industry, forest products, food and chemicals. Examples are fibre products (e.g., paper), energy, wood products, and charcoal for steel manufacture. Industrial heating is primarily steam generation for industrial processes, often in conjunction with power generation. The industry sector's final consumption of biomass is not shown in Table 2.1 since it cannot be unambiguously assigned. Also see Section 8.3.4, which addresses the biomass industry sector.

Global bioenergy use has steadily grown worldwide in absolute terms in the last 40 years, with large differences among countries. In 2006, China led all countries and used 9 EJ of biomass for energy, followed by India (6 EJ), the USA (2.3 EJ) and Brazil (2 EJ) (GBEP, 2008). Bioenergy provides a relatively small but growing share of TPES (1 to 4 % in 2006) in the largest industrialized countries (grouped as the G8 countries: the USA, Canada, Germany, France, Japan, Italy, the UK and Russia). The use of solid biomass for electricity production is particularly important in pulp and paper plants and in sugar mills. Bioenergy's share in total energy consumption is generally increasing in the G8 countries through the use of modern biomass forms (e.g., co-combustion or co-firing for electricity generation, space heating with pellets) especially in Germany, Italy and the UK (see Figure 2.8; GBEP, 2008).

By contrast, in 2006, bioenergy provided 5 to 27% of TPES in the largest developing countries (China, India, Mexico, Brazil and South Africa),

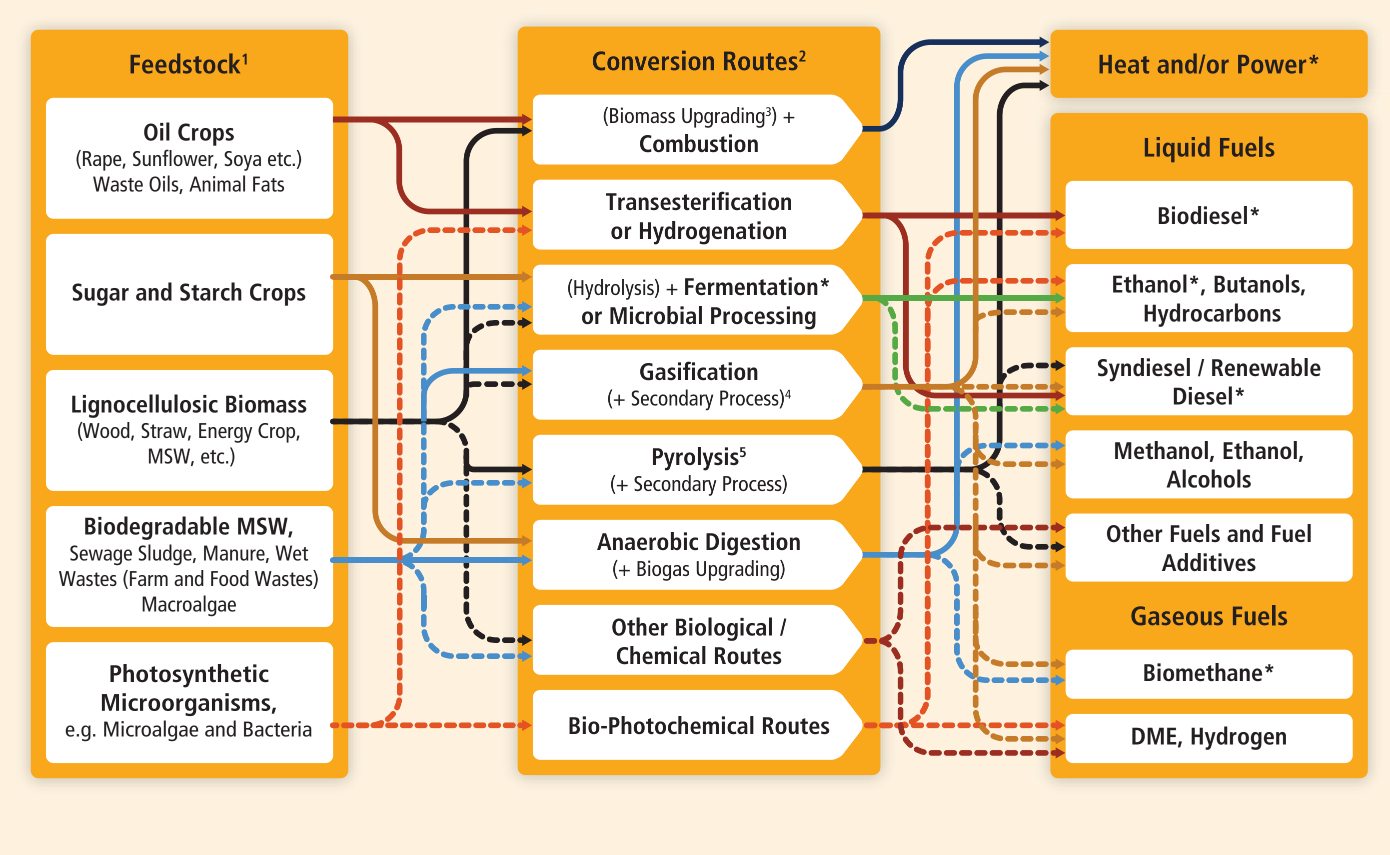


Figure 2.2 | Schematic view of the variety of commercial (solid lines, see Figure 2.6) and developing bioenergy routes (dotted lines) from biomass feedstocks through thermochemical, chemical, biochemical and biological conversion routes to heat, power, CHP and liquid or gaseous fuels (modified from IEA Bioenergy, 2009). Commercial products are marked with an asterisk.

Notes: 1. Parts of each feedstock, for example, crop residues, could also be used in other routes. 2. Each route also gives coproducts. 3. Biomass upgrading includes any one of the densification processes (pelletization, pyrolysis, torrefaction, etc.). 4. Anaerobic digestion processes release methane and CO_2 and removal of CO_2 provides essentially methane, the major component of natural gas; the upgraded gas is called biomethane. 5. Could be other thermal processing routes such as hydrothermal, liquefaction, etc. DME=dimethyl ether.

mainly through the use of traditional forms, and more than 80% of TPES in the poorest countries. The bioenergy share in India, China and Mexico is decreasing, mostly as traditional biomass is substituted by kerosene and liquefied petroleum gas within large cities. However, consumption in absolute terms continues to grow. This trend is also true for most African countries, where demand has been driven by a steady increase in wood fuels, particularly in the use of charcoal in booming urban areas (GBEP, 2008).

Turning from the technological perspectives of bioenergy to environmental and social aspects, the literature assessments in this chapter reveal positive and negative aspects of bioenergy. Sustainably produced and managed, bioenergy can provide a substantial contribution to climate change mitigation through increasing carbon stocks in the biosphere (e.g., in degraded lands), reducing carbon emissions from unsustainable forest use and replacing fossil fuel-based systems in the generation of heat, power and modern fuels. Additionally, bioenergy may provide opportunities for regional economic development (see Sections 9.3.1 and 2.5.4). Advanced bioenergy systems and end-use technologies can also substantially reduce the emissions of black carbon and other short-lived GHGs such as methane and carbon monoxide (CO), which are related to the burning of biomass in traditional open fires and kilns. If improperly designed or implemented, the large-scale expansion of bioenergy systems is likely to have negative consequences for climate and sustainability, for example, by inducing d+iLUC that can alter surface albedo and release carbon from soils and vegetation, reducing biodiversity or negatively impacting local populations in terms of land tenure or reduced food security, among other effects.

The literature on the resource potential of biomass is covered in Section 2.2, which discusses a variety of global modelling studies and the factors that influence the assessments. Section 2.2 also presents examples of resource assessments from countries and specific regions, which provide cost dimensions for these resources. The overall technology portfolio is shown in Figure 2.2 and includes commercial and developing energy carriers from modern biomass. The commercially available energy products and (conversion) technologies are discussed in Section 2.3. These are based on sugar crops (perennial sugarcane and beets), starch crops (maize, wheat, cassava etc.), and oil crops (soy, rapeseed) as feedstocks, and they expand food and fodder processing to bioenergy production. Current bioenergy production is also coupled with forest products industry residues and the pulping industry that has traditionally self generated heat and power; with dry and wet municipal wastes; with sewage sludge; and with a variety of organic wet wastes from various sectors. These wastes and residues, if left untreated, can have a major impact on climate through methane emission releases. The bioenergy market is described in Section 2.4 for traditional and modern forms, as are evolving international trade and sustainability frameworks for bioenergy. The advanced technologies for production of feedstocks and conversion to energy products are discussed in Section 2.6.

In Section 2.5, the environmental and social impacts of biomass use are addressed with emphasis on the climate change effects of bioenergy. Because of the complexity of GHG impacts and of the bioenergy chains, impacts are analyzed without and with LUC separately. These impacts span micro-, meso- and macro- scales and depend on the land cover conversion and water availability, among other factors, in specific regions. Direct land use impacts occur locally by changes in crop use or the dedication of a crop to bioenergy. The iLUC results from a market-mediated shift in land management activities (i.e., dLUC) outside the region of primary production expansion. Both are addressed in Section 2.5. The social impacts of modern and traditional biomass use are presented and related to key issues such as the impact of bioenergy on food production and sustainable development in Section 2.5.7 (also refer to Sections 9.3 and 9.4).

To reach high levels of bioenergy production and minimize environmental and social impacts, it is necessary to develop a variety of lignocellulosic biomass sources and a portfolio of conversion routes for power, heat and gaseous and liquid fuels that satisfy existing and future energy needs (Figure 2.2). With these prospects for technology improvement, innovation and integration, key conversion intermediates derived from biomass such as sugars, syngas, pyrolysis oils (or oils derived from other thermal treatments), biogas and vegetable oils (lipids) can be upgraded in conversion facilities that are capable of making a variety of products including biofuels, power and process heat, alongside other products as discussed in Section 2.6. In Section 2.7, the costs of existing commercial technologies and their trends are discussed, highlighting that over the past 25 years technological learning occurred in a variety of bioenergy systems in specific countries. Finally, Section 2.8 addresses the potential deployment of biomass for energy. It also compares biomass resource assessments from Section 2.2, informed by environmental and social impacts discussions, with the levels of deployment indicated by the scenario literature review described in Chapter 10. The role of biomass and its multiple energy products alongside food, fodder, fibre and forest products is viewed through IPCC scenario storylines (IPCC, 2000a,d) to reach significant penetration levels with and without taking into account sustainable development and climate change mitigation pathways. High and low penetration levels can be reached with (and without) climate change mitigation and sustainable development strategies. Many insights into bioenergy technology developments and integrated systems can be gleaned from these sketches, and they will be useful in further developing bioenergy sustainably with climate mitigation.

2.1.2 Previous Intergovernmental Panel on Climate Change assessments

Bioenergy has not been examined in detail in previous IPCC reports. In the most recent Fourth Assessment Report (AR4), the analysis of GHG mitigation from bioenergy was scattered among seven chapters, making it difficult to obtain an integrated and cohesive picture of the resource and mitigation potential, challenges and opportunities. The main conclusions from the AR4 report (IPCC, 2007b,d) are as follows:

- **Biomass energy demand.** Primary biomass requirements for the production of transportation fuels were largely based on the WEO (IEA, 2006) global projections, with a relatively wide range of about 14 to 40 EJ/yr of primary biomass, or 8 to 25 EJ/yr of biofuels in 2030. However, higher demand estimates of 45 to 85 EJ/yr for primary biomass in 2030 (roughly 30 to 50 EJ/yr of biofuel) were also included. For comparison, the scenario review in Chapter 10 shows biofuel production ranges of 0 to 14 EJ/yr in 2030 and 2 to 50 EJ/yr in 2050 with median values of 5 to 12 EJ/yr and 18 to 20 EJ/yr in the two GHG mitigation scenario categories analyzed. The demand for biomass-generated heat and power was stated to be strongly influenced by the availability and introduction of competing technologies such as CCS, nuclear power, wind energy, solar heating and others. The projected biomass demand in 2030 would be around 28 to 43 EJ according to the data used in the AR4. These estimates focus on electricity generation. Heat was not explicitly modelled or estimated in the WEO (IEA, 2006), on which the AR4 was based, therefore underestimating the total demand for biomass.

  Potential future demand for biomass in industry (especially new uses such as biochemicals, but also expansion of charcoal use for steel production) and the built environment (heating as well as increased use of biomass as a building material) was also highlighted as important, but no quantitative projections were included in the potential demand for biomass at the medium and longer term.

- **Biomass resource potential (supply).** According to the AR4, the largest contribution to technical potential could come from energy crops on arable land, assuming that efficiency improvements in agriculture are fast enough to outpace food demand so as to avoid increased pressure on forests and nature areas. A range of 20 to 400 EJ/yr is presented for 2050, with a best estimate of 250 EJ/yr. Using degraded lands for biomass production (e.g., in reforestation schemes: 8 to 110 EJ/yr) can contribute significantly. Although such low-yielding biomass production generally results in more expensive biomass supplies, competition with food production is almost absent and various co-benefits, such as regeneration of soils (and carbon storage), improved water retention and protection from (further) erosion may also offset part of the establishment costs. A current example of such biomass production schemes is the establishment of *Jatropha* crops (oilseeds) on marginal lands.

The technical potential in residues from forestry is estimated at 12 to 74 EJ/yr, that from agriculture at 15 to 70 EJ/yr and that from waste at 13 EJ/yr. These biomass resource categories are largely available before 2030, but also partly uncertain. The uncertainty comes from possible competing uses (e.g., increased use of biomaterials such as fibreboard production from forest residues and use of agricultural residues for fodder and fertilizer) and differing assumptions about sustainability criteria deployed with respect to forest management and agricultural intensity. The technical potential for biogas fuel from waste, landfill gas and digester gas is much smaller.

- **Carbon mitigation potential.** The mitigation potential for electricity generation from biomass reaches 1,220 Mt CO_2eq for the year 2030, a substantial fraction of it at costs lower than USD_{2005} 19.5/t CO_2. From a top-down assessment, the economic mitigation potential of biomass energy supplied from agriculture is estimated to range from 70 to 1,260 Mt CO_2eq/yr at costs of up to USD_{2005} 19.5/t CO_2eq, and from 560 to 2,320 Mt CO_2eq/yr at costs of up to USD_{2005} 48.5/t CO_2eq. The overall mitigation from biomass energy coming from the forest sector is estimated to reach 400 Mt CO_2/yr up to 2030.

2.2 Resource potential

2.2.1 Introduction

Bioenergy production interacts with food, fodder and fibre production as well as with conventional forest products in complex ways. Bioenergy demand constitutes a benefit to conventional plant production in agriculture and forestry by offering new markets for biomass flows that earlier were considered to be waste products; it can also provide opportunities for cultivating new types of crops and integrating bioenergy production with food and forestry production to improve overall resource management. However, biomass for energy production can intensify competition for land, water and other production factors, and can result in overexploitation and degradation of resources. For example, too-intensive biomass extraction from the land can lead to soil degradation, and water diversion to energy plantations can impact downstream and regional ecological functions and economic services.

As a consequence, the magnitude of the biomass resource potential depends on the priority given to bioenergy products versus other products obtained from the land—notably food, fodder, fibre and conventional forest products such as sawn wood and paper—and on how much total biomass can be mobilized in agriculture and forestry. This in turn depends on natural conditions (climate, soils, topography), on agronomic and forestry practices, and on how societies understand and prioritize nature conservation and soil/water/biodiversity protection and on how production systems are shaped to reflect these priorities (Figure 2.3).

This section focuses on long-term biomass resource potential and how it has been estimated based on considerations of the Earth's biophysical resources (ultimately net primary production: NPP) and restrictions on their energetic use arising from competing requirements, including non-extractive requirements such as soil quality maintenance/improvement and biodiversity protection. Additionally, approaches to assessing biomass resource potentials—and results from selected studies—are presented with an account of the main determining factors. These factors are treated explicitly, including the constraints on their utilization. The section ends by summarizing conclusions about biomass resource assessments, including uncertainties.

2.2.1.1 Methodology assessment

Studies quantifying biomass resource potential have assessed the resource base in a variety of ways. They differ in the extent to which the influence of natural conditions (and how these can change in the future) are considered as well as in the extent to which the types and details of important additional factors are taken into account, such as socioeconomic considerations, the character and development of agriculture and forestry, and factors connected to nature conservation and soil/water/biodiversity preservation (Berndes et al., 2003). Different types of resource potentials are assessed but the following are commonly referred to (see Glossary in Annex I):

- **Theoretical potential** refers to the biomass supply as limited only by biophysical conditions (see discussion below in this same sub-section);

- **Technical potential** considers the limitations of the biomass production practices assumed to be employed and also takes into account concurrent demand for food, fodder, fibre, forest products and area requirements for human infrastructure. Restrictions connected to nature conservation and soil/water/biodiversity preservation can also be considered. In such cases, the term *sustainable potential* is sometimes used (see Section 2.2.2); and

- **Market potential** refers to the part of the technical potential that can be produced given a specified requirement for the level of economic profit in production. This depends not only on the cost of production but also on the price of the biomass feedstock, which is determined by a range of factors such as the characteristics of biomass conversion technologies, the price of competing energy technologies and the prevailing policy regime (see Section 2.2.3).

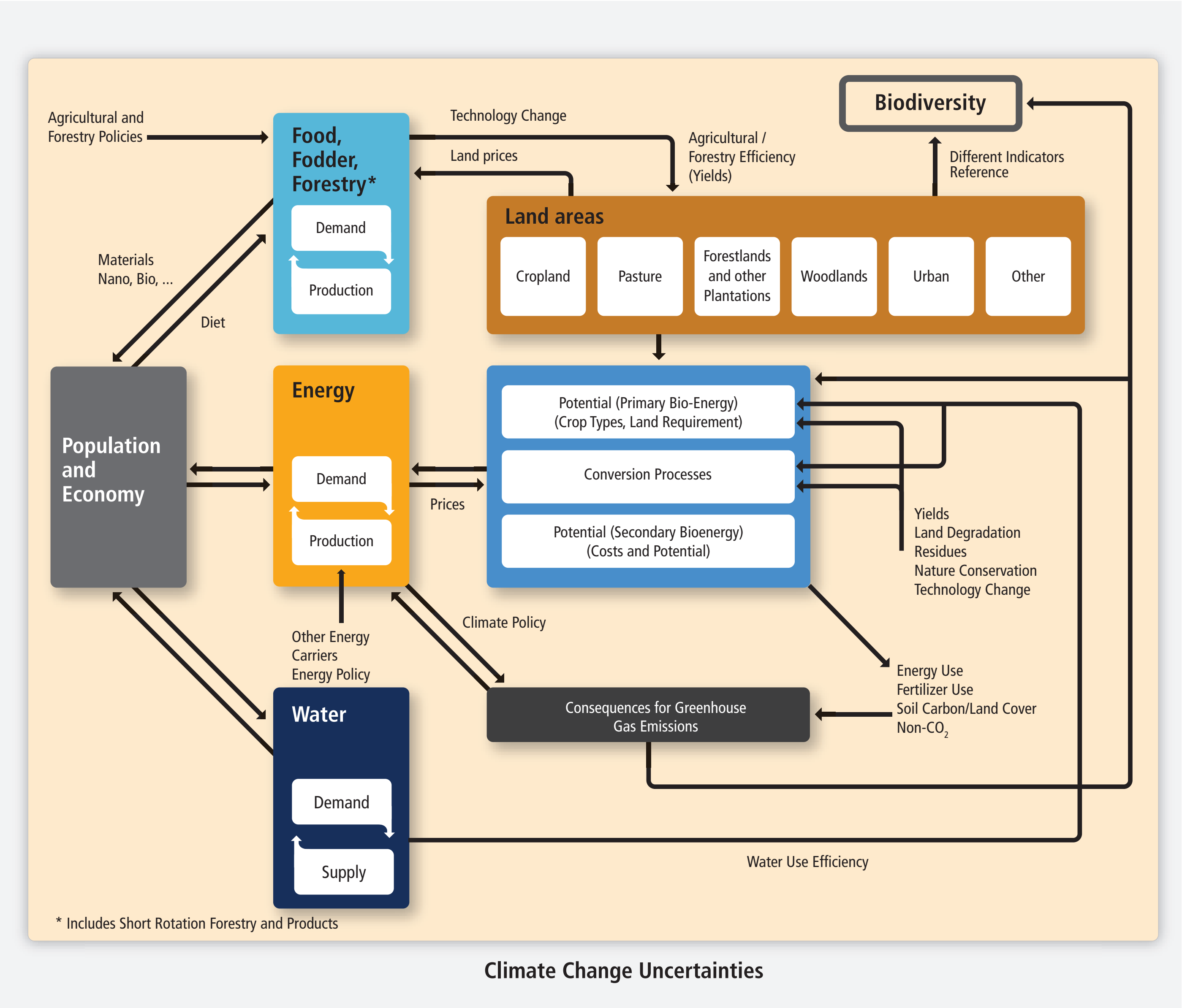


Figure 2.3 | Overview of key relationships relevant to assessment of biomass resource potentials (modified from Dornburg et al., 2010). Indirect land use and social issues are not displayed. Reproduced with permission from the Royal Society of Chemistry.

Three principal categories are—more or less comprehensively—considered in assessments of biomass resource potentials (see also Section 2.3.1.1):

- Primary residues from conventional food and fibre production in agriculture and forestry, such as cereal straw and logging residues;
- Secondary and tertiary residues in the form of organic food/forest industry by-products and retail/post consumer waste; and
- Plants produced for energy supply, including conventional food/fodder/industrial crops, surplus roundwood forestry products, and new agricultural, forestry or aquatic plants.

Given that resource potential assessments quantify the availability of residue flows in the food and forest sectors, the definition of how these sectors develop is central for the outcome. As discussed below, consideration of various environmental and socioeconomic factors as a rule reduces the assessed resource potential to lower levels.

Most assessments of the biomass resource potential considered in this section are variants of technical/market potentials employing a 'food/fibre first principle', applied with the objective of quantifying biomass resource potentials under the condition that global requirements for food and conventional forest products such as sawn wood and paper are met with priority (see, e.g., WBGU, 2009; Smeets and Faaij, 2007).

Studies that start out from such principles should not be understood as providing guarantees that a certain level of biomass can be supplied for energy purposes without competing with food or fibre production. They quantify how much bioenergy could be produced in a certain future year based on using resources not required for meeting food and fibre demands, given a specified development in the world or in a region. But they do not analyze how bioenergy expansion towards such a future level of production would—or should—interact with food and fibre production.

Studies using integrated energy/industry/land use cover models (see, e.g., Leemans et al., 1996; Strengers et al., 2004; Johansson and Azar, 2007; van Vuuren et al., 2007; Fischer et al., 2009; Lotze-Campben, 2009; Melillo et al., 2009; Wise et al., 2009; Figure 2.4) can provide insights into how an expanding bioenergy sector interacts with other sectors in society including land use and the management of biospheric carbon stocks. Studies focused on sectors can contain more detailed information on interactions with other biomass uses. Restricted scope (only selected biofuel/land uses and/or regions covered) or lack of sufficiently detailed empirical data can limit the confidence in results—especially in prospective studies. This is further discussed in Sections 2.5 and 2.8.

By considering the upper level of productivity of biomass plantations on land while assuming theoretical potentials also for worldwide agriculture and fully taking into account conservation of a viable biosphere, global modelling studies by Smeets et al. (2007) derived a maximum global potential of biomass for energy of 1,548 EJ/yr.[4] In this chapter, this figure is considered to be an estimate of theoretical potential.

2.2.1.2 Total aboveground net primary production of biomass

A first qualitative understanding of biomass technical potentials can be gained from considering the total annual aboveground net primary production (NPP: the net amount of carbon assimilated in a time period by vegetation) on the Earth's terrestrial surface. This is estimated to be about 35 Gt carbon, or 1,260 EJ/yr assuming an average carbon content of 50% and 18 GJ/t average heating value (Haberl et al., 2007), which can be compared to the current world primary energy supply of about 500 EJ/yr (IEA, 2010a). This comparison shows that total terrestrial aboveground NPP is larger, but by no more than a factor of around three, than what is required to meet society's energy demand. Establishing bioenergy as a major source of future primary energy requires that a significant part of global terrestrial NPP takes place within production systems that provide bioenergy feedstocks (removing their NPP from the trophic chains of ecosystems). In addition, total terrestrial NPP may have to be increased through fertilizer, irrigation and other inputs on lands managed for food, fodder, fibre, forest products and bioenergy.

2.2.1.3 Human appropriation of terrestrial net primary production

A comparison with biomass production in agriculture and forestry can give a perspective on the potential bioenergy supply in relation to what is presently harvested. Today's global industrial roundwood production corresponds to 15 to 20 EJ/yr, and the global harvest of major crops (cereals, oil crops, sugar crops, roots, tubers and pulses) corresponds to about 60 EJ/yr (FAOSTAT, 2011). One immediate conclusion from this comparison is that biomass extraction by agriculture and forestry will have to increase substantially in order to provide feedstocks for a bioenergy sector large enough to make a significant contribution to the future energy supply.

Studies estimating the overall human appropriation of terrestrial NPP across all human uses of biomass (HANPP, taking into account all NPP gained or lost due to human activities, including harvesting and backflows) suggest that societies already appropriate a substantial share of the world's aboveground terrestrial NPP. This provides a context for prospective future biomass extraction for bioenergy. Estimates of HANPP vary depending on its definition as well as the models and data used for the calculations. A spatially explicit calculation by Haberl et al. (2007) estimated that in the year 2000, aboveground HANPP amounted to nearly 29% of the modelled global aboveground NPP. Total human biomass harvest alone was estimated to amount to about 20% (including utilized residues and grazing), with all harvested biomass used by humans containing an energy of 219 EJ/yr (Krausmann et al., 2008).

Other HANPP estimates range from a similar level down to about half of this level (D. Wright, 1990; Imhoff et al., 2004). The HANPP concept cannot directly be used to define a certain level of biomass use that would be 'safe' or 'sustainable' because the impacts of human land use depend on how agriculture and forestry systems are shaped (Bai et al., 2008). However, it can be used as a measure of the human domination of the biosphere and provide a reference for assessing the comparative magnitude of prospective additional biomass resource potentials.

Besides biophysical factors, socioeconomic conditions also influence the biomass resource potential by defining how—and how much—biomass can be produced without causing socioeconomic impacts that might be considered unacceptable. Socioeconomic restrictions vary around the world, change as society develops and depend on how societies prioritize bioenergy in relation to other socioeconomic objectives (see also Sections 2.5 and 2.8).

4 Smeets et al. (2007) model a scenario with a fully landless animal production system with globally high feed conversion efficiency and a 4.6-fold increase in global agricultural productivity by 2050 due to technological progress and deployment that is considerably faster than has historically ever been achieved (a 1.9-fold increase for Europe and a 7.7-fold increase in sub-Saharan Africa). In that case, 72% of current agricultural area could be used for bioenergy production in 2050 and supply a theoretical potential of 1,548 EJ/yr, which is of the same magnitude as the total energy content of the world's natural aboveground net primary production on land.

2.2.2 Global and regional technical potential

2.2.2.1 Literature assessment

In an assessment of technical potential based on an analysis of the literature available in 2007 and additional modelling, Dornburg et al. (2008, 2010) arrived at the conclusion that the upper bound of the technical potential in 2050 can amount to about 500 EJ. The study assumes policy frameworks that secure good governance of land use and major improvements in agricultural management and takes into account water limitations, biodiversity protection, soil degradation and competition with food. Residues originating from forestry, agriculture and organic wastes (including the organic fraction of MSW, dung, process residues etc.) are estimated to amount to 40 to 170 EJ/yr, with a mean estimate of around 100 EJ/yr. This part of the technical potential is relatively certain, but competing applications may push net availability for energy applications to the lower end of the range. Surplus forestry other than from forestry residues has an additional technical potential of 60 to 100 EJ/yr.

The findings of the Dornburg et al. (2008, 2010) reviews for biomass produced via cropping systems is that a lower estimate for energy crop production on possible surplus, good quality agricultural and pasture lands is 120 EJ/yr. The potential contribution of water-scarce, marginal and degraded lands could amount up to an additional 70 EJ/yr. This would comprise a large area where water scarcity provides limitations and soil degradation is more severe. Assuming strong learning in agricultural technology for improvements in agricultural and livestock management would add 140 EJ/yr. The three categories added together lead to a technical potential from this analysis of up to about 500 EJ/yr (Dornburg et al., 2008, 2010). For example, Hoogwijk et al. (2005, 2009) estimate that the biomass technical potential could expand from 290 to 320 EJ/yr in 2020 to 330 to 400 EJ/yr in 2030. Developing the technical potential would require major policy efforts; therefore, actual deployment is likely to be lower and the biomass resource base will be largely constrained to a share of the biomass residues and organic wastes, some cultivation of bioenergy crops on marginal and degraded lands, and some regions where biomass is a cheaper energy supply option compared to the main reference options (e.g., sugarcane-based ethanol production), amounting to a minimum of about 50 EJ/yr (Dornburg et al., 2008, 2010).

Table 2.2 shows ranges in the assessed global technical potential for the year 2050 explicitly for various biomass categories. The wide ranges shown are due to differences in the studies' approaches to considering important factors, which are in themselves uncertain: population, economic and technology development assumed or computed can vary and evolve at different regional paces; biodiversity, nature conservation and other environmental requirements are difficult to assess and depend on numerous factors and social preferences; and the magnitude and pattern of climate change and land use can strongly influence the biophysical capacity of the environment. Furthermore, technical potentials cannot be determined precisely while uncertainties remain regarding societal preferences with respect to trade-offs in environmental impacts and the implications of increased intensification in food and fibre production, and regarding potential synergies between different forms of land use.

Although assessments employing improved data and modelling capacity have not succeeded in providing narrow distinct estimates of the technical potential of biomass, they do indicate the most influential factors that affect this technical potential. This is further discussed below, where approaches used in the assessments are treated in more detail.

2.2.2.2 The contribution from residues, dung, processing by-products and waste

As can be seen in Table 2.2, biomass resource assessments indicate that retail/post-consumer waste, dung and primary residues/processing by-products in the agriculture and forestry sectors have prospects for providing a substantial share of the total global biomass supply in the longer term. Yet, the sizes of these biomass resources are ultimately determined by the demand for conventional agriculture and forestry products and the sustainability of the land resources.

Assessments of the potential contribution from these sources to the future biomass supply combine data on future production of agriculture and forestry products obtained from food/forest sector scenarios, the possibility of use of degraded lands, and the residue factors that account for the amount of residues generated per unit of primary product produced. For example, harvest residue generation in agricultural crops cultivation is estimated based on harvest index data, that is, the ratio of harvested product to total aboveground biomass (e.g., Wirsenius, 2003; Lal, 2005; Krausmann et al., 2008; Hakala et al., 2009). The generation of logging residues in forestry, and of additional biomass flows such as thinning wood and process by-products, is estimated using similar methods (see Ericsson and Nilsson, 2006; Smeets and Faaij, 2007).

The shares of the biomass flows that are available for energy (i.e., recoverability fractions) are then estimated based on consideration of other extractive uses and requirements (e.g., soil conservation, animal feeding or bedding in agriculture, and fibre board production in the forest sector).

2.2.2.3 The contribution from unutilized forest growth

In addition to the residue flows that are linked to industrial roundwood production and processing into conventional forest products, forest growth currently not harvested is considered in some studies. This biomass resource is quantified based on estimates of the biomass increment in parts of forests that are assessed as being available for wood supply. This increment is compared with the estimated level of forest biomass extraction for conventional industrial roundwood production—and sometimes for traditional biomass, notably heating and cooking—to obtain the unutilized forest growth. Smeets and Faaij (2007) provide illustrative quantifications showing how this technical potential of biomass can vary from being a major source of bioenergy to being practically zero as a consequence of competing demand and economic and ecological considerations. A comparison with the present industrial roundwood production of about 15 to 20 EJ/yr shows that a drastic increase in forest biomass output is required to reach the higher-end technical potential assessed for the forest biomass category in Table 2.2. A special case that can play a role is forest growth that becomes available after extensive tree mortality from insect outbreaks or fires (Dymond et al., 2010).

2.2.2.4 The contribution from biomass plantations

Table 2.2 indicates that substantial supplies from biomass plantations are required for reaching the high end of the technical potential range. Land availability (and its suitability) for dedicated biomass plantations and the biomass yields that can be obtained on the available lands are two critical determinants of the technical potential. Given that surplus agricultural land is commonly identified as the major land resource for the plantations, food sector development is critical. Methods for determining land availability and suitability should consider requirements for maintaining the economic, ecological and social value of ecosystems. There are different approaches for considering such requirements, as described for a selection of studies below.

Most earlier assessments of biomass resource potentials used rather simplistic approaches to estimating the technical potential of biomass plantations (Berndes et al., 2003), but the continuous development of modelling tools that combine databases containing biophysical information (soil, topography, climate) with analytical representations of relevant crops and agronomic systems and the use of economic and full biogeochemical vegetation models has resulted in improvements over time (see, e.g., van Vuuren et al., 2007; Fischer et al., 2008; Lotze-Campen et al., 2009; Melillo et al., 2009; WBGU, 2009; Wise et al., 2009;

Table 2.2 | Global technical potential overview for a number of categories of land-based biomass supply for energy production (primary energy numbers have been rounded). The total assessed technical potential can be lower than the present biomass use of about 50 EJ/yr in the case of high future food and fibre demand in combination with slow productivity development in land use, leading to strong declines in biomass availability for energetic purposes.

Biomass category	Comment	2050 Technical potential (EJ/yr)
Category 1. **Residues from agriculture**	By-products associated with food/fodder production and processing, both primary (e.g., cereal straw from harvesting) and secondary (e.g., rice husks from rice milling) residues.	15 – 70
Category 2. **Dedicated biomass production on surplus agricultural land**	Includes both conventional agriculture crops and dedicated bioenergy plants including oil crops, lignocellulosic grasses, short-rotation coppice and tree plantations. Only land not required for food, fodder or other agricultural commodities production is assumed to be available for bioenergy. However, surplus agriculture land (or abandoned land) need not imply that its development is such that less total land is needed for agriculture: the lands may become excluded from agriculture use in modelling runs due to land degradation processes or climate change (see also 'marginal lands' below). Large technical potential requires global development towards high-yielding agricultural production and low demand for grazing land. Zero technical potential reflects that studies report that food sector development can be such that no surplus agricultural land will be available.	0 – 700
Category 3. **Dedicated biomass production on marginal lands**	Refers to biomass production on deforested or otherwise degraded or marginal land that is judged unsuitable for conventional agriculture but suitable for some bioenergy schemes (e.g., via reforestation). There is no globally established definition of degraded/marginal land and not all studies make a distinction between such land and other land judged as suitable for bioenergy. Adding categories 2 and 3 can therefore lead to double counting if numbers come from different studies. High technical potential numbers for categories 2 and 3 assume biomass production on an area exceeding the present global cropland area (ca. 1.5 billion ha or 15 million km^2). Zero technical potential reflects low potential for this category due to land requirements for, for example, extensive grazing management and/or subsistence agriculture or poor economic performance if using the marginal lands for bioenergy.	0 – 110
Category 4. **Forest biomass**	Forest sector by-products including both primary residues from silvicultural thinning and logging, and secondary residues such as sawdust and bark from wood processing. Dead wood from natural disturbances, such as fires and insect outbreaks, represents a second category. Biomass growth in natural/semi-natural forests that is not required for industrial roundwood production to meet projected biomaterials demand (e.g., sawn wood, paper and board) represents a third category. By-products provide up to about 20 EJ/yr implying that high forest biomass technical potentials correspond to a much larger forest biomass extraction for energy than what is presently achieved in industrial wood production. Zero technical potential indicates that studies report that demand from sectors other than the energy sector can become larger than the estimated forest supply capacity.	0 – 110
Category 5. **Dung**	Animal manure. Population development, diets and character of animal production systems are critical determinants.	5 – 50
Category 6. **Organic wastes**	Biomass associated with materials use, for example, organic waste from households and restaurants and discarded wood products including paper, construction and demolition wood; availability depends on competing uses and implementation of collection systems.	5 – >50
Total		**<50 – >1000**

Notes: Based on Fischer and Schrattenholzer (2001); Hoogwijk et al. (2003, 2005, 2009); Smeets and Faaij (2007); Dornburg et al. (2008, 2010); Field et al. (2008); Hakala et al. (2009); IEA Bioenergy (2009); Metzger and Huttermann (2009); van Vuuren et al. (2009); Haberl et al. (2010); Wirsenius et al. (2010); Beringer et al. (2011).

Beringer et al., 2011). Important conclusions are: a) the effects of LUC associated with bioenergy expansion can considerably influence the climate benefit of bioenergy (see Section 2.5) and b) biofuel yields from crops have frequently been overestimated by neglecting spatial variations in productivity (Johnston et al., 2009).

Figure 2.4—representing one example (Fischer et al., 2009)—shows the modelled global land suitability for selected first-generation biofuel feedstocks and for lignocellulosic plants (see caption to Figure 2.4 for information about plants included). By overlaying spatial data on global land cover derived from the best available remote sensing data combined

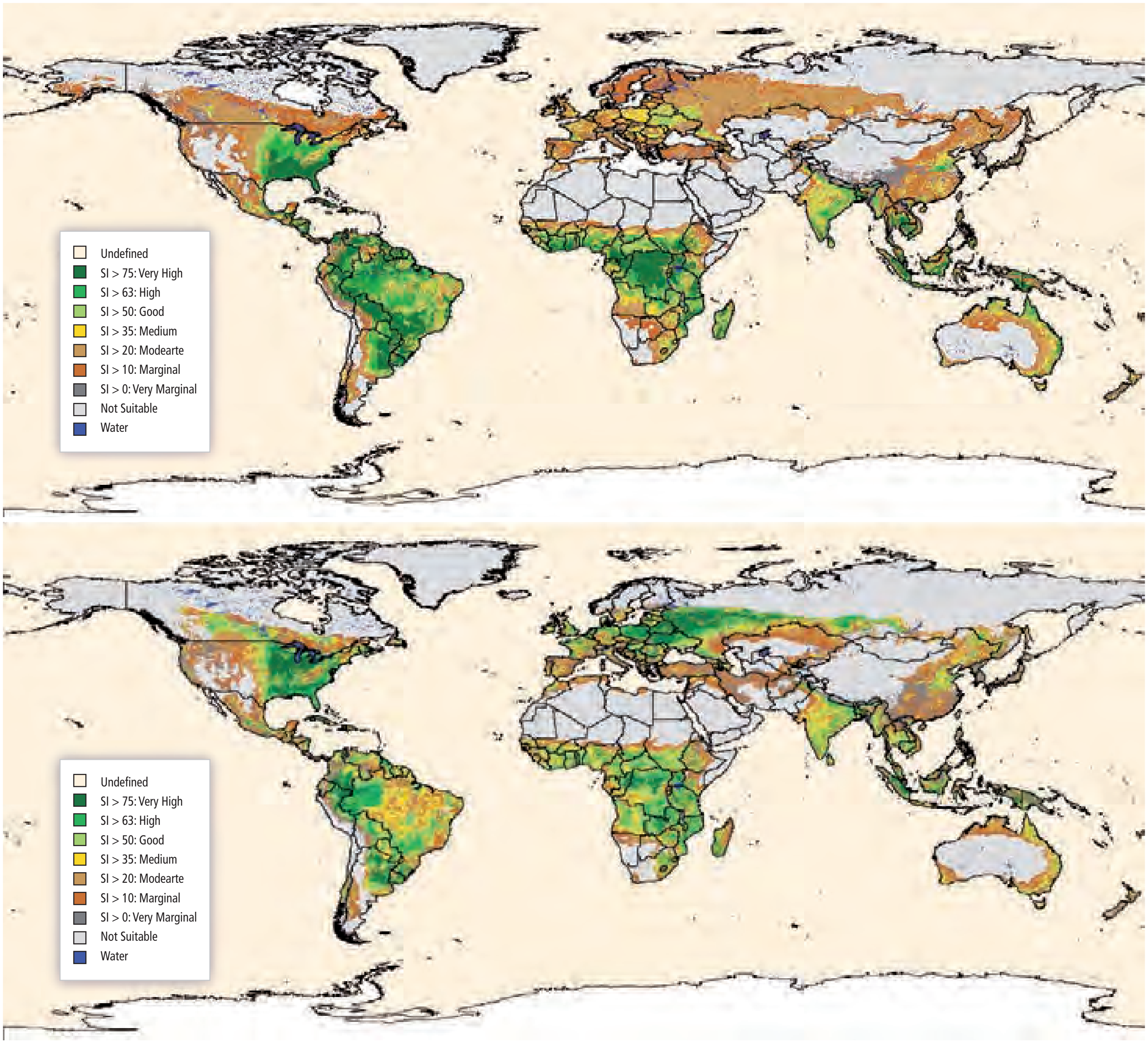


Figure 2.4 | Global land suitability for bioenergy plantations. The upper map shows suitability for herbaceous and woody lignocellulosic plants (*Miscanthus*, switchgrass, reed canary grass, poplar, willow, eucalyptus) and the lower map shows suitability for first-generation biofuel feedstocks (sugarcane, maize, cassava, rapeseed, soybean, palm oil, *Jatropha*). The suitability index (SI)[1] describes the spatial suitability of each pixel and reflects the match between crop requirements and prevailing climate, soil and terrain conditions. The map shows suitability under rain-fed cultivation and advanced management systems that assume availability of sufficient nutrients, adequate pest control and mechanization, and other practices. Results for irrigated conditions or low-input management systems would result in different pictures (Fischer et al., 2009; reproduced with permission from the International Institute for Applied Systems Analysis (IIASA)).

Note: 1. SI: suitability index. The SI used reflects the spatial suitability of each pixel and is calculated as SI = VS*0.9+S*0.7+MS*0.5+mS*0.3, where VS, S, MS and mS correspond to yield levels at 80–100%, 60–80%, 40–60% and 20–40% of the modelled maximum, respectively (Fischer et al., 2009).

with statistical information and data on protected areas, it is possible to quantify suitable lands for different land cover types. A suitability index has been used in order to represent both yield potentials[5] and suitability (see caption to Figure 2.4). For instance, almost 700 Mha (7,000 km^2), or about 20%, of currently unprotected grasslands and woodlands are assessed as suitable for soybean while less than 50 Mha (500 km^2) are assessed as suitable for oil palm (note that these land suitability numbers cannot be added because areas overlap). Considering unprotected forest land, an area roughly 10 times larger (almost 500 Mha or 5,000 km^2) is suitable for oil palm cultivation (Fischer et al., 2009, their Annex 5 and 6). However, converting large areas of forests into biomass plantations would negatively impact biodiversity and might—depending on the carbon density of converted forests—also lead to large initial CO_2 emissions that can drastically reduce the annual accumulated climate benefit of substituting fossil fuels with the bioenergy derived from such plantations. Converting grass- and woodlands with high soil carbon content to intensively cultivated annual crops can similarly lead to large CO_2 emissions, while if degraded and C-depleted pastures are cultivated with herbaceous and woody lignocellulosic plants soil carbon may instead accumulate, enhancing the climate benefit. This is further discussed in Section 2.5.

under a 'food and environment first' paradigm excluding forests and land currently used for food and fodder production. The latter includes estimates of unprotected grassland and woodland required today for ruminant livestock feeding. Calculations are based on FAOSTAT data on fodder utilization of crops, and national livestock numbers, estimated fodder energy requirements of the national herds and derived fodder gaps filled by grassland and pastures. Grassland and woodland with very low productivity or steep sloping conditions were considered unsuitable for lignocellulosic feedstock production. The results, shown in Table 2.3, represent one example of estimates of regional technical potentials of biomass resulting from a specific set of assumptions with respect to nature protection requirements, biofuel feedstock crop choice and agronomic practice determining attainable yield levels and livestock production systems determining grazing requirements. Furthermore, the results represent current agriculture practice and productivity, population, diets, climate etc. Quantifications of the technical potential of the future biomass resource need to consider how such parameters change over time.

A similar analysis (WBGU, 2009; Beringer et al., 2011) reserved current and near-future agricultural land for food and fibre production and also

Table 2.3 | Example of the technical potential of rain-fed lignocellulosic plants on unprotected grassland and woodland (i.e., forests excluded) where land requirements for food production, including grazing, have been considered at 2000 levels. Calculated based on Fischer et al. (2009); reproduced with permission from the International Institute for Applied Systems Analysis (IIASA).

Region	Total grass- and woodland area (Mha) [million km^2]	Protected areas (Mha) [million km^2]	Unproductive or very low productive areas (Mha) [million km^2]	Bioenergy area also excluding grazing land (Mha) [million km^2]	Technical potential (average yield,[1] GJ/ha/yr) [GJ/km^2/yr]	Technical Potential[2] (total, EJ/yr)
North America	659 [6.59]	103 [1.03]	391 [3.91]	111 [1.11]	165 [16,500]	19
Europe and Russia	902 [9.02]	76 [0.76]	618 [6.18]	122 [1.22]	140 [14,000]	17
Pacific OECD	515 [5.15]	7 [0.07]	332 [3.32]	97 [0.97]	175 [17,500]	17
Africa	1,086 [10.68]	146 [1.46]	386 [3.86]	275 [2.75]	250 [2,500]	69
South and East Asia	556 [5.56]	92 [0.92]	335 [3.35]	14 [0.14]	285 [28,500]	4
Latin America	765 [7.65]	54 [0.54]	211 [2.11]	160 [1.6]	280 [28,000]	45
Middle East and North Africa	107 [1.07]	2 [0.02]	93 [0.93]	1 [0.01]	125 [12,500]	0.2
World	**4,605 [46.05]**	**481 [4.81]**	**2,371 [23.71]**	**780 [7.80]**	**220 [22,000]**	**171**

Notes: 1. Calculated based on average yields of rain-fed lignocellulosic feedstocks on grass- and woodland area given in Fischer et al. (2009, p.174) and assuming an energy content of 18 GJ/t dry matter (rounded numbers). 2. If livestock grazing area can be freed up by intensification of agricultural practices and pasture use, these areas could be used for additional bioenergy production. The technical potential in this case could increase from 171 up to 288 EJ/yr.

Technical potentials of biomass plantations can thus be calculated based on assessed land availability and corresponding yield levels. Based on the results as shown in Figure 2.4, Fischer et al. (2009) estimated regional land balances of unprotected grassland and woodland potentially available for rain-fed lignocellulosic biofuel feedstock production excluded unmanaged land from bioenergy production if its conversion to biomass plantations would lead to large net CO_2 emissions to the atmosphere, or if the land was degraded, a wetland, environmentally protected or rich in biodiversity. If dedicated biomass plantations were established in the available lands, an estimated 26 to 116 EJ/yr could be produced (52 to 174 EJ with irrigation). The spatial variation of technical potential was computed from biogeochemical principles, that is, photosynthesis, transpiration, soil quality and climate. Haberl et

5 Yield potential is the yield obtained when an adapted cultivar (cultivated variety of a plant) is grown with the minimal possible stress that can be achieved with best management practices, a functional definition by Cassman (1999).

al. (2010) considered the land available after meeting prospective future food, fodder and nature conservation targets, also taking into account spatial variation in projected future productivity of bioenergy plantations, and arrived at a technical potential in 2050 in the range of 160 to 270 EJ/yr. Of the 210 EJ/yr average technical potential, 81 EJ/yr are provided by dedicated plantations, 27 EJ/yr by residues in forestry and 100 EJ/yr by crop residues, manure and organic wastes, emphasizing the importance of process optimization and cascading biomass use.

Water constraints are highlighted in the literature for agriculture (UN-Water, 2007) and for bioenergy (Berndes, 2002; Molden, 2007; De Fraiture et al., 2008; Sections 9.3.4.4 and 2.5.5.1). In a number of regions the technical potential can decrease to lower levels than what is assessed based on approaches that do not involve explicit geo-hydrological modelling (Rost et al., 2009). Such modelling can lead to improved quality bioenergy potential assessments. Planting of trees and other perennial vegetation can decrease erosive water run-off and replenish groundwater but may lead to substantial reductions in downstream water availability (Calder et al., 2004; Farley et al., 2005).

Illustrative of this, Zomer et al. (2006) report that large areas deemed suitable for afforestation within the Clean Development Mechanism (CDM) would exhibit evapotranspiration increases and/or decreases in runoff if they become forested, that is, a decrease in water potentially available offsite for other uses. This would be particularly evident in drier areas, the semi-arid tropics, and in conversion from grasslands and subsistence agriculture. Similarly, based on a global analysis of 504 annual catchment observations, Jackson et al. (2005) report that afforestation dramatically decreased stream flow within a few years of planting. Across all plantation ages in the database, afforestation of grasslands, shrublands or croplands decreased stream flow by, on average, 38%. Average losses for 10- to 20-year-old plantations were even greater, reaching 52% of stream flow.

Studies by Hoogwijk et al. (2003), Wolf et al. (2003), Smeets et al. (2007) and van Minnen et al., (2008) also illustrate the importance of biomass plantations for reaching a higher global technical potential, and how different determining parameters greatly influence the technical potential. For instance, in a scenario with rapid population growth and slow technology progress, where agriculture productivity does not increase from its present level and little biomass is traded, Smeets et al. (2007) found that no land would be available for bioenergy plantations. In a contrasting scenario where all critical parameters were instead set to be very favourable, up to 3.5 billion hectares (35 million km^2) of former agricultural land—mainly pastures and with large areas in Latin America and sub-Saharan Africa—were assessed as not required for food in 2050. A substantial part of this area was assessed as technically suitable for bioenergy plantations.

2.2.3 Economic considerations in biomass resource assessments

Some studies exclude areas where attainable yields are below a certain minimum level. Other studies exclude biomass resources judged as being too expensive to mobilize, given a certain biomass price level. These assessments address biomass resource availability and cost for given levels of production so that an owner of a facility for secondary energy production from modern biomass could assess a location and the size of a facility for a cost-effective business with a guaranteed supply of biomass throughout the year. Costs models are based on combining land availability, yield levels and production costs to obtain plant- and region-specific cost-supply curves (Walsh, 2008). These are based on projections or scenarios for the development of cost factors, including opportunity cost of land, and can be produced for different contexts and scales—including feasibility studies of supplying individual bioenergy plants and estimating the future global cost-supply curve. Studies using this approach at different scales include Dornburg et al. (2007), Hoogwijk et al. (2009), de Wit et al. (2010) and van Vuuren et al. (2009). P. Gallagher et al. (2003) exemplify the production of cost-supply curves for the case of crop harvest residues and Gerasimov and Karjalainen (2009) for the case of forest wood.

The biomass production costs can be combined with technological and economic data for related logistic systems and conversion technologies to derive market potentials at the level of secondary energy carriers such as bioelectricity and biofuels for transport (e.g., Gan, 2007; Hoogwijk et al., 2009; van Dam et al., 2009c). Using biomass cost and availability data as exogenously defined input parameters in scenario-based energy system modelling can provide information about levels of implementation in relation to a specific energy system context and possible climate and energy policy targets. Cost trends are discussed further in Section 2.7.

Figure 2.5(a) shows projections of European market potential estimated based on food sector scenarios for 2030, considering also nature protection requirements and infrastructure development (Fischer et al., 2010). Estimated production cost supply curves shown in Figure 2.5(b) were subsequently produced including biomass plantations and forest/agriculture residues (de Wit and Faaij, 2010). The key factor determining the size of the market potential was the development of agricultural land productivity, including animal production.

Figure 2.5(c) data for the USA are based on recent assessments of lignocellulosic feedstock supply cost curves conducted at county-level resolution (Walsh, 2008; Perlack et al., 2005; US DOE, 2011). Figure 2.5(d) illustrates the delivered price of biomass to the conversion facility under the baseline conditions for various production levels of lignocellulosic feedstocks.[6] Total market potential for crop-based ethanol and

6 For instance, at a biomass feedstock price of USD_{2005} 3/GJ delivered to the conversion facility, the three types of feedstocks shown in Figure 2.5(d) would provide 5.5 EJ. At higher prices there is more feedstock up to a point, for example, 1.5 EJ for the forest residues in the figure.

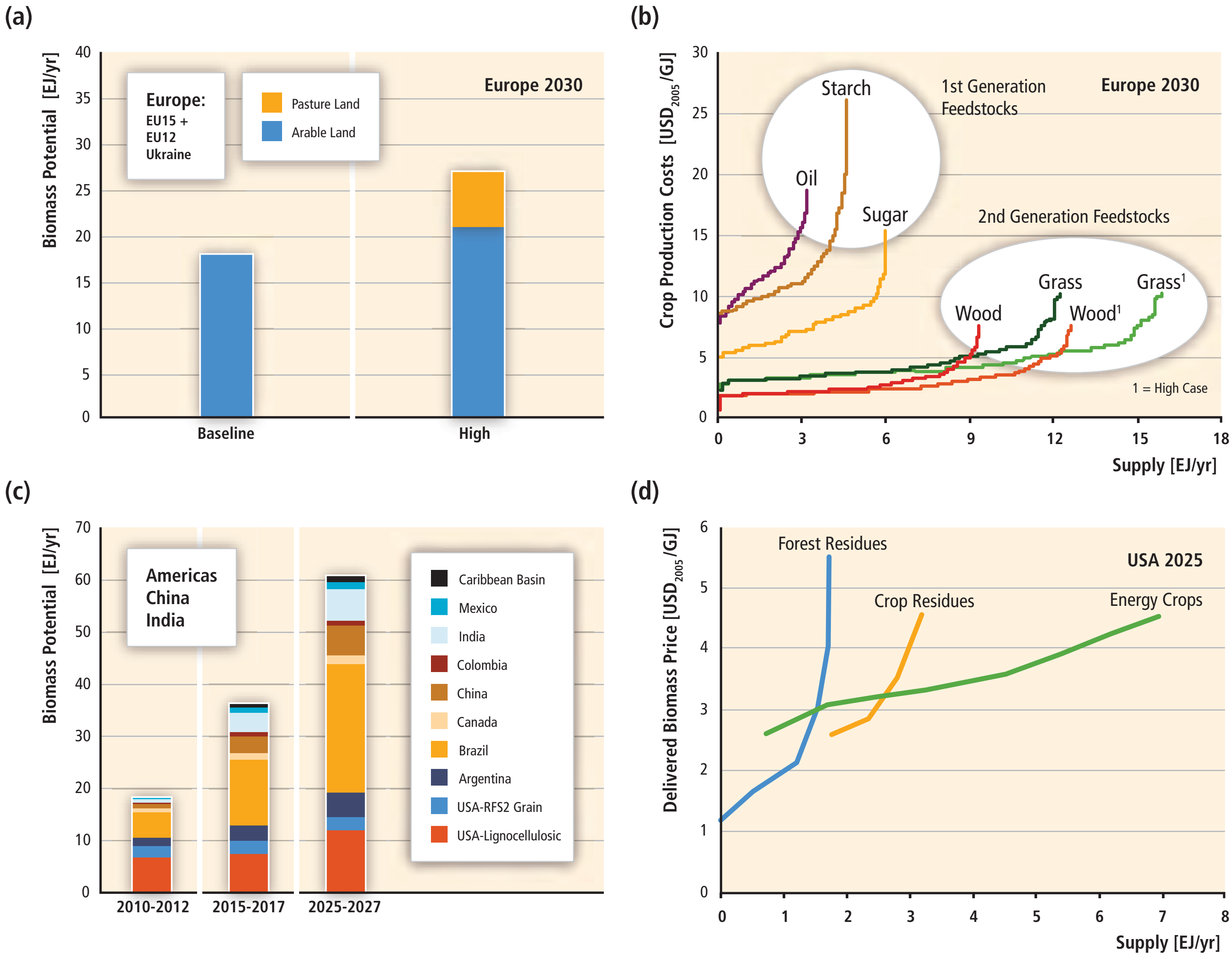


Figure 2.5 | Examples of preliminary market potentials based on feedstock cost supply curves shown in (b) for European countries and (d) for the USA. The feedstock cost supply curves for these assessments are from recent studies conducted at levels of: (a) region; (c) country based on state/province except for the USA, which is performed at a county level. In (c) the US data are for the baseline case and the other countries' cases are for a high-growth scenario (a total of 45 EJ/yr, which would decrease to 25 EJ/yr in the base case and to around 8 EJ/yr in the low case) by 2025. See text for further information. Sources: (a) Fischer et al. (2010); (b) de Wit and Faaij (2010); (c) Kline et al. (2007); Walsh (2008); EPA (2010); (d) Walsh (2008), US DOE (2011).

biodiesel are from EPA (2010) projections. In addition, Figure 2.5(c) includes preliminary estimates of high-growth scenarios of market potentials for the Americas, China and India based on historic production trends and average production costs at the state/province level (Kline et al., 2007), considering multiple crops, residues and perennial biomass crops. Market potentials were estimated based on arable land availability for bioenergy plants and some degree of environmental protection and infrastructure. High-growth market potentials are shown for years 2012, 2017 and 2027 (Kline et al., 2007). The largest supplier, Brazil, is using AgroEcological Zoning (EMBRAPA, 2010) to limit expansion to unrestricted areas with appropriate soil and climate, with no or low irrigation requirements, and low slopes for mechanized harvesting. Similar zoning is available for oil palm.[7] These steps are recommended by several of the organizations developing sustainability criteria (van Dam et al., 2010, and see Section 2.4.5).

2.2.4 Factors influencing biomass resource potentials

As described briefly above, many studies that quantify the biomass resource potential consider a range of factors that reduce it to lower levels than if they are not included. These factors are also connected to impacts arising from the exploitation of biomass resources, which are further discussed in Section 2.5. The most important factors are

7 DECRETO Nº 7172, DE 07 DE MAIO DE 2010, Brazil.

discussed below in relation to how they influence the future biomass resource potential.

2.2.4.1 Residue supply in agriculture and forestry

Soil conservation and biodiversity requirements influence technical potentials for both agriculture and forestry residues. In forestry, the combination of residue harvest and nutrient (including wood ash) input can avoid nutrient depletion and acidification and can in some areas improve environmental conditions due to reduced nutrient leaching from forests (Börjesson, 2000; Eisenbies et al., 2009). Even so, organic matter at different stages of decay plays an important ecological role in conserving soil quality as well as for biodiversity in soils and above ground (Grove and Hanula, 2006). Thresholds for desirable amounts of dead wood in forest stands are difficult to set and the most demanding species require amounts of dead wood that are difficult to reach in managed forests (Ranius and Fahrig, 2006). Dymond et al. (2010) report that estimates from studies taking into account the need for on-site sustainability can be several times lower than those that do not. Large differences were also reported by Gronowska et al. (2009). Titus et al. (2009) report wide ranges (0 to 100%) in allowed residue recovery rates for large-scale logging residue inventories and propose a 50% retention proportion as an appropriate level, noting that besides soil sustainability additional aspects (e.g., biodiversity and water quality) need to be considered.

Development of technologies for stump harvesting after felling increases the availability of residues during logging (Näslund-Eriksson and Gustavsson, 2008). Stump harvesting can also reduce the cost of site preparation for replanting (Saarinen, 2006). It can reduce damage from insects and spreading of root rot fungus, but can also lead to negative effects including reduced forest soil carbon and nutrient stocks, increased soil erosion and soil compaction (Zabowski et al., 2008; Walmsley and Godbold, 2010).

In agriculture, overexploitation of harvest residues is one important cause of soil degradation in many places in the world (Wilhelm et al., 2004; Ball et al., 2005; Blanco-Canqui et al., 2006; Lal, 2008). Fertilizer inputs can compensate for nutrient removals connected to harvest and residue extraction, but maintenance or improvement of soil fertility, structural stability and water-holding capacity requires recirculation of organic matter to the soil (Lal and Pimentel, 2007; Wilhelm et al., 2007; Blanco-Canqui and Lal, 2009). Residue recirculation leading to nutrient replenishment and carbon storage in soils and dead biomass not only contributes positively to climate change mitigation by withdrawing carbon from the atmosphere but also by reducing soil degradation and improving soil productivity. This leads to higher yields and consequently less need to convert land to croplands for meeting future food/fibre/bioenergy demand (i.e., fewer GHG emissions arising from vegetation removal and ploughing of soils). Residue removal can, all other things being equal, be increased when total biomass production per hectare becomes higher and if 'waste' from processing of crop residues that is rich in refractory compounds such as lignin is returned to the field (J. Johnson et al., 2004; Reijnders, 2008; Lal, 2008).

Principles, criteria and indicators are developed to ensure ecological sustainability (e.g., van Dam et al., 2010; Lattimore et al., 2009; Section 2.4.3) but these cannot easily be used to derive sustainable residue extraction rates. Large uncertainties are also linked to the possible future development of several factors determining residue generation rates. Population growth, economic development and dietary changes influence the demand for products from agriculture and forestry, and materials management strategies (including recycling and cascading use of material) influence how this demand translates into demand for basic food commodities and industrial roundwood.

Furthermore, changes in food and forestry sectors influence the residue/waste generation per unit of product output up or down: crop breeding leads to improved harvest index, reducing residue generation rates; implementation of no-till/conservation agriculture requires that harvest residues are left on the fields to maintain soil cover and increase organic matter in soils (Lal, 2004); shifts in livestock production to more confined and intensive systems can increase recoverability of dung but reduce overall dung production at a given level of livestock product output; and increased occurrence of silvicultural treatments such as early thinning to improve stand growth will lead to increased availability of small roundwood suitable for energy uses.

Consequently, the longer-term technical potential connected to residue/waste flows will continue to be uncertain even if more comprehensive assessment approaches are used. It should be noted that it does not necessarily follow that more comprehensive assessments of determining factors will lead to a lower technical potential of residues; earlier studies may have used conservative residue recovery rates as a precaution in the face of uncertainties (S. Kim and Dale, 2004). However, modelling studies indicate that the cost of soil productivity loss may restrict residue removal intensity to much lower levels than the quantity of biomass physically available in forestry (Gan and Smith, 2010).

2.2.4.2 Dedicated biomass production in agriculture and forestry

Studies indicate significant potential for intensifying conventional long-rotation forestry to increase forest growth and total biomass output—for instance, by fertilizing selected stands and using shorter rotations (Nohrstedt, 2001; Saarsalmi and Mälkönen, 2001)—especially in regions of the world with large forest areas that currently practice extensive forest management. Yet, the prospects for intensifying conventional long-rotation forestry to increase forest growth are not thoroughly investigated in the assessed studies of biomass resource potentials. Instead, the major source of increased forest biomass output is assumed to be fast-growing tree plantations. Besides tree plantations, short-rotation coppicing plants such as willow and perennial grasses such as switchgrass and *Miscanthus* are considered candidate bioenergy plants to become established on these lands.

It is commonly assumed that biomass plantations are established on surplus agricultural land. Intensification in agriculture is therefore a key aspect in essentially all of the assessed studies because it influences both land availability for biomass plantations (indirectly by determining the land requirements in the food sector) and the biomass yield levels obtained. High assessed technical potentials for energy plantations rely on high-yielding agricultural systems and international bioenergy trade leading to the result that biomass plantations are established globally where the production conditions are most favourable. Increasing yields from existing agricultural land is also proposed as a key component for agricultural development (Ausubel, 2000; Fischer et al., 2002; Tilman et al., 2002; Cassman et al., 2003; Evans, 2003; Balmford et al., 2005; Green et al., 2005; D. Lee et al., 2006; Bruinsma, 2009). Studies also point to the importance of diets and the food sector's biomass use efficiency in determining land requirements (both cropland and grazing land) for food (Gerbens-Leenes and Nonhebel, 2002; Smil, 2002; Carlsson-Kanyama and Shanahan, 2003; de Boer et al., 2006; Elferink and Nonhebel, 2007; Stehfest et al., 2009; Wirsenius et al., 2010).

Studies of agricultural development (e.g., Koning, 2008; Alexandratos, 2009; IAASTD, 2009) show lower expected yield growth than studies of the biomass resource potential that report very high technical potentials for biomass plantations (Johnston et al., 2009). Some observations indicate that it can be a challenge to maintain yield growth in several main producer countries and that much cropland and grazing land undergoes degradation and productivity loss as a consequence of improper land use (Cassman, 1999; Pingali and Heisey, 1999; Fischer et al., 2002). The possible consequences of climate change for crop yields are not firmly established but indicate net global negative impact, where damages will be concentrated in developing countries that will lose agriculture production potential while developed countries might gain (Fischer et al., 2002; Cline, 2007; Easterling et al., 2007; Schneider et al., 2007; Lobell et al., 2008; Fischer et al., 2009). Water scarcity can limit both intensification possibilities and the prospects for expansion of bioenergy plantations (Berndes, 2008a,b; de Fraiture et al., 2008; de Fraiture and Berndes, 2009; Rost et al., 2009; van Vuuren et al., 2009) but can be partially alleviated through on-site water management (Rost et al., 2009). Biomass resource potential studies that use biophysical data sets and modelling are able to consider water limitations on land productivity. However, assumptions about productivity growth in land use may implicitly presume irrigation development that could lead to problems in regional water availability, use and distribution among users. Empirical data are needed for use in hydrological process models to better understand and predict the hydrological effects of various land use options at the landscape level (Malmer et al., 2010). Water and land use-related aspects are further discussed in Section 2.5.

Conversely, some observations indicate that rates of gain obtained from breeding have increased in recent years after previous stagnation and that yields might increase faster again as newer hybrids are adopted more widely (Edgerton, 2009). Theoretical limits also appear to leave scope for further increasing the genetic yield potential (Fischer et al., 2009). It should be noted that studies finding high technical potential for bioenergy plantations point primarily to tropical developing countries as major contributors. These countries still have substantial yield gaps to exploit and large opportunities for productivity growth—not the least in livestock production (Fischer et al., 2002; Edgerton, 2009; Wirsenius et al., 2010). There is also a large yield growth potential for dedicated bioenergy plants that have not been subject to the same breeding efforts as the major food crops. Selection and development of suitable plant species and genotypes for given locations to match specific soil types, climate and conversion technologies are possible, but are at an early stage of understanding for some energy plants (Bush and Leach, 2007; Chapple et al., 2007; Lawrence and Walbot, 2007; Carpita and McCann, 2008; Karp and Shield, 2008). Traditional plant breeding, selection and hybridization techniques are slow, particularly for woody plants but also for grasses, but new biotechnological routes to produce both genetically modified (GM) and non-GM plants are possible (Brunner et al., 2007). GM energy plant species may be more acceptable to the public than GM food crops, but there are concerns about the potential environmental impacts of such plants, including gene flow from non-native to native plant relatives (Chapotin and Wolt, 2007; Firbank, 2008; Warwick et al., 2009; see Section 2.5.6.1).

There can be limitations on and negative aspects of further intensification aiming at farm yield increases, for example, high crop yields depending on large inputs of nutrients, fresh water and pesticides can contribute to negative ecosystem effects, such as changes in species composition in the surrounding ecosystems, groundwater contamination and eutrophication with harmful algal blooms, oxygen depletion and anoxic 'dead' zones in oceans (Donner and Kucharik, 2008; Simpson et al., 2009; Sections 2.5.5.1 and 2.6.1.2). However, intensification is not necessarily equivalent to an industrialization of agriculture, as agricultural productivity can be increased in many regions and systems with conventional or organic farming methods (Badgley et al., 2007). The potential to increase the currently low productivity of rain-fed agriculture exists in large parts of the world through improved soil and water conservation (Lal, 2003; Rockström et al., 2007, 2010), fertilizer use and crop selection (Cassman, 1999; Keys and McConnell, 2005). Available best practices[8] are not at present applied in many world regions (Godfray et al., 2010), due to a lack of dissemination, capacity building, availability of resources and access to capital and markets, with distinct regional differences (Neumann et al., 2010).

8 For example, mulching, low tillage, contour ploughing, bounds, terraces, rainwater harvesting and supplementary irrigation, drought adapted crops, crop rotation and fallow time reduction.

Conservation agriculture and mixed production systems (double-cropping, crop with livestock and/or crop with forestry) hold potential to sustainably increase land productivity and water use efficiency as well as carbon sequestration and to improve food security and efficiency in the use of limited resources such as phosphorous (Kumar, 2006; Heggenstaller et al., 2008; Herrero et al., 2010). Integration can also be based on integrating feedstock production with conversion—typically producing animal feed that can replace cultivated feed such as soy and corn (Dale et al., 2009, 2010) and also reduce grazing requirements (Sparovek et al., 2007).

Investment in agricultural research, development and deployment could produce a considerable increase in land and water productivity (Rost et al., 2009; Herrero et al., 2010; Sulser et al., 2010) as well as improve robustness of plant varieties (Reynolds and Borlaug, 2006; Ahrens et al., 2010). Multi-functional systems (IAASTD, 2009) providing multiple ecosystem services (Berndes et al., 2004, 2008a,b; Folke et al., 2004, 2009) represent alternative options for the production of bioenergy on agricultural lands that could contribute to development of farming systems and landscape structures that are beneficial for the conservation of biodiversity (Vandermeer and Perfecto, 2006).

2.2.4.3 Use of marginal lands

Biomass resource potential studies also point to marginal/degraded lands—where productive capacity has declined temporarily or permanently—as lands that can be used for biomass production. Advances in plant breeding and genetic modification of plants not only raise the genetic yield potential but also may adapt plants to more challenging environmental conditions (Fischer et al., 2009). Improved drought tolerance can improve average yields in drier areas and in rain-fed systems in general by reducing the effects of sporadic drought (Nelson et al., 2007; Castiglioni et al., 2008) and can also reduce water requirements in irrigated systems. Thus, besides reducing land requirements for meeting food and materials demand by increasing yields, plant breeding and genetic modification could make lands initially considered unsuitable available for rain-fed or irrigated production.

Some studies show a significant technical potential of marginal/degraded land, but it is uncertain how much of this technical potential can be realized. The main challenges in relation to the use of marginal/degraded land for bioenergy include (1) the large efforts and long time periods required for the reclamation and maintenance of more degraded land; (2) the low productivity levels of these soils; and (3) ensuring that the needs of local populations that use degraded lands for their subsistence are carefully addressed. Studies point to the benefits of local stakeholder participation in appraising and selecting appropriate measures (Schwilch et al., 2009) and suggest that land degradation control could benefit from addressing aspects of biodiversity and climate change and that this could pave the way for funding via international financing mechanisms and major donors (Knowler, 2004; Gisladottir and Stocking, 2005). In this context, the production of properly selected plant species for bioenergy can be an opportunity, where additional benefits involve carbon sequestration in soils and aboveground biomass and improved soil quality over time.

2.2.4.4 Biodiversity protection

Considerations regarding biodiversity can limit residue extraction as well as intensification and expansion of agricultural land area. WBGU (2009) shows that the way biodiversity is considered can have a larger impact on technical potential than either irrigation or climate change. The common way of considering biodiversity requirements as a constraint is by including requirements for land reservation for biodiversity protection. Biomass resource potential assessments commonly exclude nature conservation areas from being available for biomass production, but the focus is as a rule on forest ecosystems and takes the present level of protection as a basis. Other natural ecosystems also require protection—not least grassland ecosystems—and the present status of nature protection for biodiversity may not be sufficient for given targets. While many highly productive lands have low natural biodiversity, the opposite is true for some marginal lands and, consequently, the largest impacts on biodiversity could occur with widespread use of marginal lands.

Some studies indirectly consider biodiversity constraints on productivity by assuming a certain expansion of alternative agriculture production (to promote biodiversity) that yields less than conventional agriculture and therefore requires more land for food production (EEA, 2007; Fischer et al., 2009). However, for multi-cropping systems a general assumption of lower yields from alternative cropping systems is not consistent. Biodiversity loss may also occur indirectly, such as when productive land use displaced by energy crops is re-established by converting natural ecosystems into croplands or pastures elsewhere. Integrated energy system and land use/vegetation cover modelling have better prospects for analyzing these risks.

Bioenergy plantations can play a role in promoting biodiversity, particularly when multiple species are planted and mosaic landscapes are established in uniform agricultural landscapes and in some currently poor or degraded areas (Hartley, 2002). Agro-forestry systems combining biomass and food production can support biodiversity conservation in human-dominated landscapes (Bhagwat et al., 2008). Biomass resource potential assessments, however, as a rule assume yield levels corresponding to those achieved in monoculture plantations and therefore provide little insight into how much biomass could be produced if a significant part of the biomass plantation were shaped to contribute to biodiversity preservation.

2.2.5 Possible impact of climate change on resource potential

Technical potentials are influenced by climate change. The magnitude and spatial pattern of climate change remain uncertain[9] despite high scientific confidence that global warming and an intensification of the hydrological cycle will be a consequence of increased GHG concentrations in the atmosphere (IPCC, 2007c). Furthermore, the effect of unhistorical new changes in temperature, irradiation and soil moisture on the growth of agricultural plants is frequently uncertain (Lobell and Burke, 2008), as is the adaptive response of farmers. As a consequence, the overall magnitude and pattern of climate change effects on agricultural production, including bioenergy plantations, remain uncertain. While positive effects on plant growth may occur, detrimental impacts on productivity cannot at present be precluded for many important regions.

Uncertainty also remains about the concurrent ecophysiological effect of elevated atmospheric CO_2 concentration on plant productivity—the CO_2 fertilization effect. Under elevated CO_2 supply, the growth of plants with C_3 photosynthesis is increased unless it is hampered by increased water stress or nutrient depletion (Oliver et al., 2009). The long-term magnitude of the carbon fertilization effect is disputed, with increases in annual NPP of around 25% possible and observed in some field experiments for a doubling of atmospheric CO_2 concentration (the effect levels off at higher CO_2 concentrations), while some expect smaller gains due to co-limitations and eventual adaptations (Ainsworth and Long, 2005; Körner et al., 2007). The magnitude of the effect under agricultural management and breeding conditions may be different and is not well known.

Under climate warming, the increased requirement for transpiration water by vegetation is partially countered by increased water use efficiency (increased stomatal closure) under elevated atmospheric CO_2 concentrations, with variable regional patterns (Gerten et al., 2005). Changes in precipitation patterns and magnitude can increase or decrease plant production depending on the direction of change. Generally, some semi-arid marginal lands are projected to be more productive due to increased water use efficiency under CO_2 fertilization (Lioubimtseva and Adams, 2004). As crop production is projected to mostly decline with warming of more than 2°C (Easterling et al., 2007), particularly in the tropics, biomass for energy production could be similarly affected. Overall, the effects of climate change on biomass technical potential are found to be smaller than the effects of management, breeding and area planted (WBGU, 2009), but in any particular region they can be strong. Which regions will be most affected remains uncertain, but tropical regions are most likely to see the strongest negative impact.

9 Uncertainties arise because future GHG emission trajectories cannot be known (and are therefore studied using a variety of scenarios), the computed sensitivities of climate models to GHG forcing vary (i.e., the amount of warming that follows from a given emission scenario), and the spatial pattern and seasonality of changes in precipitation vary greatly between models, particularly for some tropical and subtropical regions (Li et al., 2006).

2.2.6 Synthesis

As discussed, narrowing down the technical potential of the biomass resource to precise numbers is not possible. A number of studies show that between less than 50 and several hundred EJ per year can be provided for energy in the future, the latter strongly conditional on favourable developments. From an assessment of the findings, it can be concluded that:

- The size of the future technical potential is dependent on a number of factors that are inherently uncertain and will continue to make long-term technical potentials unclear. Important factors are population and economic/technology development and how these translate into fibre, fodder and food demand (especially share and type of animal food products in diets) and development in agriculture and forestry.
- Additional important factors include (1) climate change impacts on future land use including its adaptation capability; (2) considerations set by biodiversity and nature conservation requirements; and (3) consequences of land degradation and water scarcity.
- Studies point to residue flows in agriculture and forestry and unused (or extensively used) agricultural land as an important basis for expansion of biomass production for energy, both in the near term and in the longer term. Consideration of biodiversity and the need to ensure maintenance of healthy ecosystems and avoid soil degradation set bounds on residue extraction in agriculture and forestry (further discussed in Section 2.5.5).
- Grasslands and marginal/degraded lands are considered to have potential for supporting substantial bioenergy production, but biodiversity considerations and water shortages may limit this potential. The possibility that conversion of such lands to biomass plantations reduces downstream water availability needs to be considered.
- The cultivation of suitable plants can allow for higher technical potentials by making it possible to produce bioenergy on lands less suited for conventional food crops—also when considering that the cultivation of conventional crops on such lands can lead to soil carbon emissions (further discussed in Section 2.5.2).
- Landscape approaches integrating bioenergy production into agriculture and forestry systems to produce multi-functional land use systems could contribute to the development of farming systems and landscape structures that are beneficial for the conservation of biodiversity and help restore/maintain soil productivity and healthy ecosystems.

- Water constraints may limit production in regions experiencing water scarcity. But the use of suitable energy crops that are drought tolerant can also help adaptation in water-scarce situations. Assessments of biomass resource potentials need to more carefully consider constraints and opportunities in relation to water availability and competing uses.

Based on this expert review of the available scientific literature, deployment levels of biomass for energy could reach a range of 100 to 300 EJ/yr around 2050 (see Section 2.8.4.1 for more detail). This can be compared with the present biomass use for energy of about 50 EJ/yr. While recent assessments employing improved data and modelling capacity have not succeeded in providing narrow, distinct estimates of the biomass resource potential, they have advanced the understanding of how influential various factors are on the resource potential and that both positive and negative effects may follow from increased biomass use for energy. One important conclusion is that the effects of LUC associated with bioenergy expansion can considerably influence the climate benefit of bioenergy (Section 2.5.5). The insights from the resource assessments can improve the prospects for bioenergy by pointing out the areas where development is most crucial and where research is needed. A summary is given in Section 2.8.4.3.

2.3 Technologies and applications

This section reviews commercial technologies for biomass feedstock production, pretreatment of solid biomass and logistics of supply chains bringing feedstocks to direct users. The users can be individuals (e.g., fuelwood for cooking or heating) or firms (e.g., industrial users or processors). Pretreated and converted energy carriers are more convenient and can be used in more applications than the original biomass and are modern solid (e.g., pellets), liquid (e.g., ethanol) and gaseous (e.g., methane) fuels from which electricity and/or heat or mobility services are produced (see Figure 2.2). The integration of modern biomass with existing and evolving electricity, natural gas, heating (residential and district, commercial and public services), industrial, agriculture/forestry, and fossil liquid fuels systems is discussed thoroughly in Chapter 8.

This section is organized along the supply chain of bioenergy and thus discusses feedstock production and the synergies with related sectors before turning to pretreatment, logistics and supply chains of solid biomass. The section then explains different state-of-the-art conversion technologies for energy carriers from modern biomass before discussing the costs, directly available from relevant literature, of these broader bioenergy systems and supply chains. Section 2.6 provides prospects for technology improvement, innovation and integration before Section 2.7 addresses relevant cost information in terms of levelized cost of production for many world regions.

2.3.1 Feedstocks

2.3.1.1 Feedstock production and harvest

The performance characteristics of major biomass production systems, dedicated plants or primary residues across the world regions are summarized in Table 2.4. The management of energy plants includes the provision of seeds or seedlings, stand establishment and harvest, soil tillage, irrigation, and fertilizer and pesticide inputs. The latter depend on crop requirements, target yields and local pedo-climatic conditions, and may vary across world regions for similar species (Table 2.4). Strategies such as integrated pest management or organic farming may alleviate the need for synthetic inputs for a given output of biomass (Pimentel et al., 2005).

Wood for energy is obtained as fuelwood or as residue. While fuelwood is derived from the logging of natural or planted forests or trees and shrubs grown in agriculture fields, residues are derived from wood waste and by-products. While natural forests are not managed for production per se, problems arise if fuelwood extraction exceeds the regeneration capacity of the forests, which is the case in many parts of the world. The management of planted forests involves silvicultural techniques similar to those used in cropping systems and includes stand establishment and tree felling (Nabuurs et al., 2007).

Biomass may be harvested several times per year (for forage-type feedstocks such as hay or alfalfa), once per year (for annual species such as wheat or perennial grasses), or every 2 to 50 years or more (for short-rotation coppice and conventional forestry, respectively). Sugarcane is harvested annually but planted every 4 to 7 years and grown in ratoons; it is considered a perennial grass. Harvested biomass is typically transported to a collection point on the farm or at the edge of the road before being transported to the bioenergy unit or to an intermediate storage facility. It may be preconditioned and densified to facilitate storage, transport and handling (see Section 2.3.2).

The species listed in Table 2.4 have different possible energy end uses and require diverse conversion technologies (see Figure 2.6). Starch and oil crops are grown and harvested annually as feedstocks for what are called first-generation liquid biofuels (ethanol and biodiesel, see Section 2.3.3). Only a fraction of the total aboveground biomass is used for biofuels, with the rest being processed for animal feed or lignocellulosic residues. Sugarcane plants are feedstocks for the production of sugar and ethanol and, increasingly, sugarcane bagasse and straw, which serve as sources of process heat and extra power in many sugar- and ethanol-producing countries (Macedo et al., 2008; Dantas et al., 2009; Seabra et al., 2010) resulting in favourable environmental footprints for these biorefinery products. Lignocellulosic plants such as perennial grasses or short-rotation coppice may be entirely converted to energy, and feature two to five times higher

Table 2.4 | Typical characteristics of the production technologies for dedicated species and their primary residues. Yields are expressed as GJ of energy content in biomass prior to conversion to energy, or of the ethanol end product for sugar and starch crops. Costs refer to private production costs or market price when costs were unavailable (data from 2005 to 2009). Key to management inputs: +: low; ++: moderate; +++: high requirements.

Feedstock type	Region	Yield	Management			Co-products	Costs	Refs.
		GJ/ha/yr [TJ/km²/yr]	Fertilizer use[1]	Water needs	Pesticides		Examples (2005-2009) USD/GJ	
OIL CROPS		**As oil**						
Oilseed rape	Europe	60–70 [6.7–7.0]	+++	+	+++	Rape cake, straw	7.2–16.0	1,2,3,22
Soybean	North America	16–19 [1.6–1.9]	++	+	+++	Soy cake, straw	11.7	3,12
	Brazil	18–21 [1.8–2.1]	++	+	+++		N/A	
Palm oil	Asia	135–200 [13.5–20.0]	++	+	+++	Fruit bunches, press fibres	N/A	
	Brazil	169 [16.9]	++	+	+++		12.6[2]	3
Jatropha	World	17–88 [1.7–8.8]	+/++	+	+	Seed cake (toxic), wood, shells	3.2	3,4,5,10,11
STARCH CROPS		**As ethanol**						
Wheat	Europe	54–58 [5.4–5.8]	+++	++	+++	Straw, DDGS[3]	5.2	3
Maize	North America	72–79 [7.2–7.9]	+++	+++	+++	Corn stover, DDGS	10.9	3
Cassava	World	43 [4.3]	++	+	++	DDGS	3.3–4	3
SUGAR CROPS		**As ethanol**						
Sugarcane	Brazil	116–149 [11.6–14.9]	++	+	+++	Bagasse, straw	1.0–2.0[2]	3,17
	India	95–112 [9.5–11.2]					N/A	3
Sugar beet	Europe	116–158 [11.6–15.8]	++	++	+++	Molasses, pulp	5.2–9.6	3,13,22
Sorghum (sweet)	China	105–160 [10.5–16.0]	+++	+	++	Bagasse	4.4	2,21
LIGNOCELLULOSIC CROPS		**As ethanol**						
Miscanthus	Europe	190–280 [19.0–28.0]	+/++	++	+		4.8–16	6,8
Switchgrass	Europe	120–225 [12.0–22.5]	++	+	+		2.4–3.2	10,14
	North America	103–150 [10.3–15.0]	++	+	+		4.4	
Short rotation (SR)	Southern Europe	90–225 [9.0–22.5]	+	++	+	Tree bark	2.9–4	10,14
Eucalyptus	South America	150–415 [15.0–41.5]	+/++	+	+		2.7	16,19
SR Willow	Europe	140 [14.0]					4.4	2,7
Fuelwood (chopped)	Europe	110 [11.0]				Forest residues	3.4–13.6	15
Fuelwood (renewable, native forest)	Central America	80–150 [8.0–15.0]					1.8–2.0	23
PRIMARY RESIDUES								
Wheat straw	Europe	60 [6.0]	+			Not Applicable	1.9	2
	USA	7–75 [0.7–7.5]					N/A	14, 20
Sugarcane straw	Brazil	90–126 [9.0–12.6]	+				N/A	17
Corn stover	North America	15–155 [1.5–15.5]	+				N/A	9,14
	India	22–30 [2.2–3.0]	+				0.9	18
Sorghum stover	World	85 [8.5]	+				N/A	9
Forest residues	Europe	2–15 [0.2–1.5]					1–7.7	15

Notes: 1. Nitrogen, phosphorus, and potassium; 2. Market price; 3. DDGS: Dried Distillers Grain with Solubles. These are illustrative cost figures or market prices from the literature. See Annex II for ranges of costs for specific commercial feedstocks over a year period.

References: 1: EEA (2006); 2: Edwards et al. (2007); 3: Bessou et al. (2010); 4: Jongschaap et al. (2007); 5: Openshaw (2000); 6: Clifton-Brown et al. (2004); 7: Ericsson et al. (2009); 8: Fagernäs et al. (2006); 9: Lal (2005); 10: WWI, (2006); 11: Maes et al. (2009); 12: Gerbens-Leenes et al. (2009);13: Berndes (2008a,b); 14: Perlack et al. (2005); 15: Asikainen et al. (2008); 16: Scolforo (2008); 17: Folha (2005); 18: Guille (2007); 19: Diaz-Balteiro and Rodriguez (2006); 20: Lal (2005); 21: Grassi et al. (2006); 22: Faaij (2006); 23: T. Johnson et al. (2009). See Bessou et al. (2010) for specific biofuel volumes per hectare for various countries; see also IEA Renewable Energy Division (2010) for additional country information.

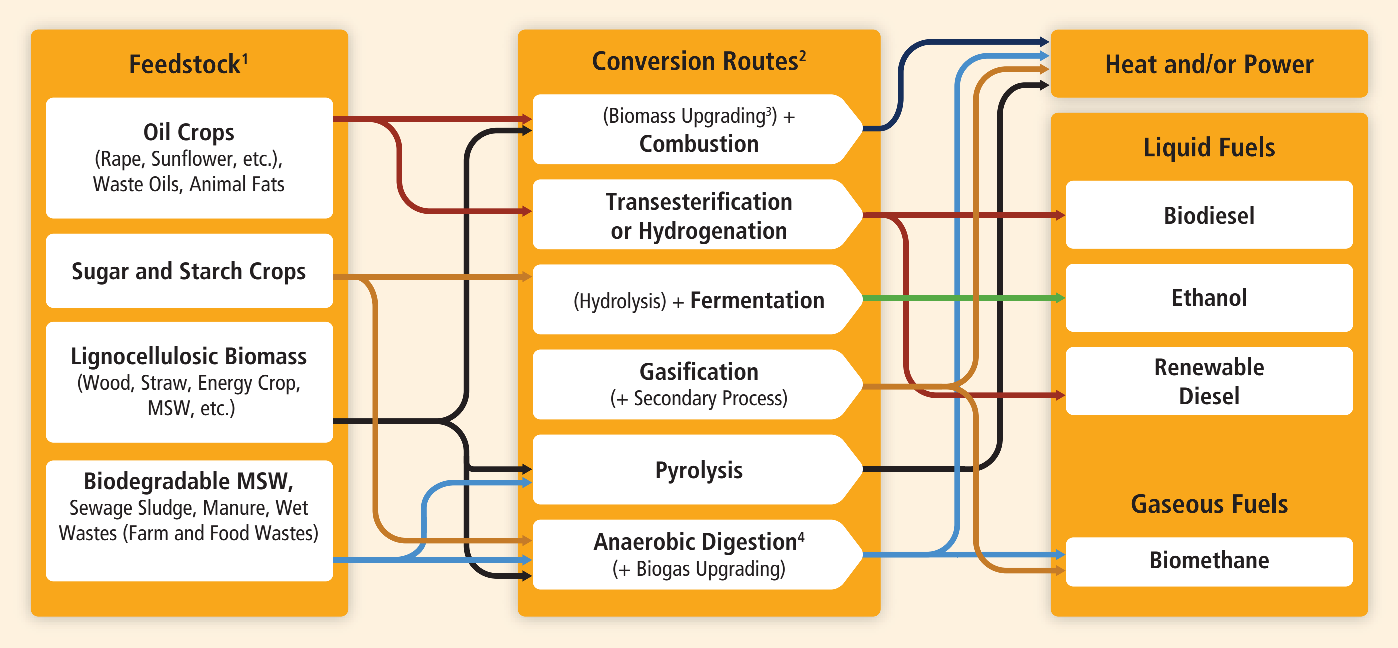


Figure 2.6 | Schematic view of commercial bioenergy routes (modified from IEA, Bioenergy, 2009).

Notes: 1. Parts of each feedstock, for example, crop residues, could also be used in other routes. 2. Each route also gives co-products. 3. Biomass upgrading includes any one of the densification processes (pelletization, pyrolysis, etc.). 4. Anaerobic digestion processes release methane and CO_2 and removal of CO_2 provides essentially methane, the main component of natural gas; the upgraded gas is called biomethane.

yields per hectare than most of the other feedstock types, while requiring far fewer synthetic inputs when managed carefully (Hill, 2007). However, their impact on soil organic matter after the removal of stands is not well understood (Wilhelm et al., 2007; Anderson-Teixeira et al., 2009). Research is underway to assess site-specific removal levels as a function of time and strategies to mitigate weather impacts on residue removal (e.g., Karlen, 2010; Zhang et al., 2010). With technologies that are currently commercial, lignocellulosic feedstocks are only providing heat and power whereas the harvest products of oil, sugar and starch crops are being converted readily to liquid biofuels and in some cases together with heat and power.

Production and harvest costs for dedicated plants vary widely according to the prices of inputs, machinery, labour and land-related costs (Ericsson et al., 2009; Table 2.4). If energy plantations are to compete with land dedicated to food production, the opportunity cost of land (the price that a farmer needs to receive in order to switch from the known annual crop cultivation to an energy crop) could be quite significant and may escalate proportionally with the demand for energy feedstocks (Bureau et al., 2010). Cost-supply curves scaling from farm to the regional level are needed to account for possible large-scale deployment scenario effects (see examples in Figures 2.5(b) and 2.5(d) for feedstock supplies in Europe (cost) and the USA (delivered price), respectively, as a function of feedstock production level, with the unit price per GJ growing several-fold as the total demand for biomass increases).

The cost of forest products depends heavily on harvesting and other logistical practices. In particular labour costs, machinery and the distance from the logging site to the conversion plant are important (Asikainen et al., 2008). This favours local, non-centralized markets especially in developing countries where forests are the dominant fuel source for households (Bravo et al., 2010).

2.3.1.2 Synergies with the agriculture, food and forest sectors

As emphasized in Section 2.2.1, bioenergy feedstock production competes with other uses for resources, chiefly land, with possible negative effects on biodiversity, water availability, soil quality and climate (see Sections 2.2.4 and 2.5). However, synergistic effects may also emerge through the design of integrated production systems, which also provide additional environmental services. Intercropping and mixed cropping are options to maximize the output of biomass per unit area farmed (WWI, 2006). Mixed cropping systems result in increased yields compared to single crops, and may provide both food/fodder and energy feedstocks from the same field (Jensen, 1996; Tilman et al., 2006b). Double-cropping systems have the potential to generate additional feedstocks for bioenergy and livestock utilization and potentially higher yields of biofuel from two crops in the same area in a year (Heggenstaller et al., 2008).

Agro-forestry systems make it possible to use land for food, fodder, timber and energy purposes with mutual benefits for the associated species (R. Bradley et al., 2008). The associated land equivalent ratios may reach up to 1.5, meaning a 50% saving in land area when combining trees with arable crops compared to monocultures (Dupraz and Liagre, 2008) and therefore an equal reduction in indirect LUC effects (see Section

2.5.3). Another option is growing an understory food crop and coppicing the lignocellulosic species to produce residual biomass for energy, similarly to short-rotation coppice (Dupraz and Liagre, 2008). Perennial plants create positive externalities such as erosion control, improved fertilizer use efficiency and reduction in nitrate leaching relative to annual plants (see Section 2.2.4.2). Lastly, the revenues generated from growing bioenergy feedstocks may provide access to technologies or inputs enhancing the yields of food crops, drive additional investments in the agricultural sector and contribute to productivity gains (De La Torre Ugarte and Hellwinckel, 2010), provided feedstock benefits are distributed to local communities (Practical Action Consulting, 2009).

2.3.2 Logistics and supply chains for energy carriers from modern biomass

Because biomass is mostly available in low-density form, it demands more storage space, transport and handling than fossil equivalents, with consequent cost implications. Biomass often needs to be processed (pretreated) to improve handling. For most bioenergy systems and chains, handling and transport of biomass from the source location to the conversion plant is an important contributor to the overall costs of energy production. Crop harvesting, storage, transport, pretreatment and delivery can amount to 20 to 50% of the total costs of energy production (J. Allen et al., 1998).

Use of a single agricultural biomass feedstock for year-round energy generation requires relatively large storage because biomass is only available for a short time following harvest in many places. In addition to such seasonal variations in biomass availability, other characteristics complicate the biomass supply chain and should be taken into account. These include multiple feedstocks with their own complex supply chains, and storage challenges such as space constraints, fire hazards, moisture control and health risks from fungi and spores (Junginger et al., 2001; Rentizelas et al., 2009).

2.3.2.1 Solid biomass supplies and market development for utilization

Over time, several stages may be observed in biomass utilization and market developments in biomass supplies. Different countries seem to follow these stages over time, but clearly differ in their respective stages of development (Faaij, 2006; Sims et al., 2010).

1. Waste treatment (e.g., MSW and use of process residues (paper industry, food industry) onsite at production facilities) is generally the starting phase of a developing bioenergy system. Resources are available and often have a disposal cost (could have a negative value) making utilization profitable and simultaneously solving waste management problems. Large- and small-scale developments are evolving along with integrated resource management.

2. Local utilization of resources from forest management and agriculture. Such resources are more expensive to collect and transport, but usually still economically attractive. Infrastructure development is needed.

3. Biomass market development at regional scale; larger-scale conversion units with increasing fuel flexibility are deployed; increasing average transport distances further improves economies of scale. Increasing costs of biomass supplies make more energy-efficient conversion facilities necessary as well as feasible. Policy support measures such as feed-in tariffs (FITs) are usually needed to develop into this stage.

4. Development of national markets with increasing numbers of suppliers and buyers; creation of a marketplace; increasingly complex logistics. Availability often increases due to improved supply systems and access to markets. Price levels may therefore decrease (see, e.g., Junginger et al., 2005).

5. Increasing scale of markets and transport distances, including cross-border transport of biofuels; international trade in biomass resources (and energy carriers derived from biomass). Biomass is increasingly becoming a globally traded energy commodity (see, e.g., Junginger et al., 2008). Bio-ethanol trade has come closest to that situation (see, e.g., Walter et al., 2008).

6. Growing role for dedicated fuel supply systems (biomass production largely or only for energy purposes). So far, most energy crops are grown because of agricultural interests and support (subsidies for farmers, use of set-aside subsidies), which concentrate on oil crops (such as rapeseed) and surplus food crops (cereals and sugar beets).

Countries that have gained substantial commercial experience with biomass supplies and biomass markets are generally able to obtain substantial cost reductions in biomass supply chains over time. In Finland and Sweden, delivery costs decreased from USD_{2005} 12 to 5/GJ from 1975 to 2003, due to factors such as scale increases, technological innovations or increased competition (Junginger et al., 2005). Similar trends are observed in the corn ethanol industry in the USA and the sugarcane ethanol industry in Brazil (see Table 2.17).

Analyses of regional and international biomass supply chains show that road transport of untreated and bulky biomass becomes uncompetitive and energy-inefficient when crossing distances of 50 to 150 km (Dornburg and Faaij, 2001; McKeough et al., 2005). When long-distance transport is required, early pretreatment and densification in the supply chain (see Sections 2.3.2.3 and 2.6.2) pays off to minimize transport costs. Taking into account energy use and related GHG emissions, well-organized logistic chains can require less than 10% of the initial energy content of the biomass (Hamelinck et al., 2005b; Damen and Faaij, 2006), but this requires substantial scale in transport, efficient pretreatment and minimization of road transport of untreated biomass.

Such organization is observed in the rapidly developing international wood pellet markets (see Sections 2.3.2.3 and 2.4.4). Furthermore, (long distance) transport costs of liquid fuels such as ethanol and vegetable oils contribute only a minor fraction of overall costs and energy use of bioenergy chains (Hamelinck et al., 2005b).

2.3.2.2 Solid biomass and charcoal supplies in developing countries

The majority of poorest households in the developing world depend on solid biomass fuels such as charcoal for cooking, and millions of small industries (such as brick and pottery kilns) generate process heat from these fuels (FAO, 2010a; IEA, 2010b; see Section 1.4.1.2). Despite this pivotal role of biomass, the sector remains largely unregulated, poorly understood, and the supply chains are predominantly in the hands of the informal sector (Sepp, 2008).

When fuelwood is marketed, trees are usually felled and cut into large pieces and transported to local storage facilities where they are collected by merchants and delivered to wholesale and retail facilities, mainly in rural areas. Some of the wood is converted to charcoal in kilns, packed into large bags and transported by hand, animal-drawn carts and small trucks to roadside sites where it is collected by trucks and sent to urban wholesale and retail sites. Thus charcoal making is an enterprise for rural populations to supply urban markets. Crop residues and dung are normally used by animal owners as a seasonal supplement to fuelwood (FAO 2010a).

Shredded biomass residues may be densified by briquetting or pelletizing, typically in screw or piston presses that compress and extrude the biomass (FAO, 1985). Briquettes and pellets can be good substitutes for coal, lignite and fuelwood because they are renewable and have consistent quality and size, better thermal efficiency, and higher density than loose biomass.

There are briquetting plants in operation in India and Thailand, using a range of secondary residues and with different capacities, but none as yet in other Asian countries. There have been numerous, mostly development agency-funded, briquetting projects in Africa, and most have failed technically and/or commercially. The reasons for failure include deployment of new test units that were not proven technically, selection of very expensive machines that did not make economic sense given the location, low local capacity to fabricate components and provide maintenance, and lack of markets for the briquettes due to uncompetitive cost and low acceptance (Erikson and Prior, 1990).

Wood pellets are made of wood waste such as sawdust and grinding dust. Pelletization machines are based on fodder-making technology and produce somewhat lighter and smaller pellets of biomass compared to briquetting. Wood pellets are easy to handle and burn because their shape and characteristics are uniform, transportation efficiency is high and energy density is high. Wood pellets are used as fuel in many countries for cooking and heating applications (Peksa-Blanchard et al., 2007).

Chips are mainly produced from plantations' waste wood and wood residues (branches and presently even spruce stumps) as a by-product of conventional forestry. They require less processing and are cheaper than pellets. Depending on end use, chips may be produced onsite, or the wood may be transported to the chipper. Chips are commonly used in automated heating systems, and can be used directly in coal-fired power stations or for CHP production (Fagernäs et al., 2006).

Charcoal is obtained by heating woody biomass to high temperatures in the absence of oxygen, and has a twice higher calorific value than the original feedstock. It burns without smoke and has a low bulk density, which reduces transport costs. In rural areas in many African countries, charcoal is produced in traditional kilns with efficiencies as low as 10% (Adam, 2009), and typically sold to urban households while rural households use fuelwood. Hardwoods are the most suitable raw material for charcoal, because softwoods incur possibly high losses during handling/transport. Charcoal from granular materials like coffee shells, sawdust and straw is in powder form and needs to be briquetted with or without a binder. Charcoal is also used in large-scale industries, particularly in Brazil from high-yielding eucalyptus plantations (Scolforo, 2008), and in many cases, in conjunction with sustainably produced wood, and also increasingly as a co-firing feedstock in oil-based electric power plants. The projected costs for charcoal production from Brazilian eucalyptus plantations are USD_{2005} 5.7 to 9.8/GJ (Fallot et al., 2009) using industrial carbonizing process.

Charcoal in Africa is predominantly produced in inefficient traditional kilns in the informal sector, often illegally. Current production, packaging and transport of charcoal are characterized by low efficiencies and poor handling, leading to losses. Introducing change to this industry requires that it be recognized and legalized, where it is found to be sustainable and not contradictory to environmental protection goals. Once legalized, it would be possible to regulate it and introduce standards addressing fuel quality, packaging and production kiln standards and better enforcement of which tree species should be used to produce charcoal (Kituyi, 2004).

2.3.2.3 Wood pellet logistics and supplies

Wood pellets are one of the most successful bioenergy-based commodities traded internationally. Wood pellets offer several advantages over other solid biomass fuels: they generally have a low moisture content and a relatively high heating value (about 17 GJ/t), which allow long-distance transport by ship without affecting the energy balance (Junginger et al., 2008). Local transport is carried out by trucks, which sets a feasible upper limit for transportation of 50 km for raw biomass (150 km for pellets) and together with the necessary storage usually represents more than 50% of the final cost. Bulk delivery of pellets is very similar to delivery of home heating oil and is carried out by the lorry driver blowing pellets into the storage space, while a suction pump takes away any dust. Storage solutions include underground tanks, container units, silos or storage within the boiler room. Design of more efficient pellet storage, charging and combustion systems for domestic users is ongoing (Peksa-Blanchard et al., 2007). International trade by ships to ports that are properly equipped for handling pellets is a major logistical barrier.[10] Freight costs are another barrier very sensitive to international trade demand. For instance, in 2004, the average price of pellets at a mill in Canada was USD_{2005} 3.4/GJ; shipped to the Netherlands, USD_{2005} 4.1/GJ (Free on Board); and delivered to the Rotterdam harbour, USD_{2005} 7.5/GJ (Junginger et al., 2008; see also Sikkema et al., 2011).

2.3.3 Conversion technologies to electricity, heat, and liquid and gaseous fuels

Commercial bioenergy routes are shown in Figure 2.6 and start with feedstocks such as forest- or agriculture-based crops or industrial, commercial or municipal waste streams and by-products. These routes deliver electricity or heat from biomass directly or as CHP, biogas and liquid biofuels, including ethanol from sugarcane or corn and biodiesel from oilseed crops. Current biomass-based commercial processes produce a limited range of liquid fuels compared to the variety of petroleum-based fuels and products.

Figure 2.2 presented a complex set of developing technological options based on second- (lignocellulosic herbaceous or woody species) and higher- (aquatic plants) generation feedstocks and a variety of second- (or higher-) generation conversion processes.[11] It also included the commercial (Figure 2.6) first-generation (oil, sugar and starch crops) and solid biomass feedstocks and conversion processes (fermentation, transesterification, combustion, gasification, pyrolysis and anaerobic digestion). Second-generation feedstocks and conversion processes can produce higher-efficiency electricity and heat, as well as a wider range of liquid hydrocarbon fuels, alcohols (including some with higher energy density), ethers, chemical products and polymers (biobased materials) in the developing biorefineries that are discussed in more detail in Section 2.6.3.4. Initial R&D on producing hydrocarbon fuels is starting with sugar and starch crops and covers the range of gasoline, diesel and jet fuel with an increasing focus on chemicals. Both improved first-generation crops (e.g., perennial sugarcane-derived) and second-generation plants suited to specific geographic regions have the potential to provide a variety of energy products, along with high-volume chemicals and materials traditionally derived from the petrochemical industry, maximizing the outputs of end products per unit of feedstock.

10 In most countries with export potential, ports are not yet equipped with storage and modern handling equipment or are poorly managed, which implies high shipping costs.

11 Biofuels produced via new processes are also called advanced or next-genereation biofuels, e.g. from lignocellulosic biomass.

2.3.3.1 Development stages of conversion technologies

The development stages of selected thermochemical, biochemical and chemical routes from solid lignocellulosic biomass, wet waste streams, sugars from sugarcane or starch crops, and vegetable oils are shown in Table 2.5 for the production of heat, power and fuels. For instance, while biomass combustion coupled with electricity generators such as turbines using steam cycles is a commercial system for electricity production (or CHP), coupling with the Stirling engine is still developing, and the Organic Rankine Cycle (ORC) is just starting commercial penetration (van Loo and Koppejan, 2002). Generally, solid wood or waste biomass is processed by thermochemical routes, and wet feedstocks and sugar or starch crops are processed biochemically or chemically and, in the case of the vegetable oils, after a mechanical pressing step (Bauen et al., 2009a). The development stages are roughly divided into R&D, demonstration, early commercial and full commercial products and processes. Precise allocation to these different stages is difficult and somewhat arbitrary, because many developments are taking place in industry and are not often documented in the peer-reviewed literature (Regalbuto, 2009; Bacovsky et al., 2010a,b). Usually, those processes that are deployable throughout the world are fully commercial technologies because their technical risk is small and financing can be obtained (Kirkels and Verbong, 2011).

Synergies between biomass industries and waste management are already established and additional synergies are evolving with the petroleum refining, chemicals, natural gas and coal industries (King et al., 2010; Kirkels and Verbong, 2011). Many bioenergy systems that are moving towards commercialization still have a high technical risk. Section 2.6.3 will describe these additional advancing conversion processes in more detail.

2.3.3.2 Thermochemical processes

Biomass combustion is a process where carbon and hydrogen in the fuel react with excess oxygen to form CO_2 and water and release heat. Direct burning of biomass is popular in rural areas for cooking. Wood and charcoal are also used as a fuel in the industry. Combustion processes are well understood and a wide range of existing commercial technologies are tailored to the characteristics of the biomass and the scale of their applications. Biomass can also be co-combusted with coal in coal-fired plants (van Loo and Koppejan, 2002; Faaij, 2006; Egsgaard et al., 2009).

Pyrolysis is the thermal decomposition of biomass occurring in the absence of oxygen (anaerobic environment) that produces a solid (charcoal), a liquid (pyrolysis oil or bio-oil) and a gas product. The relative amounts of the three co-products depend on the operating temperature and the residence time used in the process. High heating rates of the biomass feedstocks at moderate temperatures (450°C to 550°C) result in oxygenated oils as the major products (70 to 80%), with the remainder split between a biochar and gases. Slow pyrolysis (also known

Table 2.5 | Examples of stages of development of bioenergy: thermochemical (orange), biochemical (blue), and chemical routes (red) for heat, power, and liquid and gaseous fuels from solid lignocellulosic and wet waste biomass streams, sugars from sugarcane or starch crops, and vegetable oils (IEA Bioenergy, 2009; Alper and Stephanopoulos, 2009; Regalbuto, 2009).

Type of Plant	Type of Product	Process	Basic and Applied R&D	Demonstration	Early Commercial	Commercial
		Stage of Development of Process for Product(s) or System(s)				
Low Moisture Lignocellulosic	Densified Biomass		Torrefaction	Hydrothermal Oil (Hy Oil)	Pyrolysis Oil (Py Oil)	Pelletization
Low Moisture Lignocellulosic	Charcoal			Pyrolysis (Biochar)		Carbonization
Low Moisture Lignocellulosic	Heat				Small Scale Gasification	Combustion Stoves
Low Moisture Lignocellulosic	Heat	Combustion			Py/Hy Oil	Home/District/Industrial
Low Moisture Lignocellulosic	Power or CHP	Combustion Coupled with		Stirling Engine	ORC[1]	Steam Cycles
Low Moisture Lignocellulosic	Power or CHP	Co-Combustion or Co-Firing with Coal		Indirect	Parallel	Direct
Low Moisture Lignocellulosic	Power or CHP	Gasification (G) or Integrated Gasification (IG)		IG-Fuel Cell IG-Gas Turbine		
Low Moisture Lignocellulosic	Power or CHP	Gasification (G) or Integrated Gasification (IG)		IG-Combined Cycle	G and Steam Cycle	
Wet Waste	Heat or Power or Fuel	Anaerobic Digestion to Biogas		2-Stage		Landfills (1-Stage)
Wet Waste	Heat or Power or Fuel		Microbial Fuel Cell		Reforming to Hydrogen (H_2)	Small Manure Digesters
Wet Waste	Heat or Power or Fuel				Biogas Upgrading to Methane	
Wet Waste	Heat or Power or Fuel			Hydrothemal Processing to Oils or Gaseous Fuels		
Sugar or Starch Crops	Fuels	Sugar Fermentation		Butanol		Ethanol
Sugar or Starch Crops	Fuels	Microbial Processing[2]	H_2	Gasoline/ Diesel/ Jet Fuel; Biobutanol/Butanols[3]		
Oils Vegetable or Waste	Fuels	Extraction and Esterification				Biodiesel
Oils Vegetable or Waste	Fuels	Extraction and Hydrogenation			Renewable Diesel	
Oils Vegetable or Waste	Fuels	Extraction and Refining		Jet Fuel		

Notes: 1. ORC: Organic Rankine Cycle; 2. genetically engineered yeasts or bacteria to make, for instance, isobutanol (or hydrocarbons) developed either with tools of synthetic biology or through metabolic engineering. 3. Several four-carbon alcohols are possible and isobutanol is a key chemical building block for gasoline, diesel, kerosene and jet fuel and other products.

as carbonization) is practiced throughout the world, for example, in traditional stoves in developing countries, in barbecues in Western countries, and in the Brazilian steel industry (Bridgwater et al., 2003; Laird et al., 2009).

Biomass Gasification occurs when a partial oxidation of biomass happens upon heating. This produces a combustible gas mixture (called producer gas or fuel gas) rich in CO and hydrogen (H_2) that has an energy content of 5 to 20 MJ/Nm^3 (depending on the type of biomass and whether gasification is conducted with air, oxygen or through indirect heating). This energy content is roughly 10 to 45% of the heating value of natural gas. Fuel gas can then be upgraded to a higher-quality gas mixture called biomass synthesis gas or syngas (Faaij, 2006). A gas turbine, a boiler or a steam turbine are options to employ unconverted gas fractions for electricity co-production. Coupled with electricity generators, syngas can be used as a fuel in place of diesel in suitably designed or adapted internal combustion engines. Most commonly available gasifiers use wood or woody biomass and specially designed gasifiers can convert non-woody biomass materials (Yokoyama and Matsumura, 2008). Biomass gasifier stoves are also being used in many rural industries for heating and drying, for instance, in India and China (Yokoyama and Matsumura, 2008; Mukunda et al., 2010). Compared to combustion, gasification is more efficient, providing better controlled heating, higher efficiencies in power production and the possibility for co-producing chemicals and fuels (Kirkels and Verbong, 2011).

2.3.3.3 Chemical processes

Transesterification is the process through which alcohols (often methanol) react in the presence of a catalyst (acid or base) with triglycerides contained in vegetable oils or animal fats to form an alkyl ester of fatty acids and a glycerine by-product. Vegetable oil is extracted from the seeds, usually with mechanical crushing or chemical solvents prior to transesterification. The fatty acid alkyl esters are typically referred to as 'biodiesel' and can be blended with petroleum-based diesel fuel. The protein-rich residue, also known as cake, is typically sold as animal feed or fertilizer, but may also be used to synthesize higher-value chemicals (WWI, 2006; Bauen et al., 2009a; Demirbas, 2009; Balat, 2011).

The **hydrogenation** of vegetable oil, animal fats or recycled oils in the presence of a catalyst yields a renewable diesel fuel—hydrocarbons that can be blended in any proportion with petroleum-based diesel and propane as products. This process involves reacting vegetable oil or animal fats with H_2 (typically sourced from an oil refinery) in the presence of a catalyst (Bauen et al., 2009a). Although at an earlier stage of development and deployment than transesterification, hydrogenation of vegetable oils and animal fats can still be considered a first-generation route as it is demonstrated at a commercial scale.[12] Hydrogenated biofuels have a high cetane number, low sulphur content and high viscosity (Knothe, 2010).

2.3.3.4 Biochemical processes

Biochemical processes use a variety of microorganisms to perform reactions under milder conditions and typically with greater specificity compared to thermochemical processes. These reactions can be part of the organisms' metabolic functions or they can be modified for a specific product through metabolic engineering (Alper and Stephanopoulos, 2009). For instance, *fermentation* is the process by which microorganisms such as yeasts metabolize sugars under low or no oxygen to produce ethanol. Among bacteria, the most commonly employed is *Escherichia (E.) coli*, often used to perform industrial synthesis of biochemical products, including ethanol, lactic acid and others. *Saccharomyces cerevisiae* is the most common yeast used for industrial ethanol production from sugars. The major raw feedstocks for biochemical conversion today are sugarcane, sweet sorghum, sugar beet and starch crops (such as corn, wheat or cassava) and the major commercial product from this process is ethanol, which is predominantly used as a gasoline substitute in light-duty transport.

Anaerobic digestion (AD) involves the breakdown of organic matter in agricultural feedstocks such as animal dung, human excreta, leafy plant materials, urban solid and liquid wastes, or food processing waste streams by a consortium of microorganisms in the absence of oxygen to produce biogas, a mixture of methane (50 to 70%) and CO_2. In this process, the organic fraction of the waste is segregated and fed into a closed container (biogas digester). In the digester, the segregated biomass undergoes biodegradation in the presence of methanogenic bacteria under anaerobic conditions, producing methane-rich biogas and effluent. The biogas can be used either for cooking and heating or for generating motive power or power through dual-fuel or gas engines, low-pressure gas turbines, or steam turbines. The biogas can also be upgraded through enrichment to a higher heat content biomethane (85 to 90% methane) gas and injected in the natural gas grid (Bauen et al., 2009a; Petersson and Wellinger, 2009). The residue from AD, after stabilization, can be used as an organic soil amendment or a fertilizer. The residue can be sold as manure depending upon the composition of the input waste.

Many developing countries, for example India and China, are making use of AD technology extensively in rural areas. Many German and Swedish companies are market leaders in large biogas plant technologies (Faaij, 2006; Petersson and Wellinger, 2009). In Sweden, multiple wastes and manures (co-digestion) are also used and the biogas is upgraded to biomethane, a higher methane content gas, which can be distributed via natural gas pipelines and can also be used directly in vehicles.[13]

2.3.4 Bioenergy systems and chains: Existing state-of-the-art systems

Literature examples of relevant commercial bioenergy systems operating in various countries today by type of energy product(s), feedstock, major process, current and estimated future (2020 to 2030) efficiency, and estimated current and future (2020) production costs are presented in Tables 2.6 and 2.7. Current markets and potential are reviewed in Section 2.4.

Production costs presented in Tables 2.6 and 2.7 are taken directly from the available literature with no attempt to harmonize the literature data because the underlying techno-economic parameters are not always sufficiently transparent to assess the specific conditions under which

12 Many companies throughout the world have patents, demonstration plants, and have tested this technology at a commercial scale for diesel, including Neste Oil's commercial facility in Singapore (Bauen et al., 2009a; Bacovsky et al., 2010b).

13 See, for instance, the Linköping example at www.iea-biogas.net/_download/linkoping_final.pdf (IEA Bioenergy Task 37 success story).

comparable production costs can be achieved, except in cases analyzing multiple products. Section 2.7 presents complementary information on the levelized costs of various bioenergy systems and discusses specific cost determinants based on the methods specified in Annex II and the assumptions summarized in Annex II (note that only a few of the underlying assumptions included in Tables 2.6 and 2.7 were used as inputs to the data presented in Annex III).

2.3.4.1 Bioenergy chains for power, combined heat and power, and heat

Liquid biofuels from biomass have higher production costs than solid biomass (at USD_{2005} ~2 to 5/GJ) used for heat and power. Unprocessed solid biomass is less costly than pre-processed types (via densification, e.g., delivered wood pellets at USD_{2005} 10 to 20/GJ), but entails higher logistic costs and is a reason why both types of solid biomass markets developed (Sections 2.3.2.2 and 2.3.2.3). Because of economies of scale, some of the specific technologies that have proven successful at a large scale (such as combustion for electricity generation) cannot be directly applied to small-scale applications in a cost-effective fashion, making it necessary to identify suitable alternative technologies, usually adapting existing technologies used with carbonaceous fuels. This is the case for ORC technologies, which are entering the commercial stage, and Stirling engine technologies, which are still in developmental phase, or moving from combustion to gasification, coupled to an engine (IEA, 2008a).

An intermediate liquid fuel from pyrolysis is part of evolving heating and power in co-firing applications because it is a transportable fuel (see Table 2.6) and is under investigation for stationary power and for upgrading to transport fuel (see Sections 2.3.3.2 and 2.6.3.1). Pyrolysis oils are a commercial source of low-volume specialty chemicals (see Bridgwater et al., 2003, 2007).

Many bioenergy chains employ cogeneration in their systems where the heat generated as a by-product of power generation is used as steam to meet process heating requirements, with an overall efficiency of 60% or even higher (over 90%) in some cases (IEA, 2008a; Williams et al., 2009). Technologies available for high-temperature/high-pressure steam generation using bagasse as a fuel, for example, make it possible for sugar mills to operate at higher levels of energy efficiency and generate more electricity than what they require. Sugarcane bagasse and now increasingly sugarcane field residues from cane mechanical harvesting are used for process heat and power (Maués, 2007; Macedo et al., 2008; Dantas et al., 2009; Seabra et al., 2010) to such an extent that in 2009, 5% of Brazil's electricity was provided by bagasse cogeneration (EPE, 2010). Similarly, black liquor, an organic pulping product containing pulping chemicals, is produced in the paper and pulp industry and is being burnt efficiently in boilers to produce energy that is then used as process heat (Faaij, 2006). Cogeneration-based district heating in Nordic and European countries is also very popular.

A significant number of electricity generation routes are available, including co-combustion (co-firing) with non-biomass fuels, which is a relatively efficient use of solid biomass compared to direct combustion. Due to economies of scale, small-scale plants usually provide heat and electricity at a higher production cost than do larger systems, although that varies somewhat with location. Heat and power systems are available in a variety of sizes and with high efficiency. Biomass gasification currently provides an annual supply of about 1.4 GW_{th} in industrial applications, CHP and co-firing (Kirkels and Verbong, 2011). Small-scale systems ranging from cooking stoves and anaerobic digestion systems to small gasifiers have been improving in efficiency over time. Several European countries are developing digestion systems using a mixture of solid biomass, municipal waste and manures, producing either electricity or high-quality methane. At the smallest scales, the primary use of biomass is for lighting, heating and cooking (see Table 2.6).

Many region-specific factors determine the production costs of bioenergy carriers, including land and labour costs, biomass distribution density, and seasonal variation. Also, other markets and applications partly determine the value of biomass. For many bioenergy systems, biomass supply costs represent a considerable proportion of total production costs. The scale of biofuel conversion technologies, local legislation and environmental standards can also differ considerably from country to country. Even the operation of conversion systems (e.g., load factor) varies, depending on, for example, climatic conditions (e.g., winter district heating) or crop harvesting cycles (e.g., sugarcane harvest cycles and climate impact). The result is a wide range of production costs that varies not only by technology and resource type, but also by numerous regional and local factors (see examples of such ranges in Section 2.7 and Annex III).

2.3.4.2 Bioenergy chains for liquid transport fuels

Bioenergy chains for liquid transportation fuels are similarly diverse and are described below under three subsections: (1) integrated ethanol, power, and sugar from sugarcane; (2) ethanol and fodder products; and (3) biodiesel. Also covered here are 2008 to 2009 biofuels production costs by feedstock and region. Though liquid biofuels are mainly used in the transport sector, in many developing and in some developed countries they are also used to generate electricity or peak power.

Integrated ethanol, power and sugar from sugarcane
Ethanol from sugarcane is primarily made from pressed juices and molasses or from by-products of sugar mills. The fermentation takes place in single-batch, fed-batch or continuous processes, the latter becoming widespread and being more efficient because yeasts can be recycled. The ethanol content in the fermented liquor is 7 to 10% in Brazil (BNDES/CGEE, 2008), and is subsequently distilled to increase purity to about 93%. To be blended with gasoline in most applications,

Table 2.6 | Current and projected estimated production costs and efficiencies of bioenergy chains at various scales in world regions for power, heat, and biomethane from wastes directly taken from available literature data.

Feedstock/ Country/ Region	Major Process	Efficiency, Application and Production Costs; Eff. = bioenergy/biomass energy Component costs in USD_{2005}/GJ	Estimated Production Costs USD_{2005}/GJ US $cents_{2005}$/kWh	Potential Advances USD_{2005}/GJ US $cents_{2005}$/kWh
Wood log, residues, chips/ Ag. Wastes/ Worldwide	Co-combustion with coal	5 to 100 MW_e, Eff. ~30 to 40%.[1,2] >50 power plants operated or carried on experimental operation using wood logs/ residues, of which 16 are operational and using coal. More than 20 pulverized coal plants in operation.[3] Wood chips (straw) used in at least 5 (10) operating power plants in co-firing with coal.[3]	8.1 – 15 2.9 – 5.3 Inv. Cost (USD/kW): 100 – 1,300[1]	Reduce fuel cost by improved pretreatment, characterization and measurement methods.[4] Torrefied biomass is a solid uniform product with low moisture and high energy content and more suitable for co-firing in pulverized coal plants.[3] Cost reduction and corrosion-resistant materials for coal plant needed.[5]
Wood log, residues, chips/ Ag. Wastes/ Worldwide	Direct combustion	10 to 100 MW_e, Eff. ~20 to 40%.[1,2] Well deployed in Scandinavia and North America; various advanced concepts give high efficiency, low costs and high flexibility.[2] Major variable is biomass supply costs.[2]	20 – 25 7.2 – 9.2 Inv. Cost (USD/kW): 1,600 – 2,500[1]	U.S. 2020 cost projections:[6] 6.3 – 7.8 Stoker fired boilers: 7.5 – 8.1
MSW/ Worldwide	Direct combustion (gasification and co-combustion with coal	50 to 400 MW_e, Eff. ~22%, due to low-temperature steam to avoid corrosion.[7,8] Commercially deployed incineration has higher capital costs and lower (average) efficiency.[2] Four coal-based plants co-fire MSW.[3]	9.1 – 26 3.3 – 9.4[7]	New CHP plant designs using MSW are expected to reach 28 to 30% electrical efficiency, and above 85 to 90% overall efficiency in CHP.[8]
Wood/ Ag. Wastes/ Worldwide	Small scale/gas engine gasification	5 to 10 MW_e, Eff. ~15 to 30%.[1,2] First-generation concepts prove capital intensive.[2]	29 – 38 10 – 14 Inv. Cost (USD/kW): 2,500 – 5,600[1]	Increased efficiency of the gasification and performance of the integrated system. Decrease tars and emissions.[1]
Wood pellets/ EU	Direct coal co-firing or co-gasification	12.5 to 300 MW_e.[9] Used in 2 operating power plants in co-firing with coal.[3] Costs highly dependent on shipment size and distances.[9]	14 – 36 5.0 – 13[9,10]	See PELLETS@LAS Pellet Handbook and www.pelletsatlas.info.
Pyrolysis oil /EU	Coal co-combustion/ gasification	12.5 to 1,200 MW_e.[9] Costs highly dependent on shipment size and distances.[9]	19 – 42 7.0 – 15[9,10]	Develop direct conventional oil refinery integrated and/or upgrading processes allowing for direct use in diesel blends.[1]
Fuelwood/ Mostly in developing countries	Combustion for heat	0.005 to 0.05 MW_{th}, Eff. ~10 to 20%.[2] Traditional devices are inefficient and generate indoor pollution. Improved cook stoves are available that reduce fuel use (up to 60%) and cut 70% of indoor pollution. Residential use (cooking) application.[2]	Inv. Cost (USD/kW): 100[2]	New stoves with 35 to 50% efficiency also reduce indoor air pollution more than 90%.[2] See Section 2.5.7.2.
		1 to 5 MW_{th}, Eff. ~70 to 90% for modern furnaces.[2] Existing industries have highly polluting low-efficiency kilns.[11]	Inv. Cost (USD/kW): 300 – 800[2]	More widespread use of improved kilns to cut consumption by 50 to 60% and reduce pollution.[11]
Organic Waste/MSW/ Worldwide	Landfill with methane recovery	Eff. ~10 to 15% (electricity).[2] Widely applied for electricity and part of waste treatment policies of many countries.[2]	Biogas: 1.3 – 1.7[12]	Continued efficiency increases are expected.
Organic Waste/MSW/ Manures/ Sweden/ EU in expansion	Anaerobic co-digestion, gas clean up, compression, and distribution	Widely applied for homogeneous wet organic waste streams and waste water.[2] To a lesser extent used for heterogeneous wet wastes such as organic domestic wastes.[2]	Fuel: 2.4 – 6.6[13] Elec.: 48 – 59[1] 17 – 21[1]	Improvements in biomass pretreatment, the biogas cleansing processes, the thermophilic process, and biological digestion (already at R&D stage).[1, 17]
		Costs do not include credits for sale of fertilizer by-product.[14]	Fuel: 15 – 16 Inv. Cost (USD/kW): 13,000[14]	In commercial use in Sweden, other EU countries. State of California study shows potential for the augmentation of natural gas distribution.[14]
Manures/ Worldwide	Household digestion	Cooking, heating and electricity applications. By-product liquid fertilizer credit possible.	1 to 2 years payback time	Large reductions in costs by using geomembranes. Improved designs and reduction in digestion times.[15]

Continued next Page →

Feedstock/ Country/ Region	Major Process	Efficiency, Application and Production Costs; Eff. = bioenergy/biomass energy Component costs in USD_{2005}/GJ	Estimated Production Costs USD_{2005}/GJ US $cents_{2005}$/kWh	Potential Advances USD_{2005}/GJ US $cents_{2005}$/kWh
Manures/Finland	Farms	Biogas from farms 0.018 to 0.050 MW_e.[16]	Elec.: 77 – 110 Inv. Cost (USD/kW): 14000 – 23000[16]	Improved designs and reduction in digestion times. Improvements in the understanding of anaerobic digestion, metagenomics of complex consortia of microorganisms.[12]
Manures/Food residues	Farms/Food Industry	Biogas from farm animal residues and food processing residues at 0.15 to 0.29 MW_e.[16]	Elec.: 70 – 89 Inv. Cost (USD/kW): 12000 – 15000[16]	

Abbreviations: Inv. = Investment; Elec. = Electricity. References: 1. Bauen et al. (2009a); 2. IEA Bioenergy (2007); 3. Cremers (2009) (see IEA co-firing database at www.ieabcc.nl/database/cofiring.php); 4. Econ Poyry (2008); 5. Egsgaard et al. (2009); 6. NRC (2009b); 7. Koukouzas et al. (2008); 8. IEA (2008a); 9. Hamelinck (2004); 10. Uslu et al. (2008); 11. REN21 (2007); 12. Cirne et al. (2007); 13. Sustainable Transport Solutions (2006); 14. Krich et al. (2005); 15. Müller, (2007); 16. Kuuva and Ruska (2009); 17. Petersson and Wellinger, 2009.

ethanol should be anhydrous and the mixture has to be further dehydrated to reach a grade of 99.8 to 99.9% (WWI, 2006).

Ethanol and fodder products

The dominant dry mill (or dry grind) process (88% of US production) for ethanol fuel manufactured from corn starts with hammer milling the whole grain into a coarse flour, which is cooked into a slurry, then hydrolyzed with alpha amylase enzymes to form dextrins, next hydrolyzed by gluco-amylases to form glucose that is finally fermented by yeasts (the last two processes can be combined). The byproduct is distillers' grains with solubles, an animal feed (McAloon et al., 2000; Rendleman and Shapouri, 2007) that can be sold wet to feedlots near the biorefinery or be dried for stabilization and sold. The most common source of process heat is natural gas. From the early 1980s to 2005, the energy intensity of average dry mill plants in North America has been reduced by 14% for every cumulative doubling of production (learning rate, see Table 2.17; Hettinga et al., 2007, 2009). Since then, 10 cumulative doublings (see also Section 2.7.2) have occurred and the industry continues to improve its energy performance with, for instance, CHP ((S&T)[2] Consultants, 2009). The impacts of this and other process improvements have been estimated to continue such that, by 2022, the projected production cost is USD_{2005} 16/GJ, reduced from USD_{2005} 17.5/GJ in 2009 (EPA, 2010). Table 2.7 presents examples of process improvements from membrane separation for ethanol to enzymes operating at lower temperature, etc. A similar process to corn dry milling is wheat-to-ethanol processing, starting with a malting step, and either enzyme or acid hydrolysis leading to sugars for fermentation.

Biodiesel

Biodiesel is produced from oil seed crops like rapeseed or soybeans, or from trees such as oil seed palms. It is also produced from a variety of greases and wastes from cooking oils or animal fats. This wide range of feedstocks, from low-cost wastes to more expensive vegetable oils, produces biodiesel fuels with more variable properties that follow those of the starting oil seed plant. Fuel standards' harmonization is still under development as are a variety of non-edible oil seed plants (Knothe, 2010; Balat, 2011). Examples of producing regions are shown in Figure 2.7.

Snapshot of 2008 to 2009 biofuels costs from multiple feedstocks and world regions

A snapshot of ranges of biofuels production costs for 2008 to 2009 (primarily 2009) is shown in Figure 2.7 for various world regions based on a variety of feedstocks including wastes and processing streams from the manufacture of sugar (molasses). The snapshot is based on various literature sources such as the recent comparison of costs for Asian Pacific Economic Countries (Milbrandt and Overend, 2008, updated),[14] and data from Table 2.7.[15] For production volumes of these countries see Figure 2.9. For ethanol production, feedstock costs represent about 60 to 80% of the total production cost while, for biodiesel from oil seeds, the proportion is higher (80 to 90%) (data from 2008 to 2009). Latin and Central American sugarcane ethanol is found to have had the lowest production costs over this period, followed by Asian, Pacific and North American starch crops, then by European Union (EU) sugar beet and finally EU grains. Molasses production costs are lower in India and Pacific countries than in Other Asia countries. For biodiesel production, Latin America has the lowest costs, followed by Other Asia countries palm oil, Other Asia rapeseed and soybean, and then North American soybean and EU rapeseed. Biodiesel production costs are generally somewhat higher than for ethanol, but can reach those of ethanol for countries with higher-productivity plants or a lower cost base such as Indonesia/Malaysia and Argentina.

There is significant room for feedstock improvement, mainly its productivity (see also Section 2.6.1), and also for its conversion to products based on the projected increases in efficiency shown in Table 2.7. In an analysis of US biofuel production, the US Environmental Protection Agency (EPA) projected costs based on the Forest and Agricultural Sector Optimization Model (FASOM) and found significant room for improvement (see

14 The study addressed biofuels production, feedstock availability, economics, refuelling infrastructure, use of alternative fuel vehicles, trade, and policies.

15 The ranges of production costs shown here include a variety of waste streams and feedstocks with a broader geographic distribution than those summarized in Section 2.7 and detailed in Annex III. Data in Annex III cover broad ranges of a few feedstocks varying their costs, investment capital, co-products, and financial assumptions. From these transparent techno-economic data, it is possible for the reader to change assumptions and recalculate approximate production costs in specific regions.

Table 2.7 | Current and projected estimated production costs and efficiencies of commercial biofuels in various countries directly taken from available literature data. Also provided is the range of direct reductions of GHG emissions from these routes compared to the fossil fuel replaced (see Section 2.5 for detailed GHG emissions discussion). Parts A and B address ethanol and biodiesel fuels, respectively.

A: Ethanol

Feedstock/ Process	Country/ Region	Efficiency, Application and Production Costs; Eff. = bioenergy/ biomass energy Component costs in USD_{2005}/GJ	Estimated Production Costs USD_{2005}/GJ	Direct GHG Reduction (%) from Fossil Reference (FR)	Potential Advances in Cost Reductions and Efficiency USD_{2005}/GJ
Sugarcane pressed, juice fermented to ethanol, bagasse to process heat and power, and increasingly sale of electricity.	Brazil	Eff. ~38%,[1] ~41% (ethanol only);[2] 170 million l/yr, FC: 11.1; CC*: 3.7 w/o CR.[2]	14.8 w/o CR.[2]	79 to 86% (w/o and w/ CPC); FR: gasoline.[4]	9 – 10.[1] Eff. ~50%.[5] Mechanized harvest and efficient use of sugarcane straw and leaves.[6] Biorefineries with multiple products.[5] Improved yeasts.
	Australia	Eff. ~38%, ~41% (ethanol only), FC: 24.8; CC*: 7 w/o CR.[3]	31.8 w/o CR.[3]		
Corn grain dry milling process for ethanol, fodder (DGS) for animal feed		Eff. ~62%;[2,8] 89% of production.[5] 30% co-product feed DGS sold wet.[5,8] 250 million l/yr plant, FC: 14.1[2] – 29.4[11]; CC*: 6 and CR: 3.8 – 4.4.[2]	20–21 w/ CR[2,15,19] 17.5[5] 31 w/ CR.[11]	35 to 56% for various CPC methods; FR: gasoline 35% (system expansion); Process Heat: NG.[12,13]	Eff. ~64%.[11] Industry Eff. ~65 to 68%. Estimated production cost:16.[5,8] US projected low temperature starch enzyme hydrolysis/fermentation, corn dry fractionation, biodiesel from oil in 90% of mills, membrane ethanol separation, and CHP.[5]
	France	170 million l/yr, FC: 29.3; CC*: 10.5 and CR: 5.[11]	34.8 w/ CR.[11]	60%[9,14]	
Wheat similar to corn to ethanol, fodder (DGS)	EU (UK)	Eff. ~53 to 59%.[11,16] 250 million l/yr plant, FC: 36.2; CC*: 10.5 and CR: 6.[11]	40.7 w/ CR.[11]	40%, DGS to energy.[17] 2 to 80% w/ DGS to energy -8 to 70% w/ DGS to feed.[18]	2020 Eff. ~64%.[11]
	Australia (from waste)	30 million l/yr plant, FC: 14.4; CC*: 8.6 and CR: 0.2.[3]	22.8 w/ CR.[3]	55% wheat starch NG, 27% wheat-coal, 59% wheat w/ straw firing.[3]	
Sugar beet crushing, ferment sugar to ethanol and residue	EU (UK)	Eff. ~12%.[1,16,19] 250 million l/yr plant, FC: 21.6; CC*: 11 and CR: 8.2.[11]	24.4 w/ CR.[11]	28 to 66%, alternate co-product use.[17,18]	2020 Eff. ~15%.[1]
Cassava mashing, cooking, fermentation to ethanol	Thailand/ China	Thailand's process with 38 million l, and feed productivity 20 to 21 t/ha.[16,20,21] China ethanol plant operating at partial capacity.[22]	Thailand: 26[23]	Thailand: 45%.[24] China: 20% with anaerobic digestion energy.[25]	
Molasses by-product of sugar production	Thailand/ Australia	About 3% of molasses could be used for ethanol in Thailand. FC: 10.9 and 10; CC*: 10.1 and CR: 5.7.[23]	Thailand: 21[23] Australia: 16[3]	27 to 59% depending on co-product credit method (Australia).[26,27]	

Continued next Page →

Table 2.7; EPA, 2010). The IEA has similarly estimated cost reductions for Organisation for Economic Co-operation and Development (OECD) countries' rapeseed biodiesel by 2030 (IEA Bioenergy, 2007). Further discussions of historical and future cost expectations are provided in Section 2.7.

2.3.5 Synthesis

The key currently commercial technologies are heat production (ranging from home cooking to district heating), power generation from biomass via combustion, CHP, co-firing of biomass and fossil fuels, and first-generation liquid biofuels from oil crops (biodiesel) and sugar and starch crops (ethanol). Several bioenergy systems have been deployed competitively, most notably sugarcane ethanol and heat and power generation from wastes and residues. Other biofuels have also undergone cost and environmental impact reductions and reached significant scales but still require government subsidies.

Modern bioenergy systems involve a wide range of feedstock types, residues from agriculture and forestry, various streams of organic waste, and dedicated crops or perennial systems. Existing bioenergy systems rely mostly on wood, residues and waste for heat and power production, and agricultural crops for liquid biofuels. The economics and yields of feedstocks vary widely across world regions and feedstock types. Energy yields per unit area range from 16 to 200 GJ/ha (1.6 to 20 TJ/km^2) for

B: Biodiesel

Feedstock/ Process	Country	Efficiency, Application and Production Costs; Eff. = bioenergy/biomass energy Component costs in USD_{2005}/GJ	Estimated Production Costs USD_{2005}/GJ	Direct GHG Reduction (%) from Fossil Reference (FR)	Potential Advances in Cost Reductions and Efficiency USD_{2005}/GJ
Rape seed	Germany	Eff. ~29%; for the total system it is assumed that surpluses of straw are used for power production.[27]	31 – 50.[1]	31 to 70%, alternate co-product use.[9,17,28]	25 – 37 for OECD.[1] New methods using bio-catalysts; Supercritical alcohol processing. Heterogeneous catalysts or bio-catalysts. New uses for glycerine. Improved feedstock productivity.[30]
	France	55 GJ/ha/yr (EU), 220 million l/yr plant, FC: 40.5; CC*: 2.7 and CR: 1.7.[11]	41.5 w/ CR.[11]		
	UK	220 million l/yr plant, FC: 35.6; CC*: 4.2 and CR: 11.3.[11]	28.5 w/ CR.[11]		
Oil palm	Indonesia Malaysia Asian countries[20]	163 GJ/ha/yr. 220 million l/yr plant, FC: 25.1; CC*: 2.7 and CR: 1.7.[11]	26.1 w/ CR.[11]	35 to 66%, alternate co-product use.[31] (tropical fallow land, residue to power, good management).[28]	
Vegetable oils	109 countries	Costs neglect some countries with high production costs. FC: 0.6 – 21; CC*: 2.3 – 3.7 and CR: 0 – 6.2.[3,11,29]	4.2 – 17.9.[3,11,31]	N/A	US projected 2020 waste oil ester cost 14.[5] About 50 billion l projected from 119 countries.[29]

Abbreviations: *Conversion costs (CC) include investment costs and operating expenses; CR = Co-product Revenue; CPC = coproduct credit; FC = feedstock cost; FR = fossil reference; N/A = not available.

References: 1. IEA Bioenergy (2007a); 2. Tao and Aden (2009); 3. Beer and Grant 2007; 4. Macedo et al. (2008); 5. EPA (2010); 6. Seabra et al. (2010); 7. UK DfT (2003); 8. Rendleman and Shapouri (2007); 9. Bessou et al. (2010); 10. Wang et al. (2011); 11. Bauen et al. (2009a); 12. Wang et al. (2010); 13. Plevin (2009); 14. Ecobilan (2002); 15. Bain (2007); 16. Fulton et al. (2004); 17. Edwards et al. (2008); 18. Edwards et al. (2007); 19. Hamelinck (2004); 20. Koizumi and Ohga (2008); 21. Milbrandt and Overend (2008); 22. GAIN (2009a; for China); 23. GAIN (2009c; for Thailand); 24. Nguyen and Gheewala et al. (2008); 25. Leng et al. (2008); 26. Beer et al. (2001); 27. Beer et al. (2000); 28. Reinhardt et al. (2006); 29. Johnston and Holloway (2007); 30. Bhojvaid (2007); 31. Wicke et al. (2008).

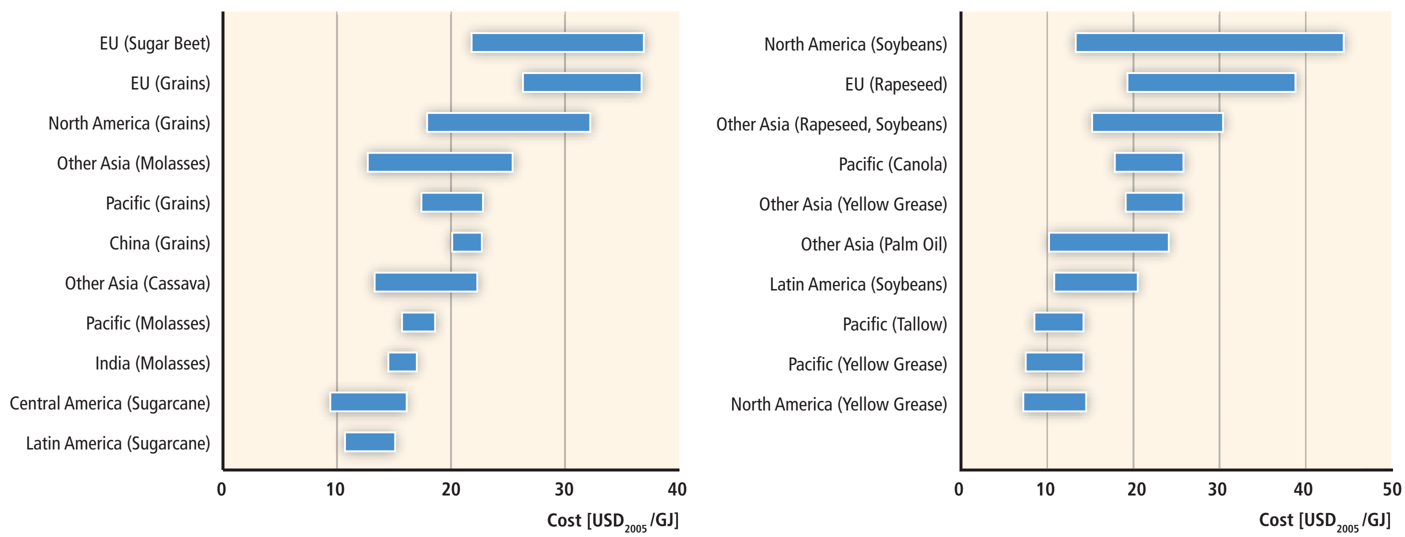


Figure 2.7 | Snapshots of regional ranges of current (2008-2009) estimated production costs for ethanol and biodiesel from various biomass feedstocks and wastes based on Milbrandt and Overend (2008) and Table 2.7.

Notes: The upper value of the range of soybean diesel in North America is due to the single point estimate of Bauen et al. (2009a). Other estimates are in the USD_{2005} 12 to 32/GJ range.

biofuel feedstocks, from 80 to 415 GJ/ha (8 to 41.5 TJ/km^2) for lignocellulosic feedstocks, and from 2 to 155 GJ/ha (0.2 to 15.5 TJ/km^2) for residues, while costs range from USD_{2005} 0.9 to 16/GJ/ha (USD_{2005} 0.09 to 1.6/TJ/km^2). Feedstock production competes with the forestry and food sectors, but the design of integrated production systems such as agro-forestry or mixed cropping may provide synergies along with additional environmental services.

Handling and transport of biomass from production sites to conversion plants may contribute 20 to 50% of the total costs of bioenergy production. Factors such as scale increases, technological innovation and increased competition have contributed to decrease the economic and energy costs of supply chains by more than 50%. Densification via pelletization or briquetting is required for transport distances over 50 km. International costs of delivering densified feedstocks are sensitive to trade and are in the USD_{2005} 10 to 20/GJ range for pellet fuels, and competitive with other market fuels in several regions, thus explaining why such markets are increasing. Charcoal made from biomass is a major fuel in developing countries, and should benefit from the adoption of higher-efficiency kilns and densification technologies.

A significant number of electricity generation routes are available and co-combustion (co-firing) is a relatively efficient way to use solid biomass compared to direct combustion. Small-scale plants usually provide heat and electricity at a higher production cost than larger systems, although this varies somewhat with location. Heat and power systems are available in a variety of sizes and efficiencies. Biomass gasification currently provides about 1.4 GW_{th} of industrial applications, CHP and co-firing. Small-scale systems ranging from cooking stoves and anaerobic digestion systems to small gasifiers have been improving in efficiency over time. Several European countries are developing digestion systems using a mixture of solid biomass, municipal waste and manures, producing either electricity or high-quality methane from upgrading. Many applications, including transport systems, are developing and have the potential to further increase their effectiveness. Technologies at small scales, primarily stoves for heating, continue to improve but diffusion is slow.

Sugarcane-, sugar beet-, and cereal grain-derived ethanol production reached a high level of energy efficiency in major producing countries such as Brazil, the USA, and the EU. The ethanol industry in Center South Brazil significantly increased its cogeneration efficiency and supplied 5% of the country's electricity in 2009. Development of ethanol from waste streams from sugar processing is occurring in India, Pacific and other Asian countries that produce relatively low-cost ethanol but with limited production volumes. Biodiesel production from waste fats and greases has a lower feedstock cost than from rapeseed and soybean but waste fat and grease volumes are limited.

Biofuel production economics is of key importance for future expansion of the biofuels industry. The future development of sustainable biofuels also depends on a balanced scorecard that includes economic, environmental, and social metrics (see Section 2.5). Resolution of technical, economic, social, environmental and regulatory issues remains critical to further development of biofuels. The development of a global market and industry is described in the next section.

2.4 Global and regional status of market and industry development

2.4.1 Current bioenergy production and outlook[16]

Biomass provides about 10% (50.3 EJ in 2008) of the annual global primary energy supply. As presented in Table 2.1, about 60% (IEA accounted) to 70% (including unaccounted informal sector) of this biomass is used in rural areas and relates to charcoal, wood, agricultural residues and manure used for cooking, lighting and space heating, generally by the poorer part of the population in developing countries. Modern bioenergy use (for power generation and CHP, heat or transport fuels) accounted for a primary biomass supply of 11.3 EJ (IEA, 2010a,b; see Table 2.1) in 2008, up from 9.6 EJ[17] in 2004 (IPCC, 2007d), and a rough estimate of 8 EJ in 2000 (IEA Bioenergy, 2007).

The use of solid biomass for energy increased at an average annual growth rate of 1.5%, but secondary energy carriers from modern biomass such as liquid and gaseous fuels increased at 12.1 and 15.4% average annual growth rates, respectively, from 1990 to 2008 (IEA, 2010a). As a result, biofuels' share of global road transport fuel use was 2% in 2008. In 2009, the production of ethanol and biodiesel increased by 10 and 9%, respectively, to 90 billion litres; biofuels provided nearly 3% of global road transport fuel use in 2009, as oil demand decreased for the first time since 1980 (IEA, 2010b). Government policies in various countries led to a five-fold increase in global biofuels production from 2000 to 2008. Biomass and renewable waste power generation was 259 TWh (0.93 EJ) in 2007 and 267 TWh (0.96 EJ) in 2008, representing 1% of the world's electricity, which doubled since 1990 (from 131 TWh or 0.47 EJ). Industrial biomass heating accounts for 8 EJ while space and water heating for building applications account for 3.4 EJ (IEA, 2010b; see Table 2.1).

Most of the increase in the use of biofuels in 2007 and 2008 occurred in the OECD, mainly in North America and Europe. Excess capacity was installed in expectation of increased demand with mandates and subsidies in many countries; however, feedstock and oil price increases and the worsening overall economic conditions during and after the credit crunch made many of these facilities unprofitable. As a result, some are underutilized, more so in biodiesel than in ethanol production. Some plants are not in operation and some businesses failed. Asia Pacific and Latin American markets are growing, primarily

16 This sub-section is largely based on the WEO 2009 (IEA, 2009b) and 2010 (IEA, 2010b) and the Global Biofuels Center assessments, web-based biofuels news, reports, trade, and market information (Hart Energy Publishing, LP, www.globalbiofuelscenter.com/).

17 The 9.6 EJ is an estimated equivalent primary biomass energy deducting the non-biogenic MSW that was included in the AR4 study (IPCC, 2007d), or about 0.4 EJ of plastics (estimated based on subsequent IEA 2005 data).

in developing countries due to economic development. Despite this anticipated short-term downturn, world use of biofuels for road transport is projected to recover in the next few years (IEA, 2010b).

The WEO (IEA, 2010b) projections for 2020 to 2035 are summarized in Table 2.8 (in terms of global TPES from biomass); Table 2.9 (in terms of global biofuel demand, i.e., secondary energy); and Table 2.10 (in terms of global electricity generation)—all of them comparing a baseline case (Current Policies) and a mitigation scenario reaching an atmospheric CO_2 concentration of 450 ppm by 2100.

The overall TPES from biomass in the 450 ppm CO_2 stabilization scenario increases to 83 (95) EJ/yr in 2030 (2035) adding 14 (12) EJ to the Reference (Current Policies) scenario (see Table 2.8).

and many of the technologies needed are at the demonstration to early commercialization stages of development in 2011 (see Tables 2.5 and 2.15; IEA Renewable Energy Division, 2010).

Global biomass and renewable waste electricity generation is also projected to increase in both scenarios, reaching 5.6% of global electricity generation by 2035 in the 450-ppm scenario as shown in Table 2.10. The climate change driver nearly doubles the anticipated penetration levels of biopower compared to the projected levels owing to continuation of current policies.

In the WEO (IEA, 2010b), biomass industrial heating applications for process steam and space and hot water heating for buildings would each double in absolute terms from 2008 levels by 2035, offsetting some of the expected decrease in the major component of the heating category, traditional biomass, as the total heating demand is projected to decrease in 2035. Industrial and building heating is seen as an area for continued biomass growth. In fact, biomass is very efficiently used in CHP plants, supplying a district heating network. Biomass combustion to produce electricity and heat in CHP plants is an efficient and mature technology and is already competitive with fossil fuels in certain locations (IEA, 2008a).

Table 2.8 | IEA WEO scenarios: global TPES from biomass projections (EJ/yr) for 2020 to 2035 (IEA, 2010b).

Year	2007	2008	2020		2030		2035	
Scenario	Actual	Actual	Baseline	450 ppm	Baseline	450 ppm	Baseline	450 ppm
EJ/yr	48	50	60	63	66	83	70	95
Delta, EJ	2		3		17		25	

Table 2.9 | IEA WEO scenarios: global biofuels demand projections (EJ/yr) for 2020 to 2035 reported in secondary energy terms of the delivered product according to IEA data (IEA, 2010b).

Year	2008	2009	2020		2030		2035	
Scenario	Actual	Actual	Baseline	450 ppm	Baseline	450 ppm	Baseline	450 ppm
EJ/yr	1.9	2.1	4.5	5.1	5.9	11.8	6.8	16.2
% Global road transport	2	3	4.4	7	4.4	11 (and air)	5	14 (and air)
% Advanced biofuels			Deployment			60		66

Table 2.10 | IEA WEO scenarios: primary biomass and renewable waste electricity generation projections for 2030 (IEA, 2009, 2010b) and 2035 (IEA, 2010b).

Year	2008	2030		2035	
Scenario	Actual	Baseline, Reference case	450 ppm Scenario	Current Policies	450 ppm Scenario
TWh/yr (EJ/yr)	267 (0.96)	825 (3.0)	1380 (5.0)	1052 (3.8)	1890 (6.8)
% Global electricity	0.96	2.4	4.5	2.7	5.6
TWh/yr (EJ/yr)		840 (3.0)	1450 (5.2)		
% Global electricity		2.4	4.8		

The use of liquid and gaseous energy carriers from modern biomass is growing, in particular biofuels, with a 37% increase from 2006 to 2009 (IEA, 2010c). Regions that currently have strong policy support for biofuels are projected to take the largest share of the eight-fold increase in the market for biofuels that occurs from 2008 to 2035. This is led by the USA (where one-third of the increase occurs), followed by Brazil, the EU and China. To highlight the scale, 7 EJ of advanced biofuels (second generation) is greater than, for example, India's 2007 oil consumption,

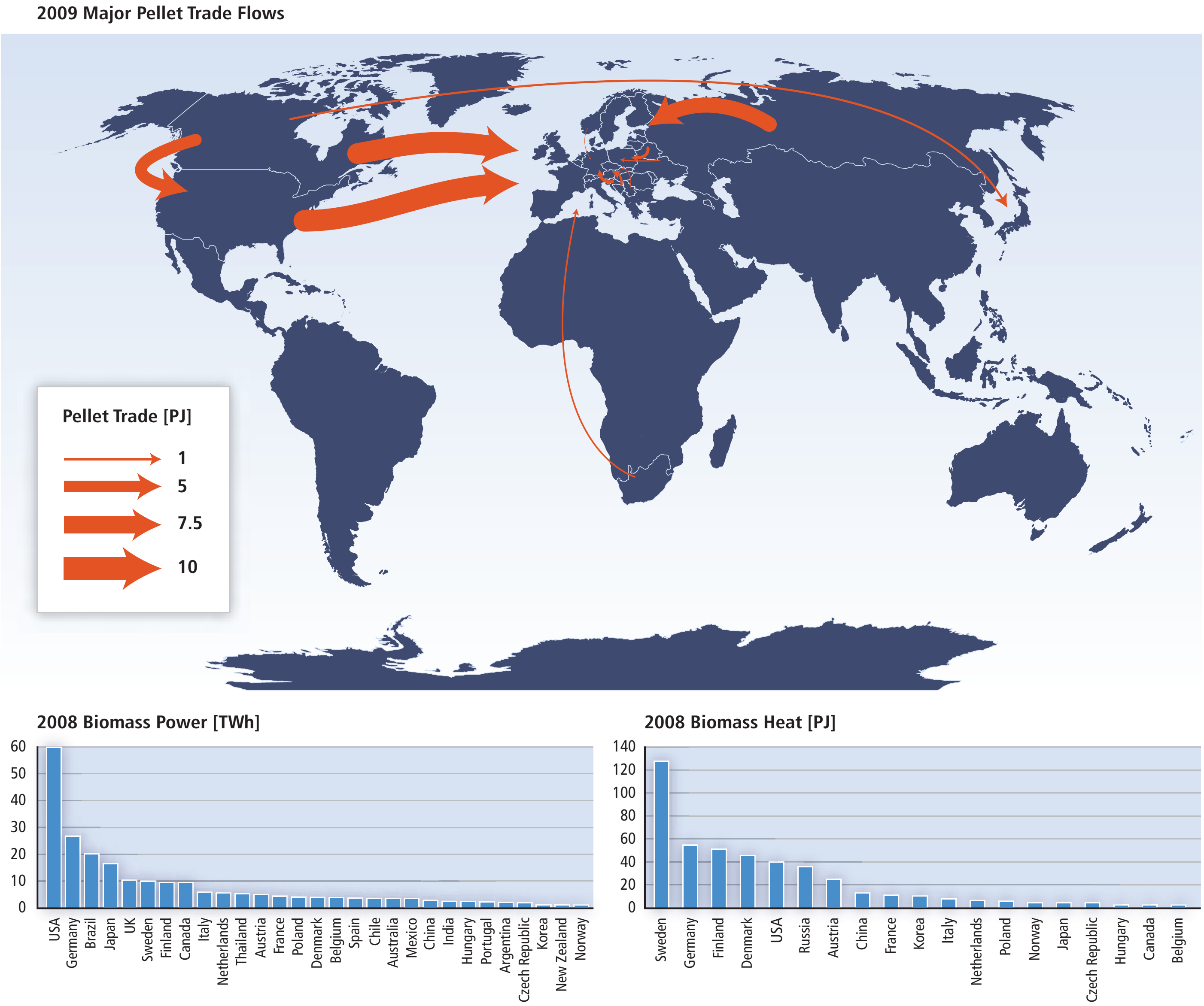


Figure 2.8 | Examples of biomass electricity generation and heating for select countries in 2008 and of the 2009 global trade in wood pellets. Sources: bar chart data from IEA (2010c); trade flow data reproduced from Sikkema et al. (2011) with permission from the Society of Chemical Industry and John Wiley & Sons, Ltd.

The use of solid biomass for electricity production is important, especially from pulp and paper plants and sugar mills. Bioenergy's share of total energy consumption is increasing in the G8 countries (e.g., co-combustion for electricity generation, building heating with pellets), especially in Germany, Italy and the UK (IEA, 2009b). The electricity generation and biomass heating are shown in Figure 2.8. Worldwide biomass heating statistics are uncertain (Sims, 2007) for developed countries. In Europe, biomass heating applications in the building sector are cost competitive and are shown in Figure 2.8. For developing countries, the statistics are less developed, as tools to collect data from informal sectors are lacking (see Table 2.1).

2.4.2 Traditional biomass, improved technologies and practices, and barriers

Biomass is an important traditional fuel in developing countries, where on average it accounts for 22% of the energy mix;[18] in the poorest countries it accounts for more than 80% (see IEA, 2010c). Traditional sources of biomass include mostly wood fuels but also agriculture residues and dung, and they contribute essentially to domestic heating and cooking. The number of people dependent on biomass for cooking is estimated at

18 Average contribution to the energy mix from renewable and waste combustibles was 48, 20, 24, 27, and 10% for Africa, Latin America, India, Non-OECD Asia, and China, respectively, while only 4% for the OECD countries in 2008 (IEA, 2010c).

2.7 billion (for 2008) and is projected to increase to 2.8 billion by 2030 (IEA, 2010b). Many thousand biomass-based small industries—such as brick making, food, charcoal, bakeries and others—provide employment and income to people. Most of these technologies are resource intensive, highly polluting and exhibit low efficiencies (see Tables 2.1 and 2.6; FAO, 2010b). However, there is currently a significant and growing market for improved technologies. Also, several programmes at the global, national and local levels are in place to disseminate more efficient technology options.

2.4.2.1 Improved biomass cook stoves

Most developing countries have initiated some type of improved cook stove (ICS) programme since the 1980s. The World Bank Energy Sector Management Assistance Program (World Bank, 2010) reviewed in depth the international experience on improved stoves and summarized significant lessons learned for developing countries and, in particular, for Bangladesh, the objective of the study. For Eastern African countries, see Karekezi and Turyareeba (1995). Many programmes are in operation, sponsored by development agencies, governments, nongovernmental organizations (NGOs) and the private sector. By the end of 2009, 173 million energy saving stoves were in use in China. Other countries were not very successful in disseminating ICS. Over the past 10 years, a whole new generation of advanced biomass stoves and dissemination approaches have been developed, and the field is now bursting with innovations (World Bank, 2010).

A variety of technologies are used, including direct combustion, small-scale gasification, small-scale anaerobic digestion, direct use of a liquid fuel (ethanol) or combinations of technologies.[19] As a result, combustion efficiency has been greatly improved relative to the alternative open fires. The cost ranges from less than USD 10 for the simpler models to more than USD 100 or more for more sophisticated models and USD 100 to 300 for institutional stoves (e.g., schools, hospitals, and barracks) according to 2007 to 2009 cost range data. Fuel savings are 30 to 60%, measured in field conditions, to more than 90%, measured in pilot testing of the most advanced models (Berrueta et al., 2008; World Bank, 2010). There are also significant reductions in GHG emissions and indoor air pollutants (Section 2.5.4).

By 2008 an estimated 820 million people (around 30% of the 2.7 billion that rely on traditional biomass for cooking, see Section 1.4.1.2) in the world were using some type of improved cook stove for cooking (Legros et al., 2009), and more than 160 stove programmes are in place worldwide, with recently launched large-scale national programmes in India, Mexico and Peru, as well as large donor-based programmes in Africa. The UN Foundation-led Global Alliance for Clean Cookstoves started in 2010 to promote the dissemination and adoption of 100 million advanced cook stoves by 2020.[20]

Two main lines of technology development have been followed. Mass-scale approaches—some of which use state-of-the-art manufacturing facilities—rely on centralized production of stoves or critical components, with distribution channels that can even include different countries. As a result, there are companies that produce more than 100,000 stoves per year (Bairiganjan et al., 2010). A second approach relies more on strengthening regional capabilities, giving more emphasis to local employment creation; sometimes the stoves are built onsite rather than sold on markets, such as the Patsari Stove in Mexico and Groupe Energies Renouvelables, Environnement et Solidarités (GERES) in Cambodia (Bairiganjan et al., 2010). Improved stove designs to appeal to consumers, market segmentation and microfinance mechanisms have also been developed (Hilman et al., 2007).

Incentives and barriers

Cookstove programmes have been successful in countries where proper assessment was made of the local needs in terms of technology, cooking devices, user needs and institutional setting. Financial incentives have helped with the dissemination, while an enabling institutional environment by governments—such as in China—has also helped promote new technologies. Finally, accurate monitoring and evaluation has been critical for successful stove adoption and use (Bairiganjan et al., 2010; Venkataraman et al., 2010). Other drivers for increased adoption of ICS have included: (1) cooking environments where users feel smoke is a health problem and annoyance; (2) a short consumer payback (few months); (3) donor or government support extended over at least five years; and (4) financial support to build local institutions and develop local expertise. Government assistance has been more effective in technical advice and quality control. Carbon offset projects are increasingly providing new financing for these activities, either through the Voluntary Market (Gold Standard) or, increasingly, through the CDM. Successful programmes with low-cost but efficient ICS report that local poor residents purchased cookstoves without support of programmes because of fuel savings (World Bank, 2010).

Several barriers need to be overcome for a rapid diffusion of ICS. There are needs for (1) substantial increases in R&D;[21] (2) more field testing and stove customization for users' needs; and (3) strict product specifications and testing and certification programmes. Finally, it is important to better understand the patterns of stove adoption given the multiple devices and fuels as well as mechanisms to foster their long-term use.

19 These ICS technologies include improvements in the combustion chamber (such as the Rocket 'elbow'), insulation materials, heat transfer ratios, stove geometry and air flow (Still et al., 2003). The most reliable of these use small electric blowers to stabilize the combustion, but there are also designs using natural air flow (World Bank, 2010).

20 See www.cleancookstoves.org.

21 Particularly for new insulating materials as well as robust designs that endure several years of rough use, and small-scale gasification.

2.4.2.2 Biogas systems

Convenient cooking and lighting are also provided by biogas production using household-scale biodigesters.[22] Biodigesters have the distinct co-benefits of enhancing the fertilizer value of the dung in addition to reducing the pathogen risks of human waste. Early stage results have been mixed because of quality control and management problems, which have resulted in a large number of failures. Smaller-scale biogas experience in Africa has been often disappointing at the household level as the capital cost, maintenance and management support required have been higher than expected. The experience gained, new technology developments (such as the use of geo-membranes), better understanding of the resources available to users, such as dung, and better market segmentation are improving the success of new programmes (Kishore et al., 2004).[23]

Incentives and barriers

Key factors for project success include a proper understanding of users' needs and resources.[24] For example, the role of NGOs, networks and associations in transfer, capacity building, extension and adoption of biogas plants in rural India was found to be very important (Myles, 2001). Financial mechanisms, including microfinance schemes and carbon offset projects under the CDM, are also important in the implementation of household biogas programmes. Barriers to increased biogas adoption include lack of proper technical standards; insufficient financial mechanisms to achieve desired profits relative to the digesters' investment, installation and equipment costs; and relatively high costs of technologies and of labour (e.g., geological investigations into proper site installations). Other related barriers include poor reliability and performance of the designs and construction, and limited application of knowledge gained from the operation of existing plants to the design of new plants.

Many other small-scale bioenergy applications are emerging, including systems aimed at transport and productive uses of energy and electricity. The market penetration is still limited, but many of these systems show important benefits in terms of livelihood, new income, revenues and efficiency (Practical Action Consulting, 2009).

2.4.3 Modern biomass: Large-scale systems, improved technologies and practices, and barriers

The deployment of large-scale bioenergy systems faces a wide range of barriers. Economic barriers appear most prominent for currently commercial technologies constrained by feedstock availability and by meeting sustainability requirements (Fagernäs et al., 2006; Mayfield et al., 2007), while technical barriers predominate for developing technologies such as second-generation biofuels (Cheng and Timilsina, 2010). Non-technical barriers are related to deployment policies (fiscal incentives, regulations and public finance), market creation, supply chain, infrastructure development, community engagement, collaboration and education (Mayfield et al., 2007; Adams et al., 2011). No single barrier appears to be most critical, but the interactions among different individual barriers seem to impede rapid bioenergy expansion. The relative importance of the barriers hinges on the particular value chain and context considered. In particular, national regulations, such as price-driven FITs for bioelectricity and quantity-driven blending level mandates for biofuels, play a major role in the emergence of large-scale projects, alongside public finance through government loans or guarantee programmes (Table 2.11; Section 11.5.3; Chum and Overend, 2003; Fagernäs et al., 2006). The priorities also depend on the stakeholder groups involved in the value chain and differ from feedstock producers to fuel producers and through to end users (Adams et al., 2011). Scale also matters, because barriers perceived by national governments differ from those perceived by stakeholders and communities in the vicinity of bioenergy projects.[25]

Technical and non-technical barriers may be overcome by appropriate policy frameworks, economic instruments such as government support tied to private investment support for first-of-a kind commercial plants to decrease investment risk,[26] sustained RD&D efforts, and catalysis of coordinated multiple private sector activities[27] (IATA, 2009; Regalbuto, 2009; Sims et al., 2010). In 2009, global public RD&D efforts were USD 0.6 billion and 0.2 billion for biofuels and biomass to energy, respectively, and biofuels public funding increased by 88% from 2008. Corporate RD&D efforts were USD 0.2 billion each for the two areas (UNEP/SEFI/Bloomberg, 2010). Venture capital and private equity investing was

22 By the end of 2009, there were 35 million household biodigesters in China and in India (Gerber, 2008; REN21, 2009, 2010). There is also significant experience with commercial biogas use in Nepal. Müller (2007) reviewed existing biogas technologies and case studies with contributions from China, Thailand, India, South Africa, Kenya, Rwanda, and Ghana.

23 For example, the high first cost (which can run up to USD 300 for some systems, including the digestion chamber unit) of traditional systems is being reduced considerably by new designs that reduce the digestion time, increase the specific methane yield and use alternate or multiple feedstocks (such as leafy material and food wastes), substantially reducing the size and cost of the digestion unit (Lehtomäki et al., 2007).

24 The Hedon Household Network provides references to the experience in the field at www.hedon.info. One example is www.hedon.info/docs/20060531_Report_(final)_on_Biogas_Experts_Network_Meeting_Hanoi.pdf.

25 For instance, the impacts of bioenergy development on landscapes are a barrier to adoption of new bioenergy conversion plants by some farmers as local acceptance decreases with increased local traffic to supply biomass (van der Horst and Evans, 2010). Some governments are more sensitive to increased efficiencies in GHG abatement and competitiveness of bioenergy with other energy sources, which often means increased scale (Adams et al., 2011) unless technologies succeed in increasing their throughput to accommodate smaller-scale applications without as large of a cost penalty (see Section 2.6.2).

26 See, for instance, the US Department of Energy's integrated biorefinery projects, including first-of-a-kind commercial plants, www1.eere.energy.gov/biomass/integrated_biorefineries.html; see also the IEA Bioenergy Task 39 interactive site with pilot, demonstration and commercial biofuels plants: biofuels.abc-energy.at/demoplants/projects/mapindex.

27 See, for instance, the European Industrial Bioenergy Initiative, a multi-industry partnership across the bioenergy value chains, www.biofuelstp.eu/eibi.html.

Table 2.11 | Key policy instruments in selected countries where E = electricity, H = heat, T = transport, Eth = ethanol and BD = biodiesel (modified after GBEP, 2008; updated with data from the REN21 global interactive map (see note 4 to Figure 2.9); reproduced with permission from GBEP).

Country	Policy Instruments							
	Binding Targets/ Mandates[1]	Voluntary Targets[1]	Direct Incentives[2]	Grants	Feed-in Tariffs	Compulsory grid connection	Sustainability Criteria	Tariffs
Brazil	E, T		T					removed
China		E, T^4	T	E, T	E, H	E, H		n/a
India	T, (E^3)	T(BD)	E	E, H, T	E			n/a
Mexico	(E^3)	(T)	(E)			(E)		Eth
South Africa	T, E	E, (T)	(E), T					n/a
Canada	E, T, H	E^4, T^4	T	E, H, T				Eth
France		E^3, H^3, T	E, H, T		E			as EU below
Germany	E^3, T		H	H	E	E	(E, H, T)	as EU below
Italy	E^3	E^3, T	T	E, H, T	E	E		as EU below
Japan		E, H, T				E		Eth, B-D
Russia		(E, H, T)	(T)					n/a
UK	E^3, T^3	E^3, T	E, H, T	E, H, T	E		T	as EU below
USA	T, T^4, E^4	E^4	E, H, T	E, T	E			Eth
EU	E^3, T	E^3, H^3, T	T	E, H, T		E	(T)	Eth, B-D

Notes: 1. blending or market penetration; 2. fiscal incentives: tax reductions; public finance: loan support/guarantees; 3. target applies to all RE sources; 4. target is set at a sub-national level.

estimated at USD 1.1 billion and 0.4 billion for biofuels and biomass to energy, respectively (UNEP/SEFI/Bloomberg, 2010). A significant fraction of the venture capital investment was in the USA (Curtis, 2010). There was significant first-generation biofuels industry consolidation in the USA and in Brazil. Major global oil company investments occurred in both countries and in the EU (IATA, 2009; Curtis, 2010; IEA, 2010b; UNEP/SEFI/Bloomberg, 2010).

Addressing knowledge gaps in the sustainability of bioenergy systems, as discussed in Section 2.5, is reported as crucial to enable public and private decision making and increase public acceptance. Those gaps are mostly related to feedstock production and the associated impacts on land use, biodiversity, water, and food prices (WWI, 2006; Adams et al., 2011). Other suggested R&D avenues include more sustainable feedstocks and conversion technologies (WWI, 2006), increased conversion efficiency (Cheng and Timilsina, 2010) and overall chain optimization (Fagernäs et al., 2006).

Integrating bioenergy production with other industries/sectors (such as forest, food/fodder, power, or chemical industries) should improve competitiveness and utilize raw materials more efficiently (Fagernäs et al., 2006). For instance, industrial symbiosis evolved over 50 years in the city of Kalundborg, Denmark, as a community of businesses located together on a common property voluntarily entered into several bilateral contracts to enhance environmental, economic and social performance in managing environmental and resource issues by sharing resources in close cooperation with government authorities (Grann, 1997).[28] The Kalundborg experience increased the viability of the businesses involved over the years and developed a community thinking systems approach that could be applied to many other industrial settings (Jacobsen, 2006).

2.4.4 Global trade in biomass and bioenergy

Global trade in biomass feedstocks (e.g., wood chips, raw vegetable oils, agricultural residues) and especially of energy carriers from modern

28 The latest addition is a wheat straw-to-ethanol demonstration plant to the complex of a coal power plant, an oil refinery, biotechnology companies, district heating, fish aquaculture, landfill plant with gas collection, fertilizer production, gypsum (plaster), soil remediation and water treatment facilities, and others. Waste products (e.g., heat, gas and sulphur, ash, hot water, yeasts, fertilizers, waste slurries, solid wastes) from one company become a resource for use by one or more companies, and a nearby town, in a well-functioning industrial ecosystem. (See, for instance, www.kalundborg.dk/Erhvervsliv/The_Green_Industrial_Municipality/Cluster_Biofuels_Denmark_(CBD).aspx and www.inbicon.com/Biomass Refinery/Pages/Inbicon_Biomass_Refinery_at_Kalundborg.aspx.)

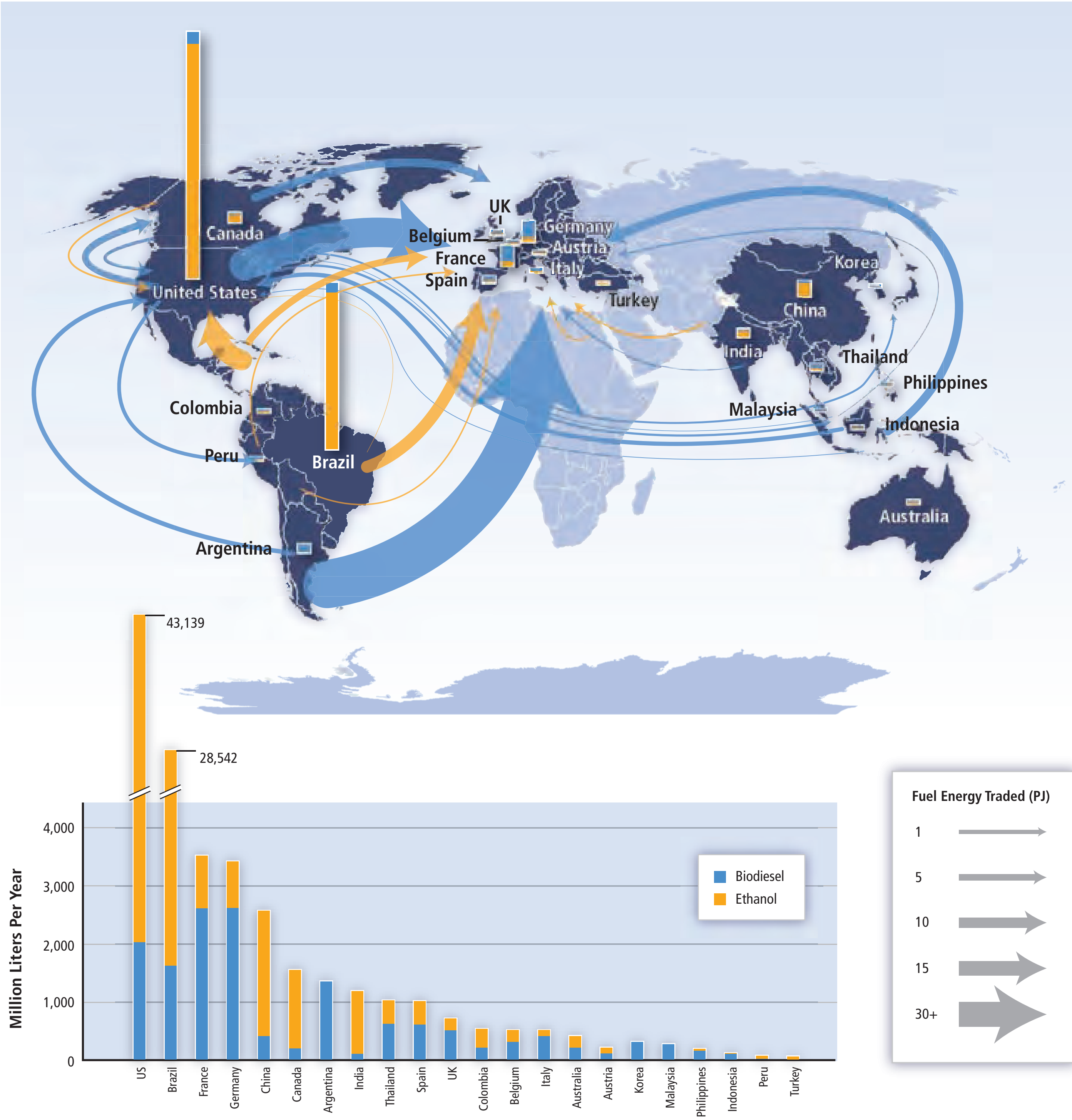


Figure 2.9 | Global biofuels production and main international trade, 2009. Biofuel volume sources: GAIN (2009a,b,[1] 2010a-j[2]); EIA (2010a); EurObserv'ER (2010); RFA (2010);[3] REN21 (2010).[4] Trade flows: Lamers et al. (2010).[5] The total intra-EU biodiesel and ethanol trade corresponds to 78 and 116 PJ, respectively (Lamers et al., 2011).

Notes: 1. Data for China and Indonesia. 2. Data for Argentina, Australia, Brazil, Canada, India, Korea, Malaysia, Peru, The Philippines, Thailand and Turkey. 3. www.ethanolrfa.org/pages/statistics. 4. See www.ren21.net/REN21Activities/ for updated information on biofuels volumes and targets for the various countries and other policy information and interactive tools (www.map.ren21.net). 5. For trade flows used in Figure 2.9 see www.chem.uu.nl/nws; for detailed data see Lamers et al. (2011).

bioenergy (e.g., ethanol, biodiesel, wood pellets) is growing rapidly. While practically no liquid biofuels or wood pellets were traded in 2000, the world net trade of liquid biofuels amounted to 120 to 130 PJ in 2009 (Figure 2.9), compared to about 75 PJ for wood pellets (Figure 2.8). Larger quantities of these products are expected to be traded internationally in the future, with Latin America and sub-Saharan Africa as potential net exporters and North America, Europe and Asia expected as net importers (Heinimö and Junginger, 2009). Trade can therefore become an important component of the sustained growth of the bioenergy sector. Figure 2.9 shows 2009 biofuels production in many countries along with the net global trade streams of bioethanol and biodiesel (see also Table 2.9). In 2008, around 9% of global biofuel production was traded internationally (Junginger et al., 2010). Production and trade of these three commodities are discussed in more detail below.

Global fuel *ethanol production* grew from around 0.375 EJ in 2000 to more than 1.6 EJ in 2009 (Lamers et al., 2011). The USA and Brazil, the two leading ethanol producers and consumers, accounted for about 85% of the world's production. In the EU, total consumption of ethanol for transport in 2009 was 94 PJ (3.6 Mt), with the largest users being France, Germany, Sweden and Spain (Lamers et al., 2011; EurObserv'ER, 2010). Data related to fuel *bioethanol trade* are imprecise on account of the various potential end uses of ethanol (i.e., fuel, industrial and beverage use) and also because of the lack of proper codes for biofuels in global trade statistics. As an estimate, a net amount of 40 to 51 PJ of fuel ethanol was traded in 2009 (Lamers et al., 2011).

World *biodiesel production* started below 20 PJ in 2000 and reached about 565 PJ in 2009 (Lamers et al., 2011). The EU produced 334 PJ (roughly two-thirds of the global production), with Germany, France, Spain and Italy being the top EU producers (EurObserv'ER, 2010). EU27 biodiesel production rates levelled off towards 2008 (FAPRI, 2009).[29] The intra-European biodiesel market has become more competitive, and the 2009 overcapacity has already led to the closure of (smaller, less vertically integrated, less efficient, remote, etc.) biodiesel plants in Germany, Austria and the UK. As shown in Figure 2.9, other main biodiesel producers include the USA, Argentina and Brazil. Biodiesel consumption in the EU amounted to about 403 PJ (8.5 Mt) (EurObserv'ER, 2010), with Germany and France consuming almost half of this amount. Net international *biodiesel trade* was below 1 PJ before 2005 but grew very fast from this small base to more than 80 PJ in 2009, as shown in Figure 2.9 (Lamers et al., 2011).

Production, consumption and trade of *wood pellets* have grown strongly within the last decade and are comparable to ethanol and biodiesel in terms of global trade volumes. As a rough estimate, in 2009, more than 13 Mt (230 PJ) of *wood pellets* were produced primarily in 30 European countries, the USA and Canada (Figure 2.8). Consumption was high in many EU countries and the USA. The largest EU consumers were Sweden (1.8 Mt or 32 PJ), Denmark, the Netherlands, Belgium, Germany and Italy (roughly 1 Mt or 18 PJ each). Main *wood pellet trade* routes lead from Canada and the USA to Europe (especially Sweden, the Netherlands and Belgium) and to the USA. In 2009, other minor trade flows were also reported, for example, from Australia, Argentina and South Africa to the EU. Canadian producers also started to export small quantities to Japan. Total imports of wood pellets by European countries in 2009 were estimated to be about 3.9 Mt (69 PJ), of which about half can be assumed to be intra-EU trade (Sikkema et al., 2010, 2011).

2.4.5 Overview of support policies for biomass and bioenergy[30]

Typical examples of support policies are shown in Table 2.11. For instance, *liquid biofuels* policies include the (former) Brazilian Proálcool programme, regulations in the form of mandates in many EU countries and the USA fiscal incentives such as tax exemptions, production tax credits and accelerated depreciation (WWI, 2007). The majority of successful policies for *heat* from biomass in recent decades have focused on more centralized applications for heat or CHP in district heating and industry (Bauen et al., 2009a). For these sectors, a combination of direct support schemes with indirect incentives has been successful in several countries, such as Sweden (Junginger, 2007). Both quota systems and FITs have been implemented in support of bioenergy *electricity* generation, though FITs have gradually become the more popular incentive. The effectiveness and efficiency of FITs and quota systems for promoting RE generation (including for bioenergy) has been thoroughly debated. A full discussion of these instruments can be found in Section 11.5.3. Next to FITs or quotas, almost all countries that have successfully stimulated bioenergy development have applied additional public finance relating to investment support and soft loans along with fiscal measures (GBEP, 2008). Additionally, grid access for renewable power is an important issue that needs to be addressed. Priority grid access for renewable sources is applied in most countries where bioenergy technologies have been successfully deployed (Sawin, 2004).

Support policies (see Table 2.11) have strongly contributed in past decades to the growth of bioenergy for electricity, heat and transport fuels. However, several reports also point out the costs and risks associated with support policies for biofuels. According to the WEO (IEA, 2010b), the annual global government support for biofuels in 2009, 2008 and 2007 was USD_{2009} 20 billion, 17.5 billion and 14 billion, respectively, with corresponding EU spending of USD_{2009} 7.9 billion, 8.0 billion and 6.3 billion and corresponding US spending of USD_{2009} 8.1 billion, 6.6 billion and 4.9 billion. The US spending was driven by energy security and fossil fuel import reduction goals. Concerns about food prices, GHG emissions and environmental impacts have also led to many countries rethinking biofuels blending targets. For example, Germany revised its blending target for 2009 downward from 6.25 to 5.25%.[31] Addressing these concerns led also to the incorporation of environmental and social

29 While most EU Member States (MS) increased their production volumes, the German biodiesel market shrunk both in supply and demand due to a change in the policy framework phasing out tax exemptions for neat biodiesel at the pump. At the same time biodiesel export to other EU MS became less and less feasible for German (and other) producers due to increasing shares of competitively priced biodiesel imports, mainly from the USA in the period from 2006 to 2008 and also from Argentina in the years 2008 and 2009 (Lamers et al., 2011).

30 Non-technology-specific policy issues are covered in Chapter 11 of this report.

31 Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit decision published on 22.10.2008 and available at www.bmu.de/pressearchiv/16_legislaturperiode/pm/42433.php.

sustainability criteria for biofuels in the EU Renewable Energy Directive. Although seemingly effective in supporting domestic farmers, the effectiveness of biofuel policies in reaching the climate change and secure energy supply objectives is coming under increasing scrutiny. It has been argued that these policies have been costly and have tended to introduce new distortions to already severely distorted and protected agricultural markets—at both domestic and global levels. This has not tended to favour an efficient international production pattern for biofuels and their feedstocks (FAO, 2008a; Bringezu et al., 2009). An overall biomass strategy would have to consider all types of use of food and non-food biomass (Bringezu et al., 2009).

The main drivers behind government support for the sector have been concerns over climate change and energy security as well as the desire to support the agricultural sector through increased demand for agricultural products (FAO, 2008a). According to the REN21 global interactive map (see note 4 to Figure 2.9) a total of 69 countries had one or several biomass support policies in place in 2009 (REN21, 2010; Section 11.2).

2.4.5.1 Intergovernmental platforms for exchange on bioenergy policies and standardization

Several multi-stakeholder initiatives exist in which policymakers can find advice, support and the possibility of exchanging experiences on policymaking for bioenergy. Examples of such international organizations and forums supporting the further development of sustainability criteria and methodological frameworks for assessing GHG mitigation benefits of bioenergy include the Global Bioenergy Partnership (GBEP from the G8+5),[32] the IEA Bioenergy Agreement,[33] the International Bioenergy Platform at the Food and Agriculture Organization (FAO),[34] the OECD Roundtable on Sustainable Development,[35] and standardization organizations such as the European Committee for Standardization[36] and the International Organization for Standardization[37] (ISO) that are actively working toward the development of sustainability standards.

32 The GBEP provides a forum to inform policy development frameworks, promote sustainable biomass and bioenergy development, facilitate investments in bioenergy, promote project development and implementation, and foster R&D and commercial bioenergy activities. Membership includes individual countries, multilateral organizations, and associations.

33 The IEA Bioenergy Agreement provides an umbrella organization and structure for a collective effort in the field of bioenergy including non-OECD countries interested in the topics from RD&D to policies. It brings together policy and decision makers and national experts from research, government and industry across the member countries.

34 See ftp.fao.org/docrep/fao/009/A0469E/A0469E00.pdf.

35 See www.oecd.org/dataoecd/14/3/46063741.pdf.

36 See www.cen.eu/cen/Sectors/TechnicalCommitteesWorkshops/CENTechnicalCommittees/Pages/default.aspx TC335 for solid biofuels standards, TC19 for liquid biofuels, and TC 383 for sustainability criteria for biofuels.

37 See www.iso.org/iso/standards_development/technical_committees/list_of_iso_technical_committees.htm TC 248 for sustainability criteria for biofuels, TC 238 for solid biofuels, TC255 for biogas, and TC 28/SC 7 for liquid biofuels.

2.4.5.2 Sustainability frameworks and standards

Governments are stressing the importance of ensuring sufficient climate change mitigation and avoiding unacceptable negative effects of bioenergy as they implement regulating instruments. For example, the Renewable Energy Directive (European Commission, 2009) provides mandatory sustainability requirements for liquid transport fuels.[38] Also, in the USA, the Renewable Fuel Standard—included in the 2007 Energy Independence and Security Act (EISA, 2007)—mandates minimum GHG reductions from renewable fuels, discourages use of food and fodder crops as feedstocks, permits use of cultivated land and estimates (indirect) LUC effects to set thresholds of GHG emission reductions for categories of fuels (EPA, 2010; see also Section 2.5). The California Low Carbon Fuel Standard set an absolute carbon intensity reduction standard and periodic evaluation of new information, for instance, on indirect land use impacts.[39] Other examples are the UK Renewable Transport Fuel Obligation, the German Biofuel Sustainability Ordinance, and the Cramer Report (The Netherlands). With the exception of Belgium, no mandatory sustainability criteria for solid biomass (e.g., wood pellets) have been implemented—the European Commission will review this at the end of 2011 (European Commission, 2010).

The development of impact assessment frameworks and sustainability criteria involves significant challenges in relation to methodology, process development and harmonization. As of a 2010 review, nearly 70 ongoing certification initiatives exist to safeguard the sustainability of agriculture and forestry products, including those used as feedstock for the production of bioenergy (van Dam et al., 2010). Within the EU, a number of initiatives started or have already set up certification schemes in order to guarantee a more sustainable cultivation of energy crops and production of energy carriers from modern biomass (e.g., ISCC[40]; REDCert[41] 2010 in Germany; or the NTA8080/8081 (NEN[42]) in the Netherlands). Many initiatives focus on the sustainability of liquid biofuels including primarily environmental principles, although some of them, such as the Council for Sustainable Biomass Production and the Better Sugarcane Initiative, the Roundtable for Sustainable Biofuels (RSB) and the Roundtable for Responsible Soy, include explicit socioeconomic impacts of bioenergy production. Principles such as those from the RSB have already led to a Biofuels Sustainability Scorecard used by the Inter-American Development Bank for the development of projects.

38 These requirements are: specific GHG emission reductions must be achieved, and the biofuels in question must not be produced from raw materials being derived from land of high value in terms of biological diversity or high carbon stocks.

39 The California Air Resources Board requires 10% absolute emissions reductions from fossil energy sources by 2020 and considers direct lifecycle emissions of the biofuels and also indirect LUC as required by legislation (CARB, 2009).

40 International Sustainability and Carbon Certification, Koeln, Germany, www.iscc-system.org/index_eng.html

41 REDcert Certification System, www.redcert.org

42 NTA 8080 - Sustainabley Produced Biomass. Dutch Normalization Institute (NEN), Delft, The Netherlands, www.sustainable-biomass.org/publicaties/3950

The proliferation of standards that has taken place over the past four years, and continues, shows that certification has the potential to influence local impacts related to the environmental and social effects of direct bioenergy production. Many of the bodies involved conclude that for an efficient certification system there is a need for further harmonization, availability of reliable data, and linking indicators at micro, meso and macro levels (see Figure 2.15). Considering the multiple spatial scales, certification should be combined with additional measurements and tools at regional, national and international levels.

The role of bioenergy production in iLUC is still uncertain; current initiatives have rarely captured impacts from iLUC in their standards, and the time scale becomes another important variable in assessing such changes (see Section 2.5.3). Addressing unwanted LUC requires overall sustainable agricultural production and good governance first of all, regardless of the end use of the product or of the feedstocks.

2.4.6 Main opportunities and barriers for the market penetration and international trade of bioenergy

2.4.6.1 Opportunities[43]

The prospects for biofuels for road transport depend on developments in competing low-carbon and oil-reducing technologies for road transport (e.g., electric vehicles). Biofuels may in the longer term be increasingly used within the aviation industry, for which high energy density carbon fuels are necessary (see Section 2.6.3), and also in marine shipping.

The development of international markets for bioenergy has become an essential driver to develop available biomass resources and market potential, which are currently underutilized in many world regions. This is true for both (available) residues as well as possibilities for dedicated biomass production (through energy crops or multifunctional systems such as agro-forestry). Export of biomass-derived commodities for the world's energy market can provide a stable and reliable income for rural communities in many (developing) countries, thus creating an important incentive and market access.[44]

Also on the demand side, large biomass users that rely on a stable supply of biomass can benefit from international bioenergy trade, as this enables (often very large) investments in infrastructure and conversion capacity.[45]

Introduction of incentives based on political decisions is a driving force and has triggered an expansion of bioenergy trade. For example, wood pellet imports in the Netherlands and Belgium have been driven respectively through a feed-in premium system and a Green Certificate system. However, the success of policies has varied, due partly to the nature of the design and implementation of the given policy but also to the fact that the institutions related to the incentives are different. For a full discussion of influencing factors outside of policies (e.g., institutions, network access), see Section 11.6.

Another driver is the utilization of established logistics for existing commodities. Taking again the example of wood pellet co-firing in large power plants, the existing infrastructure at ports and storage facilities used to supply coal and other dry bulk goods can (partially, and after adaptations) also be used for wood pellets, making cost-efficient transport and handling possible. Another form of integrated supply chain is bark, sawdust and other residues from imported roundwood, which is common in, for example, Northern Europe. Finally, the concept of regional biomass processing centres has been proposed to deal with supply side challenges and also to help address social sustainability concerns (Carolan et al., 2007).

2.4.6.2 Barriers

Major risks and barriers to deployment are found all along the bioenergy value chain and concern all final energy products (bioheat, biopower, and biofuel for transport).[46] On the supply side, there are challenges related to securing quantity, quality and price of biomass feedstock, irrespective of the origin of the feedstock (energy crops, wastes or residues). There are also technology challenges related to the varied physical properties and chemical composition of the biomass feedstock and challenges associated with the poor economics of current power and biofuel technologies at small scales. On the demand side, the main challenges are the stability and supportiveness of policy frameworks and investors' confidence in the sector and its technologies, in particular to overcome financing challenges associated with demonstrating the reliable operation of new technologies at commercial scale.[47] In the power and heat sectors, competition with other RE sources may also be an issue. Public acceptance and public perception are also critical factors in gaining support for energy crop production and bioenergy facilities.

Specifically for the bioenergy trade, Junginger et al. (2010) identified a number of (potential) barriers:

Tariffs. As of January 2007, import tariffs apply in many countries, especially for ethanol and biodiesel. Tariffs (expressed in local currency and year) are applied on bioethanol imports by both the EU (€ 0.192 per litre) and the USA (USD 0.1427 per litre and an additional 2.5%

43 This sub-section is largely based on Junginger et al. (2008).

44 Exports of ethanol from Brazil and wood pellets from Canada are examples where export opportunities (at least partially) were drivers to further develop the supply side.

45 Utilities in the Netherlands and Belgium import large amounts of wood pellets to co-fire with coal, as domestic biomass resources are very limited and of varying quality.

46 Most of the remainder of this paragraph is based on Bauen et al. (2009a).

47 Some governments have jointly financed first-of-a-kind commercial technological development with the private sector in the past five years, but the financial crisis is making it difficult to complete the private financing needed to continue to obtain government financing.

ad valorem subsidy). In general, the most-favoured nation tariffs range from roughly 6 to 50% on an ad valorem equivalent basis in the OECD, and up to 186% in the case of India (Steenblik, 2007). Biodiesel used to be subject to lower import tariffs than bioethanol, ranging from 0% in Switzerland to 6.5% in the EU and the USA (Steenblik, 2007). However, in July 2009, the European Commission confirmed a five-year temporary imposition of anti-dumping and anti-subsidy rights on American biodiesel imports, with fees standing between € 213 and 409 per tonne (local currency and year) (EurObserv'ER, 2010). These trade tariffs were a reaction to the so-called 'splash-and-dash' practice, in which biodiesel blended with a 'splash' of fossil diesel was eligible for a USD 1 per gallon subsidy (equivalent to USD 300/t) in 2008-2009; see Lamers et al. (2011) for detailed information on the various tariffs, trade regimes, and policies worldwide.

Technical standards describe in detail the physical and chemical properties of fuels. Regulations pertaining to the technical characteristics of liquid transport fuels (including biofuels) exist in all countries. These have been established in large part to ensure the safety of the fuels and to protect consumers from buying fuels that could damage their vehicles' engines. Regulations include maximum percentages of biofuels that can be blended with petroleum fuels and regulations pertaining to the technical characteristics of the biofuels themselves. In the case of biodiesel, the latter may depend on the vegetable oils used for the production, and thus regulations might be used to favour biodiesel from domestic feedstocks over biodiesel from imported feedstocks. Technical barriers for the bioethanol trade also exist. For example, the different demands for maximum water content have negative impacts on trade. However, in practice, most market actors have indicated that they see technical standards as an opportunity enabling international trade rather than as a barrier (Junginger et al., 2010).

Sustainability criteria and biomass and biofuels certification have been developed in increasing numbers in recent years as voluntary or mandatory systems (see Section 2.4.5.2); such criteria, so far, do not apply to conventional fossil fuels. Three major concerns in relation to the international bioenergy trade are:

1. Criteria, especially those related to environmental and social issues, could be too stringent or inappropriate to local environmental and technological conditions in producing developing countries (van Dam et al., 2010). The fear of many developing countries is that if the selected criteria are too strict or are based on the prevailing conditions in the countries setting up the certification schemes, only producers from those countries may be able to meet the criteria, and thus these criteria may act as trade barriers. As the criteria are extremely diverse, ranging from purely commercial aims to rainforest protection, there is a danger that a compromise could result in overly detailed rules that lead to compliance difficulties, or, on the other hand, in standards so general that they become meaningless. Implementing binding requirements is also limited by World Trade Organization rules.

2. With current developments by the European Commission, different European governments, several private sector initiatives, and initiatives of round tables and NGOs, there is a risk that in the short term a multitude of different and partially incompatible systems will arise, creating trade barriers (van Dam et al., 2010). If they are not developed globally or with clear rules for mutual recognition, such a multitude of systems could potentially become a major barrier for international bioenergy trade instead of promoting the use of sustainable biofuels production. A lack of transparency in the development of some methodologies, for example, in the EU legislation, is an issue. Also, the eventual existence of different demands for proving compliance with the criteria for locally produced biomass sources and imported ones is a potential barrier. Finally, lack of international systems may cause market distortions.

   Production of 'uncertified' biofuel feedstocks will continue and enter other markets in countries with lower standards or for non-biofuel applications that may not have the same standards. The existence of a 'two-tier' system would result in failure to achieve the safeguards envisaged (particularly for LUC and socioeconomic impacts).

3. Finally, note that to ensure that biomass commodities are being produced in a sustainable manner, some chain of custody (CoC) method must be used to track biomass and biofuels from production to end use. Generally, the three types of CoC methods are segregation (also known as track-and-trace), book-and-claim and mass-balance. While this is not necessarily a major barrier, it may cause additional cost and administrative burdens.

Logistics are a pivotal part of the system and essential to set up biomass fuel supply chains for large-scale biomass systems. Various studies have shown that long-distance international transport by ship is feasible in terms of energy use and transportation costs (e.g., Sikkema et al., 2010, 2011), but availability of suitable vessels and meteorological conditions (e.g., winter in Scandinavia and Russia) need to be considered. One logistical barrier is a general lack of technically mature technologies to densify biomass at low cost to facilitate transport, although technologies are being developed (Sections 2.3.2 and 2.6.2).

Sanitary and phytosanitary (SPS) measures may be faced by feedstocks for liquid biofuels or technical regulations applied at borders. SPS measures mainly affect feedstocks that, because of their biological origin, can carry pests or pathogens. One of the most common SPS measures is a limit on pesticide residues. Meeting pesticide residue limits is usually not difficult but on occasion has led to the rejection of imported shipments of crop products, especially from developing countries (Steenblik, 2007).

2.4.7 Synthesis

The review of developments in biomass use, markets and policy shows that bioenergy has seen rapid developments over the past years. The use of modern biomass for liquid and gaseous energy carriers is growing, in particular biofuels (with a 37% increase from 2006 to 2009). Projections from the IEA, among others, but also many national targets, count on biomass delivering a substantial increase in the share of RE. International trade in biomass and biofuels has also become much more important over recent years, with roughly 6% (reaching levels of up to 9% in 2008) of biofuels (ethanol and biodiesel only), and one-third of all pellet production for energy use, traded internationally in 2009. Pellets have proven to be an important facilitating factor in both increasing utilization of biomass in regions where supplies are constrained as well as mobilizing resources from areas where demand is lacking. Nevertheless, many barriers remain to developing well-working commodity trading of biomass and biofuels that at the same time meets sustainability criteria.

The policy context for bioenergy, and in particular biofuels, in many countries has changed rapidly and dramatically in recent years. The debate on food versus fuel competition and the growing concerns about other conflicts have resulted in a strong push for the development and implementation of sustainability criteria and frameworks as well as changes in temporization of targets for bioenergy and biofuels. Furthermore, the support for advanced biorefinery and second-generation biofuel options is driving bioenergy in more sustainable directions.

Persistent policy and stable policy support has been a key factor in building biomass production capacity and working markets, required infrastructure and conversion capacity that gets more competitive over time. These conditions have led to the success of the Brazilian programme to the point that ethanol production costs are lower than those of gasoline. Brazil achieved an energy portfolio mix that is substantially renewable and that minimized foreign oil imports. Sweden, Finland, and Denmark also have shown significant growth in renewable electricity and in management of integrated resources, which steadily resulted in innovations such as industrial symbiosis of collocated industries. The USA has been able to quickly ramp up production with the alignment of national and sub-national policies for power in the 1980s and for biofuels in the 1990s to present, as petroleum prices and instability in key producing countries increased; however, as oil prices decreased, policy support and bioenergy production decreased for biopower and is increasing again with environmental policies and sub-national targets.

Countries differ in their priorities, approaches, technology choices and support schemes for further development of bioenergy. Although this means increased complexity of the bioenergy market, this also reflects the many aspects that affect bioenergy deployment—agriculture and land use, energy policy and security, rural development and environmental policies. Priorities, stage of development and geographic access to the resources, and their availability and costs differ widely from country to country.

As policies surrounding bioenergy and biofuels become more holistic, using sustainability demands as a starting point is becoming an overall trend. This is true for the EU, the USA and China, but also for many developing countries such as Mozambique and Tanzania. This is a positive development but is by no means settled (see also Section 2.5). The 70 initiatives registered worldwide by 2009 to develop and implement sustainability frameworks and certification systems for bioenergy and biofuels, as well as agriculture and forestry, can lead to a fragmentation of efforts (van Dam et al., 2010). The needs for harmonization and for international and multilateral collaboration and dialogue are widely stressed at present.

2.5 Environmental and social impacts[48]

Recent studies have highlighted both positive and negative environmental and socioeconomic effects of bioenergy and the associated agriculture and forestry LUC (IPCC, 2000b; Millennium Ecosystem Assessment, 2005). Like conventional agriculture and forestry systems, bioenergy can exacerbate soil and vegetation degradation associated with overexploitation of forests, too intensive crop and forest residue removal, and water overuse (Koh and Ghazoul, 2008; Robertson et al., 2008). Diversion of crops or land into bioenergy production can influence food commodity prices and food security (Headey and Fan, 2008). With proper operational management, the positive effects can include enhanced biodiversity (C. Baum et al., 2009; Schulz et al., 2009), soil carbon increases and improved soil productivity (Tilman et al., 2006a; S. Baum et al., 2009), reduced shallow landslides and local flash floods, reduced wind and water erosion and reduced sediment volume and nutrients transported into river systems (Börjesson and Berndes, 2006). For forests, bioenergy can improve growth and productivity, improve site conditions for replanting and reduce wildfire risk (Dymond et al., 2010). However, forest residue harvesting can have negative impacts such as the loss of coarse woody debris that provides essential habitat for forest species.

Biofuels derived from purpose-grown agricultural feedstocks are water intensive (see Section 9.3.4.4 for comparisons of renewable and non-renewable power sources; Berndes, 2002; King and Weber, 2008; Chiu et al., 2009; Dominguez-Faus et al., 2009; Gerbens-Leenes et al., 2009; Wu et al., 2009; Fingerman et al., 2010). Their influence on water resources and the wider hydrologic cycle depends on where, when and how the biofuel feedstock is produced. Among different bioenergy supply chains, across the spectrum of feedstocks, cultivation systems and conversion technologies, water demand varies greatly (Wu et al., 2009; Fingerman et al., 2010, De La Torre Ugarte, et al., 2010). While biofuel made from irrigated crops requires extraction of large volumes of water from lakes, rivers and aquifers, use of agricultural or forestry residues as bioenergy feedstocks does not generally require much additional land or water. Rain-fed feedstock production does not require water extraction from

48 A comprehensive assessment of social and environmental impacts of all RE sources covered in this report can be found in Chapter 9.

water bodies, but it can still reduce downstream water availability by redirecting precipitation from runoff and groundwater recharge to crop evapotranspiration. Using water for bioenergy has very different social and ecological consequences depending upon the state of the resource base from which that water was drawn.

Few universal conclusions about the socioeconomic and environmental implications of bioenergy can currently be drawn, given the multitude of rapidly evolving bioenergy sources, the complexities of physical, chemical and biological conversion processes, the multiple energy products, and the variability in environmental conditions. Thus, the positive and negative effects of bioenergy are a function of the socioeconomic and institutional context, the types of lands and feedstocks used, the scale of bioenergy programmes and production practices, the conversion processes, and the rate of implementation (e.g., Kartha et al., 2006; Firbank, 2008; E. Gallagher, 2008; OECD-FAO, 2008; Royal Society, 2008; UNEP, 2008b; Howarth et al., 2009; Pacca and Moreira, 2009; Purdon et al., 2009; Rowe et al., 2008).

Bioenergy system impact assessments (IAs) must be compared to the IAs of replaced systems.[49] The methodologies and underlying assumptions for assessing environmental (Sections 2.5.1 through 2.5.6) and socioeconomic (Section 2.5.7) effects (see Table 2.12 for examples of these impacts) differ greatly and therefore the conclusions reached by these studies are inconsistent (H. Kim et al., 2009). One particular challenge for socioeconomic IAs is that their boundaries are difficult to quantify and are a complex composite of numerous interrelated factors, many of which are poorly understood or unknown. Social processes have feedbacks that are difficult to clearly define with an acceptable level of confidence. Environmental IAs include many quantifiable impact categories but still lack data and are uncertain in many areas. The outcome of an environmental IA depends on methodological choices, which are not yet standardized or uniformly applied throughout the world.

49 A 'rebound effect' could be included, usually fossil fuels, but also other primary energy sources (Barker et al., 2009).

2.5.1 Environmental effects

Studies of environmental effects, including those focused on energy balances and GHG emission balances, usually employ methodologies in line with the principles, framework, requirements and guidelines in the ISO 14040:2006 and 14044:2006 standards for Life Cycle Assessment (LCA) discussed in Section 9.3.4.1. An earlier specific method for assessing GHG balances of biomass and bioenergy systems was developed by Schlamadinger et al. (1997).

Key issues for bioenergy LCAs are system definition including spatial and dynamic boundaries, functional units, reference system, and the selection of methods for considering energy and material flows across system boundaries (Soimakallio et al., 2009a; Cherubini and Strømman, 2010). As part of cascading cycles, many processes create multiple products; for example, biomass is used to produce biomaterials while co-products and the biomaterial itself are used for energy after their useful life (Dornburg and Faaij, 2005). Such cascading results in significant data and methodological challenges because environmental effects can be distributed over several decades and in different geographical locations (Cherubini et al., 2009b).

Most of the assumptions and data used in LCA studies of existing bioenergy systems are related to first-generation biofuels and to conditions and practices in Europe or the USA, although studies are becoming available for Brazil, China and other countries (see examples in Tables 2.7, 2.13, and 2.15). Ongoing development of biomass production and conversion technologies makes many of these studies of commercial technologies outdated.[50] LCA studies of prospective bioenergy options involve projections of technology performance and have relatively greater uncertainties (see, e.g., Figure 9.9). The way that uncertainties

50 For instance, using a 2006 reference that analyzed an industrial system in 2002 will not represent the industry in 2010 because learning occurred in commercial technologies that exhibited a significant accumulation of production volume such as in the USA and in Brazil; an example of wide-spread adoption of a different technology in this industry is the USA where dry milling has become the major route to ethanol production (see Sections 2.3.4 and 2.7.2).

Table 2.12 | Environmental and socioeconomic impacts of bioenergy: example areas of concern with selected impact categories (synthesized from the literature review by van Dam et al., 2010).

Example areas of concern	Examples of impact categories
Global, regional, off-site environmental effects	GHGs; albedo; acidification; eutrophication; water availability and quality; regional air quality
Local/onsite environmental effects	Soil quality; local air quality; water availability and quality; biodiversity and habitat loss
Technology	Hazards; emissions; congestion; safety; genetically modified organisms/plants
Human rights and working conditions	Freedom of association; access to social security; job creation and average wages; freedom from discrimination; no child labour and minimum age of workers; freedom of labour (no forced labour); rights of indigenous people; acknowledgment of gender issues
Health and safety	Impacts on workers and users; safety conditions at work
Food security	Replacement of staple crops; safeguarding local food security
Land and property rights	Acknowledgment of customary and legal rights of land owners; proof of ownership; compensation systems available; agreements by consent
Participation and well-being of local communities	Cultural and religious values; contribution to local economy and activities; compensation for use of traditional knowledge; support to local education; local procurement of services and inputs; special measures to target vulnerable groups

and parameter sensitivities are handled across the supply chain to fuel production significantly impacts the results (Sections 2.5.2 through 2.5.6). Studies combining several LCA models and/or Monte Carlo analysis provide bioenergy system uncertainties and levels of confidence for some bioenergy options (e.g., Soimakallio et al., 2009b; Hsu et al., 2010; Spatari and MacLean, 2010).

Most bioenergy system LCAs are designated as attributional to the defined process system boundaries. Consequential LCAs analyze bioenergy systems beyond these boundaries, in the context of the economic interactions, chains of cause and effect in bioenergy production and use, and effects of policies or other initiatives that increase bioenergy production and use. Consequential LCAs can investigate systemic responses to bioenergy expansion (e.g., how the food system changes if increasing volumes of cereals are used as biofuel feedstock or how petroleum markets respond if increased biofuels production results in reduced petroleum demand—see Section 2.5.3 and Figure 2.13). The outcome of *any* measure to reduce a certain use can be affected by a rebound effect—in the case of bioenergy, if increased production of solid, liquid and gaseous biofuels leads to lower demand for fossil fuels, this in turn could lead to lower fossil fuel prices and increased fossil fuel demand (Rajagopal et al., 2011; Stoft, 2010).[51] Similarly, when considering co-products, LCAs should ideally model displacement of alternative products as a dynamic result of market interactions. Consequential LCAs therefore require auxiliary tools such as economic equilibrium models.

2.5.2 Modern bioenergy: Climate change excluding land use change effects

The ranges of GHG emissions for bioenergy systems and their fossil alternatives per unit energy output are shown in Figure 2.10 for several uses (transport, power, heat) calculated based on LCA methodologies (land use-related net changes in carbon stocks and land management impacts

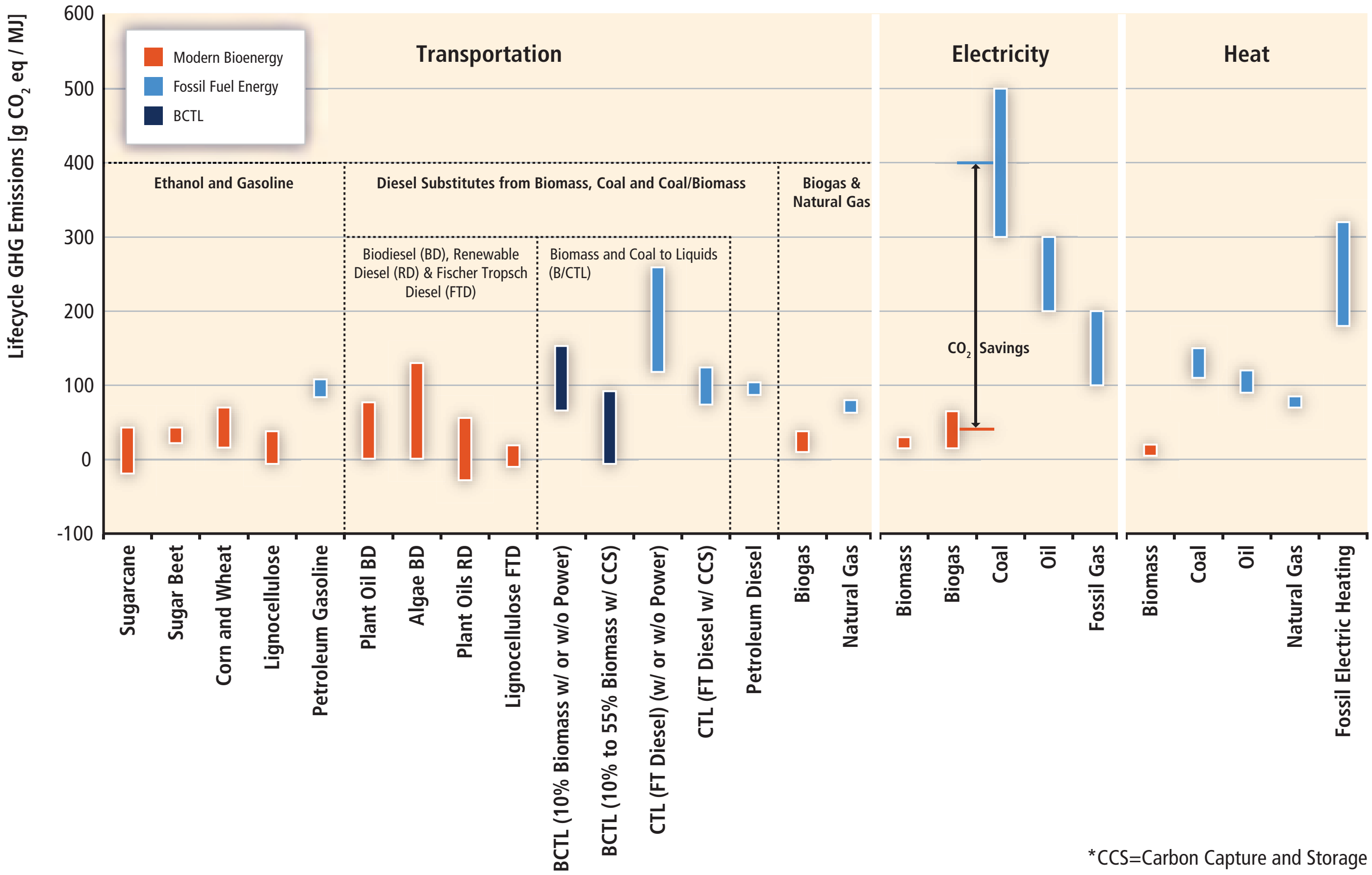


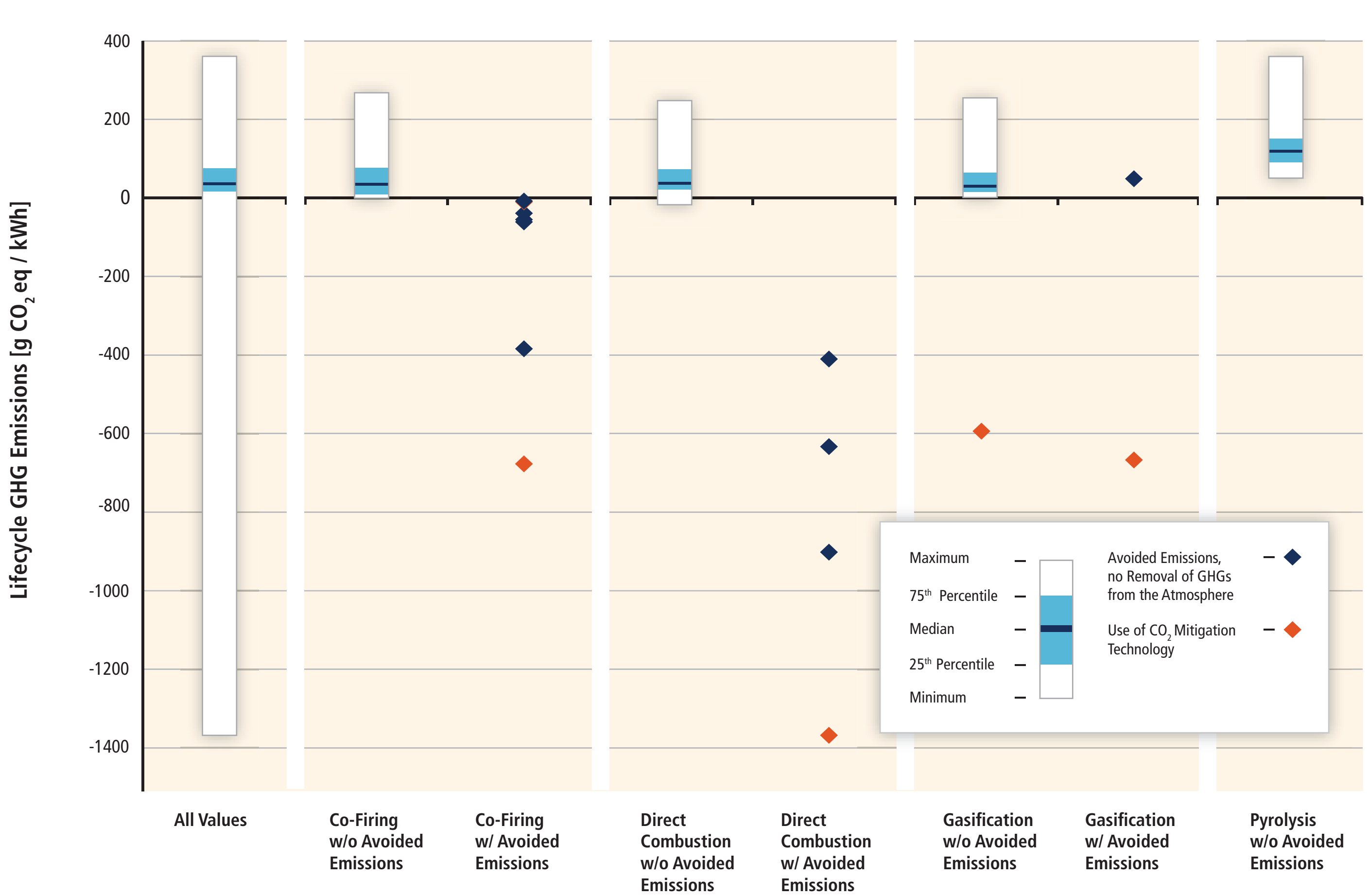
Figure 2.10 | Ranges of GHG emissions per unit energy output (MJ) from major modern bioenergy chains compared to conventional and selected advanced fossil fuel energy systems (land use-related net changes in carbon stocks and land management impacts are excluded). Commercial and developing (e.g., algae biofuels, Fischer-Tropsch) systems for biomass and fossil technologies are illustrated.

Data sources: Wu et al. (2005); Fleming et al. (2006); Hill et al. (2006, 2009); Beer and Grant (2007); Wang et al. (2007, 2010); Edwards et al. (2008); Kreutz et al. (2008); Macedo and Seabra (2008); Macedo et al. (2008); NETL (2008, 2009a,b); CARB (2009); Cherubini et al. (2009a); Huo et al. (2009); Kalnes et al. (2009); van Vliet et al. (2009); EPA (2010); Hoefnagels et al. (2010); Kaliyan et al. (2010); Larson et al. (2010); 25th to 75th percentile of all values from Figure 2.11.

51 The same rebound effect applies to other RE technologies displacing incumbent fossil technologies.

are excluded). Meta-analyses to quantify the influence of bioenergy systems on climate are complicated because of the multitude of existing and rapidly evolving bioenergy sources, the complexities of physical, chemical and biological conversion processes, and feedstock diversity and variability in site-specific environmental conditions—together with differences between studies in method interpretation, assumptions and data. Due to this, review studies report varying estimates of GHG emissions and a wide range of results have been reported for the same bioenergy options, even when temporal and spatial considerations are constant (see, e.g., S. Kim and Dale, 2002; Fava, 2005; Farrell et al., 2006; Fleming et al., 2006; Larson, 2006; von Blottnitz and Curran, 2007; Rowe et al., 2008; Börjesson, 2009; Cherubini et al., 2009a; Menichetti and Otto, 2009; Soimakallio et al., 2009b; Hoefnagels et al., 2010; Wang et al., 2010, 2011).

For electricity generated by various technologies, GHG emissions per kWh generated are detailed in Figure 2.11, based on published estimates from lifecycle GHG emissions (land use-related net changes in carbon stocks and land management impacts are excluded) of an extensive review of biopower LCAs.[52] Figure 2.11 shows that the majority of lifecycle GHG emission estimates cluster between about 16 and 74 g CO_2eq/kWh (4.4 and 21 g CO_2eq/MJ), with one estimate reaching



	All Values	Co-Firing w/o Avoided Emissions	Co-Firing w/ Avoided Emissions	Direct Combustion w/o Avoided Emissions	Direct Combustion w/ Avoided Emissions	Gasification w/o Avoided Emissions	Gasification w/ Avoided Emissions	Pyrolysis w/o Avoided Emissions
Estimates:	228	54	7	102	4	45	2	14
References:	53	19	4	26	3	20	1	3

Figure 2.11 | Lifecycle GHG emissions of biopower technologies per unit of electricity generation, including supply chain emissions (land use-related net changes in carbon stocks and land management impacts are excluded). Co-firing is shown for the biomass portion only (without GHG emissions and electricity output associated with coal). Included in the avoided GHG emissions category are only estimates in which the use of the feedstock itself (e.g. residues and wastes) leads to avoided emissions, for example, in the form of avoided methane emissions from landfills (most common in the literature).[1] Estimates that include avoided emissions from the production of co-products are not included in the avoided GHG emissions category. Individual data points were used instead of box plots for estimates with avoided emissions because of high variability. Red diamonds indicate that a carbon mitigation technology (CCS or carbonate formation by absorption) was considered. Along the bottom of the figure and aligned with each column are the number of estimates and the number of references (CCS estimates in parentheses) producing the distributions.

Note: 1. 'Negative estimates' within the terminology of lifecycle assessments presented in this report refer to avoided emissions. Unlike the case of bioenergy combined with CCS, avoided emissions do not remove GHGs from the atmosphere. Due to the inclusion of a non-CCS carbon sequestration technology and non-landfilling related reference cases of avoided emissions credits, estimates displayed here vary slightly from the aggregated values in Figure 9.8.

52 See Annex II for the complete list of references providing estimates for this figure and description of the literature review method.

360 g CO_2eq/kWh (100 g CO_2eq/MJ).[53] Again, variability is caused by differences in study methods, agricultural practice, technology performance and maturity of development (see Section 2.3.3). While the range and central tendency of each evaluated technology are similar to each other, the figure shows that depending on business-as-usual assumptions, avoided GHG emissions (here, mostly methane from landfills) from non-harvest wastes and residues can more than outweigh the GHG emissions associated with the biomass supply chains. Technologies with high conversion efficiency reach lower GHG emissions per kWh generated than less efficient technologies do. Though not displayed here, CHP and other integrated systems with many products could also be an effective way to minimize GHG emissions per unit of primary energy (e.g., in terms of primary energy), though the way co-products are considered in the quantification and allocation of GHG emissions can lead to different results. In the end, the economic value of outputs plays a decisive role, but climate policies that influence the cost of GHG emissions may alter the balance of products.

LCA aspects found to be especially important for GHG results are: (1) assumptions regarding GHG emissions from biomass production where LUC emissions (see Section 2.5.3) and nitrous oxide (N_2O) emissions are especially important; (2) methods used for considering co-products; (3) assumptions about conversion process design, process integration and the type of process fuel used in the conversion of biomass to solid or fluid fuels; (4) the performance of end-use technology, that is, vehicle technology or power/heat plant performance; and (5) the reference system.

N_2O emissions can have an important impact on the overall GHG balance of biofuels (Smeets et al., 2009; Soimakallio et al., 2009b). N_2O emissions vary considerably with environmental and management conditions, including soil water content, temperature, texture, carbon availability, and, most importantly, nitrogen fertilizer input (Bouwman et al., 2002; Stehfest and Bouwman, 2006). Emission factors are used to quantify N_2O emissions as a function of nitrogen fertilizer input. Crutzen et al. (2007) proposed that N_2O emissions from fresh anthropogenic nitrogen are considerably higher than results based on the IPCC's recommended tier 1 method and that N_2O emissions from biofuels consequently have been underestimated by a factor of two to three. IPCC tier 1 and Crutzen et al. (2007) estimates use different accounting approaches. About one-third of agricultural N_2O emissions are due to newly-fixed nitrogen fertilizer (A. Mosier et al., 1998) and two-thirds occur as nitrogen is recycled internally in animal production or by using plant residues as fertilizers. Recent modelling efforts by Davidson (2009) support the conclusion that emission factors based on Crutzen et al. (2007) overestimate the emissions. Using N_2O emissions factors from Crutzen et al. (2007) makes a specific bioenergy plantation responsible for all N_2O emissions taking place subsequently, even for the part of the applied nitrogen that is recirculated into other agriculture systems and substituted for other nitrogen input. See Bessou et al. (2010) for an overview of reactive nitrogen emissions impacts on LCAs.

Process fuel choice is critical and the use of coal especially can drastically reduce the climate benefit of bioenergy. Process integration and the use of biomass fuels or surplus heat from nearby energy/industrial plants can lower net GHG emissions from the biomass conversion process. For example, Wang et al. (2007) showed that GHG emissions for US corn ethanol can vary significantly—from a 3% increase if coal is the process fuel to a 52% reduction if wood chips are used or if improved dry milling processes are used (Wang et al., 2011). Similarly, the low fossil GHG emissions reported for Swedish cereal ethanol plants are explained by their use of biomass-based process energy (Börjesson, 2009). Sugarcane ethanol plants that use the fibrous by-product bagasse as process fuel can provide their own heat, steam and electricity and export surplus electricity to the grid (Macedo et al., 2008). Further improvements are possible as mechanical harvesting becomes established practice, because harvest residues can also be used for energy (Seabra et al., 2010).

However, the marginal benefit of using surplus heat or biomass for the conversion process depends on local economic circumstances and on alternative uses for the surplus heat and biomass (e.g., it could displace coal-based heat or power generation elsewhere). GHG reductions per unit weight of total biomass could be small when biomass is used both as a feedstock and as a process fuel for conversion to biofuels. This underscores the importance of using several indicators in bioenergy option evaluations (see also Section 9.3.4).

Practical uses of indicators to design and establish projects

As shown above, climate change effects can be evaluated based on indicators such as g CO_2eq per MJ (Figure 2.10) or per kWh (Figure 2.11), for which the reference system matters greatly (cf. bioenergy GHG emissions with those from coal and natural gas). Other indicators include mileage per hectare or per unit weight of biomass or per vehicle-km (see Section 8.3.1.3).[54] Limiting resources may define the extent to which land management and biomass-derived fuels can contribute to climate change mitigation, making the following indicators relevant in different contexts (Schlamadinger et al., 2005).

The *displacement factor* indicator describes the reduction in GHG emissions from the displaced energy system per unit of biomass used (e.g., tonne of carbon equivalent per tonne of carbon contained in the biomass that generated the reduction). This indicator does not discourage fossil inputs in the bioenergy chain if these inputs increase the displacement efficiency but it does not consider costs.

The indicator *relative GHG savings* describes the percentage emissions reduction with respect to the fossil alternative for a specific biomass

53 Note that the distributions in Figure 2.11 do not represent an assessment of likelihood; the figure simply reports the distribution of currently published literature estimates that passed screens for quality and relevance.

54 For example, the higher land use efficiency of electric vehicles using bioelectricity compared to ethanol cars reported by Campbell et al. (2009) is partly due to the assumed availability of advanced future drive trains for the bioelectricity option but not for the ethanol option.

use.[55] GHG savings favour biomass options with low GHG emissions. However, this indicator alone cannot distinguish between different biomass uses, such as transport fuel, heat, electricity or CHP, to determine which use reduces emissions more. It ignores the amount of biomass, land or money required, and it can be distorted as each use can have different reference systems.

The indicator *GHG savings per ha (or m² or km²) of land* favours biomass yield and conversion efficiency but ignores costs.[56] Intensified land use that increases the associated GHG emissions (e.g., due to higher fertilizer input) can still improve the indicator value if the amount of biomass produced increases sufficiently.

The indicator *GHG savings per monetary unit input* tends to favour the lowest cost, commercially available bioenergy options. Prioritization based on monetary indicators can lock in current technologies and delay (or preclude) future, more cost-effective or GHG reduction-efficient bioenergy options because their near-term costs are higher.

The usefulness of two indicators for considering local and regional bioenergy options is shown in Table 2.13. In the Finnish study, the use of logging residues in modern CHP plants receives a high ranking in relative GHG savings whether the displaced fossil source is coal or natural gas. However, the displacement factor indicator is only high when coal is displaced and is medium for natural gas displacement. The biodiesel from annual crops option receives the lowest ranking (<1) for both indicators, while the Fischer-Tropsch diesel, with or without electricity from wood residues, receives different rankings depending on indicator and plant configuration but is in all cases higher than crop-derived biodiesel. The standalone plant is the best option from the perspective of relative GHG savings. But if the displacement factor is used the integrated plant is preferable. From the plant owner's perspective, local monetary indicators enable assessment of additional costs of the integrated plant, the relative prices for biomass versus electricity, relative prices for fossil diesel versus CO_2 emissions, as well as existing policy support (and its duration). The differences between the two indicators highlight the need to consider the biomass system when planning bioenergy projects at specific locations. For example, in cases where the displacement factor is less than 1, using biomass to displace fossil fuels would increase net emissions (with respect to the global carbon sink baseline) at least within the next decades. The use of such biomass resources could be sustainable; but is not climate or emissions neutral during that period. Additional fossil carbon reductions may then be needed to achieve low GHG concentration stabilization levels.

For North American corn ethanol, technology improvements from 1995 to 2005 are reflected in both indicators. Implementation of improvements in plant efficiency with existing cogeneration systems brings

Table 2.13 | Two indicators of GHG performance facilitate ranking of new technologies using forest residues and comparison with current agricultural biofuel. Two indicators show improvement of technology performance with time for commercial ethanol systems and project the impact of technology improvements. Ranking: High >70; Low <30.

		Fossil energy reference	Displacement factor[1]	Relative GHG savings[2] (%)
Finnish modern CHP plant (from logging residues)		Coal	78	86[e]
		Natural gas	30	86[e]
Finnish Fischer-Tropsch diesel[3] as a stand-alone plant or integrated with a pulp and paper mill plant; with/without electricity	Standalone plant	Fossil diesel	39[a]	78[f]
	Integrated plant, minimize biomass		50[b]	55[g]
	Integrated plant, minimize electricity		50[c]	78[h]
Finnish biodiesel (rapeseed oil)		Fossil diesel	-9[d]	-15[i]
North American ethanol (corn) powered by natural gas (NG) dry mill		Fossil gasoline		
1995			18	26
2005			24	39
2015 with CHP[3]			31	55
2015 with CHP and CCS[3]			51	72
Brazilian ethanol (sugarcane)		Fossil gasoline/ electricity marginal NG		
2005–2006 (average 44 mills)			29	79
2020 CHP[3] (mechanical harvest)			36	120
2020 CHP and CCS[3]			51	160

Notes: 1. Tonne of carbon equivalent displaced per tonne of biomass carbon in the feedstock. 2. With respect to the fossil alternative and excluding LUC. 3. Projected performance

Uncertainty ranges: For displacement factors a. 35–46; b. 21–61; c. 45–57; d. -107–7. For relative GHG savings e. 60–94; f. 67–90; g. 31–86; h. 69–89; i. -150–5

References: Finland, Soimakallio et al. (2009b); North America, (S&T)2 Consultants (2009); and Brazil, Möllersten et al. (2003) and Macedo et al. (2008).

55 Relative GHG savings are used, for instance, in the EU Directive on Renewable Energy (European Commission, 2009).

56 See Bessou et al. (2010) for examples of LCA emissions as a function of area needed for a variety of feedstocks and biofuels in specific countries.

both indicators to medium range but improves the GHG reduction more than the displacement factor indicator. Application of developing CCS is projected to improve both indicators significantly and bring the GHG reduction indicator to high. In all Brazilian sugarcane ethanol cases, the GHG reduction indicator is high while the displacement factor is low to medium, which is expected because marginal natural gas, not coal, is the displaced fossil fuel and this is a site characteristic (EPE, 2010). The land use indicator differentiates the corn and sugarcane ethanol systems as producing 3,500 and 7,500 litres/ha, respectively. By 2020, biomass productivity increases and also CHP are projected to increase the land use indicator for corn and sugarcane ethanol systems to 4,500 and 12,000 litres/ha, respectively (Möllersten et al., 2003; Macedo et al., 2008; (S&T)[2] Consultants, 2009). See also Wang et al. (2011) for more recent data confirming these trends.

2.5.3 Modern bioenergy: Climate change including land use change effects

Bioenergy is different from the other RE technologies in that it is a part of the terrestrial carbon cycle. The CO_2 emitted due to bioenergy use was earlier sequestered from the atmosphere and will be sequestered again if the bioenergy system is managed sustainably, although emissions and sequestration are not necessarily in temporal balance with each other (e.g., due to long rotation periods of forest stands). In addition to changes in atmospheric carbon, bioenergy use may cause changes in terrestrial carbon stocks. The significance of land use and LUC (e.g., Leemans et al., 1996) and forest rotation (Marland and Schlamadinger, 1997) was demonstrated in the 1990s when dLUC effects were also considered in LCA studies (e.g., Reinhardt, 1991; DeLuchi, 1993). DeLuchi (1993) also called for consideration of indirect effects and iLUC. These effects were first considered about 10 years later (Jungk and Reinhardt, 2000), but most LCA studies have not considered iLUC. LUC can affect GHG emissions in a number of ways, including when biomass is burned in the field during land clearing; when the land management practice changes so that the carbon stocks in soils and vegetation change and/or non-CO_2 emissions (N_2O, ammonium (NH_4^+)) change; and when LUC results in changes in rates of carbon sequestration, that is, CO_2 assimilation by the land increases or decreases relative to the case in which LUC is absent.

Schlamadinger et al. (2001) proposed that bioenergy can have direct/indirect, positive/negative effects on biospheric carbon stocks and that crediting under the CDM could stimulate development of systems that function as a positive carbon sink. Recently, negative effects have been re-emphasized, and studies have estimated LUC emissions associated with, primarily, biofuels for transport. Other bioenergy systems and impact categories (e.g., biodiversity, eutrophication; see Section 2.2.4) have received less attention (see Section 9.3.4). There has been little connection with earlier research in the area of land use, LUC and forestry that partly addressed similar concerns, for example, direct environmental and socioeconomic impacts and leakage (Watson, 2000b).

The quantification of the net GHG effects of dLUC occurring on the site used for bioenergy feedstock production requires definition of reference land use and carbon stock data for relevant land types. Carbon stock data can be uncertain but still appear to allow quantification of dLUC emissions with sufficient confidence for guiding policy (see, e.g., Gibbs et al., 2008).

The quantification of the GHG effects of iLUC is more uncertain. Existing methods for studying iLUC effects employ either (1) a deterministic approach where global LUC is allocated to specific biofuels/feedstocks grown on specified land types (Fritsche et al., 2010); or (2) economic equilibrium models integrating biophysical information and/or biophysical models (Edwards et al., 2010; EPA, 2010; Hertel et al., 2010a,b; Plevin et al., 2010). In the second approach, the amount (and approximate location) of additional land required to produce a specified amount of bioenergy is typically projected. This land is then distributed over land cover categories in line with historic LUC patterns, and iLUC emissions are calculated in the same way as dLUC emissions are. There are inherent uncertainties in this approach because models are calibrated against historic data and are best suited for studying existing production systems and land use regimes. Difficult aspects to model include innovation and paradigm shifts in land use including the presently little-used biomass and mixed production systems described in Sections 2.3 and 2.6. There are also studies that compare scenarios with and without increases in bioenergy to derive LUC associated with the bioenergy expansion (e.g., Fischer et al., 2009). Despite the uncertainties, important conclusions can be drawn from these studies.

Production and use of bioenergy influences climate change through:

- Emissions from the bioenergy chain including non-CO_2 GHG and fossil CO_2 emissions from auxiliary energy use in the biofuel chain.
- GHG emissions related to changes in biospheric carbon stocks often caused by associated LUC.
- Other non-GHG related climatic forcers including particulate and black carbon emissions from small-scale bioenergy use (Ramanathan and Carmichael, 2008), aerosol emissions associated with forests (Carslaw et al., 2010) and changes in surface albedo. Reduction in albedo due to the introduction of perennial green vegetative cover can counteract the climate change mitigation benefit of bioenergy in regions with seasonal snow cover or a seasonal dry period (e.g., savannas). Conversely, albedo increases associated with the conversion of forests to energy crops (e.g., annual crops and grasses) may reduce the net climate change effect from the deforestation (Schwaiger and Bird, 2010).
- Effects due to the bioenergy use, such as price effects on petroleum that impact consumption levels. The net effect is the difference between the influence of the bioenergy system and of the energy system (often fossil-based) that is displaced. Current fossil energy

chains and evolving non-conventional sources have land use impacts (Gorissen et al., 2010; Liska and Perrin, 2010; Yeh et al., 2010), but LUC has a tighter link to bioenergy because of its close association with agriculture and forestry.

- Other factors include the extent and timing of the reversion of cultivated land when the use for bioenergy production ends and how future climate change impacts relative to present impacts are treated (DeLucchi, 2010).

Mitigation efforts over the next two to three decades will influence prospects for achieving lower stabilization levels (van Vuuren et al., 2007; den Elzen et al., 2010). For instance, the dynamics of terrestrial carbon stocks in LUC and long-rotation forestry lead to GHG mitigation trade-offs between biomass extraction for energy use and the alternative to leave the biomass as a carbon store that could further sequester more carbon over time (Marland and Schlamadinger, 1997; Marland et al., 2007; Righelato and Spracklen, 2007). Observations indicate that old forests can be net carbon sinks (Luyssaert et al., 2008; Lewis et al., 2009) but fires, insect outbreaks and other natural disturbances can quickly convert a forest from a net sink to an emitter (Kurz et al., 2008a,b; Lindner et al., 2010).

Short- and long-term indicators

Indicators such as *carbon debt* (Fargione et al., 2008) and *ecosystem carbon payback time* (Gibbs et al., 2008) focus on upfront LUC emissions arising from the conversion of land to bioenergy production. The balance between short- and long-term emissions and the climate benefits of bioenergy projects are reflected in indicators that describe the dynamic effect of GHG emissions (see also Section 9.3.4), for example, *cumulative warming impacts* or *global warming potential* (Kirschbaum, 2003, 2006; Dornburg and Marland, 2008; Fearnside, 2008). These indicators have been used, to a limited extent, to describe bioenergy dynamic climate effects (Kendall et al., 2009; Kirkinen et al., 2009; Levasseur et al., 2010; O'Hare et al., 2009).

Figure 2.12 shows dLUC effects on GHG balances for liquid biofuels using the ecosystem carbon payback time indicator. The left diagram shows payback times with current yields and conversion efficiencies and the right diagram shows the effect of higher yields (set to equal the top 10% of area-weighted yields). The payback times in Figure 2.12 neglect the GHG emissions associated with production and distribution of the transport fuels. Because these emissions currently tend to be higher for biofuels than for gasoline and diesel, the payback times are underestimated. The payback times in Figure 2.12 are calculated assuming constant GHG savings from the gasoline/diesel displacement. Higher GHG savings, that is, reducing the payback times, would be achieved if the biofuels conversion efficiency improved, if more carbon intensive transport fuels were replaced, or if the produced biomass displaced carbon-intensive fossil options for heat/power (Figure 2.10). Further biomass yield increases would reduce payback times but may require higher agronomic inputs that lead to increased GHG emissions, notably N_2O. The payback times would increase if the feedstock production resulted in land degradation over time, impacting yield levels or requiring increased input to maintain yield levels.

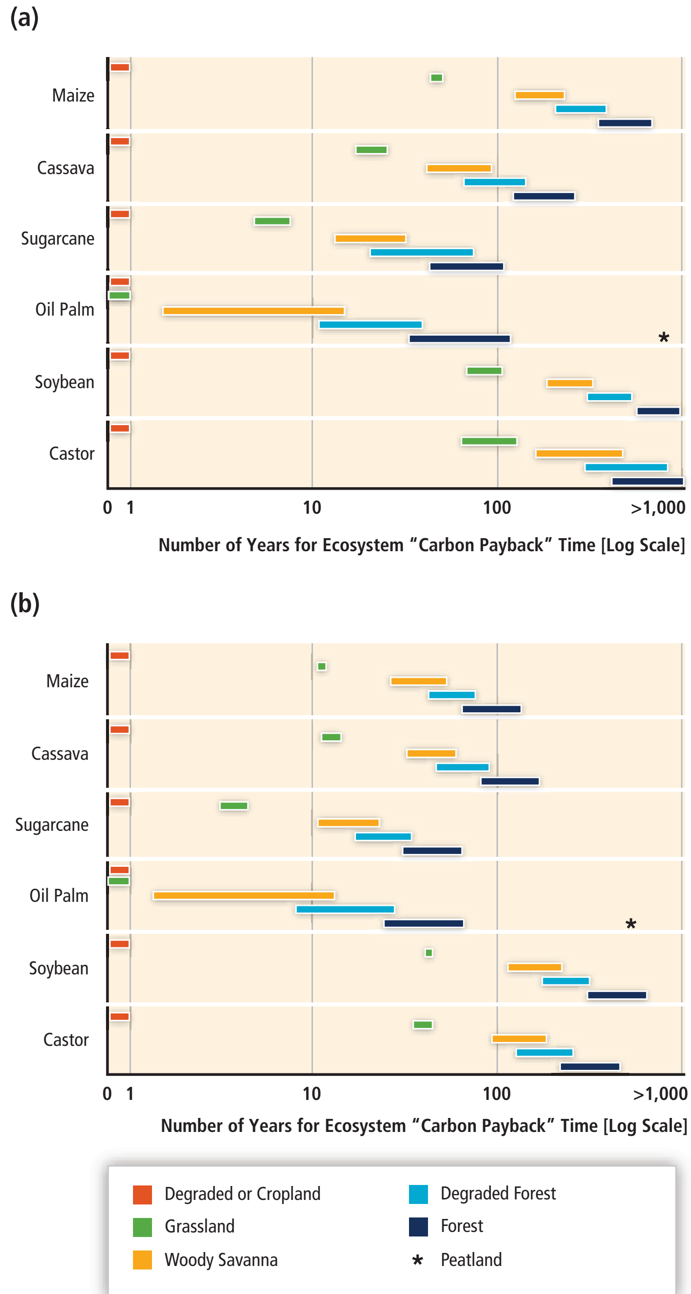


Figure 2.12 | The ecosystem carbon payback time for potential biofuel crop expansion pathways across the tropics comparing the year 2000 agricultural system shown in (a) with a future higher yield scenario (b) which was set to equal the top 10% of area-weighted yields. The asterisk represents oil palm crops grown in peatlands with payback times greater than 900 years in the year 2000 compared to 600 years for a 10% increase in crop productivity. Based on Gibbs et al. (2008) and reproduced with permission from IOP Publishing Ltd.

As shown, all biofuel options have significant payback times when dense forests are converted into bioenergy plantations. The starred points represent very long payback times for oil palm establishment on tropical peat swamp forests because drainage leads to peat oxidation and causes CO_2 emissions that occur over several decades and that can be several times higher than the displaced emissions of fossil diesel (Hooijer et al., 2006; Edwards et al., 2008, 2010). Under natural conditions, these tropical peat swamp forests have negligible CO_2 emissions and small methane emissions (Jauhiainen et al., 2008). Payback times are practically zero when degraded land or cropland is used, and they are relatively low for the most productive systems when grasslands and woody savannas are used (not considering the iLUC that can arise if these lands were originally used, for example, for grazing).

Targeting unused marginal and degraded lands for bioenergy production can thus mitigate dLUC emissions. For some options (e.g., perennial grasses, woody plants, mechanically harvested sugarcane), net gains of soil and aboveground carbon can be obtained (Tilman et al., 2006b; Liebig et al., 2008; Robertson et al., 2008; Anderson-Teixeira et al., 2009; Dondini et al., 2009; Hillier et al., 2009; Galdos et al., 2010). In this context, land application of biochar produced via pyrolysis could be an option to sequester carbon in a more stable form and improve the structure and fertility of soils (Laird et al., 2009; Woolf et al., 2010).

Bioenergy does not always result in LUC. Bioenergy feedstocks can be produced in combination with food and fibre, avoiding land use displacement and improving the productive use of land (Section 2.2). These possibilities may be available for bioenergy options that can use lignocellulosic biomass but also for some other options that use waste oil and oil seeds such as *Jatropha* (Section 2.3). The use of post-consumer organic waste and by-products from the agricultural and forest industries does not cause LUC if these biomass sources are wastes, that is, they were not utilized for alternative purposes. On the other hand, if not utilized for bioenergy, some biomass sources (e.g., harvest residues left in the forest) would retain organic carbon for a longer time than if used for energy. Such delayed GHG emissions can be considered a benefit in relation to near-term GHG mitigation, and this is an especially relevant factor in longer-term accounting for regions where biomass degradation is slow (e.g., boreal forests). However, as noted above, natural disturbances can convert forests from net sinks to net sources of GHGs, and dead wood left in forests can be lost in fires. In forest lands susceptible to periodic fires, good silviculture practices can lead to less frequent, lower intensity fires that accelerate forest growth rates and soil carbon storage. Using biomass removed in such practices for bioenergy can provide GHG and particulate emission reductions.

For different world regions, Edwards et al. (2010) describe the comparison of six equilibrium models to quantify LUC associated with a standard biofuel shock defined as a marginal increase in demand for first-generation ethanol or biodiesel from a base year.[57] All models showed significant LUC (dLUC and iLUC were not considered separable) with variations between models in terms of the extent of LUC and its distribution over regions and crops. A follow-on study by Hiederer et al. (2010) compared the ranges of LUC emissions shown in Figure 2.13 for common biofuel crops as a function of the 'biofuel shock' (0.2 to 1.5 EJ) for select studies. Figure 2.13 also shows the 2010 EPA model results with a relatively high resolution of land use distribution[58] for Brazil resulting in mid-range LUC emissions for sugarcane ethanol (5 to 10 g CO_2eq/MJ), similar to the European study (Al-Riffai et al., 2010) estimate of 12 g CO_2eq/MJ. The Brazilian study with measured LUC dynamics for common crops and native vegetation between 2005 and 2008 by Nassar et al. (2010) obtained 8 g CO_2eq/MJ for iLUC and dLUC, with the latter being nearly zero. Fischer et al. (2010) obtained 28 g CO_2eq/MJ using a deterministic methodology and assuming a high risk of deforestation. Model results from Figure 2.13 show all other crops as having higher LUC values than sugarcane ethanol. In the US maize ethanol case, Plevin et al. (2010) report a plausible range of 25 to 150 g CO_2eq/MJ based on uncertainty analysis of various model parameters and assumptions.

The utility of these models to study scenarios is illustrated with an analysis of the relative contributions of changes in yield and land area to increased crop output along with assumptions about trade-critical factors in model-based LUC estimates (D. Keeney and Hertel, 2009). Subsequent model improvements incorporate crop yields, by-product markets interactions, and trade and policy assumptions, and analyze past and project future usage with existing (2010) EU and US policies, finding LUC in other countries such as Latin America and Oceania to be primarily at the expense of pastureland followed by commercial forests (Hertel et al., 2010a,b).

Lywood et al. (2009b) report that the extent to which output change comes from increased crop yield or land area changes varies between crops and regions. They estimate that yield growth contributed 80 and 60% of the incremental output growth for EU cereals and US maize, respectively, between 1961 and 2007. Conversely, area expansion

57 Biofuel shock (Hertel et al., 2010a,b) is introduced in general equilibrium models by changing some economic parameters (e.g., subsidies to ethanol production) to reach predetermined volume levels (i.e., sum of government mandates for a certain year). The comparison of new and previously determined equilibrium enables estimates of land area changes impacted directly to meet mandates and those indirectly involved to compensate for that agricultural production no longer available, its co-products and its impact throughout the global economic chain. These studies have high uncertainties. Partial equilibrium models were also included in Edwards et al. (2010).

58 Based on the Nassar et al. (2009) Brazilian Land Use Model, which shows a lower share of LUC due to deforestation. More recently, Nassar et al. (2010) obtained elasticities for models from direct data (statistical and satellite-based) of land use substitution over time. The matrix elasticity results for major crops in various regions provide a deterministic estimate for the d+iLUC of sugarcane ethanol of about 8 g CO^2eq/MJ. Higher substitution coefficients are found for soy into native vegetation.

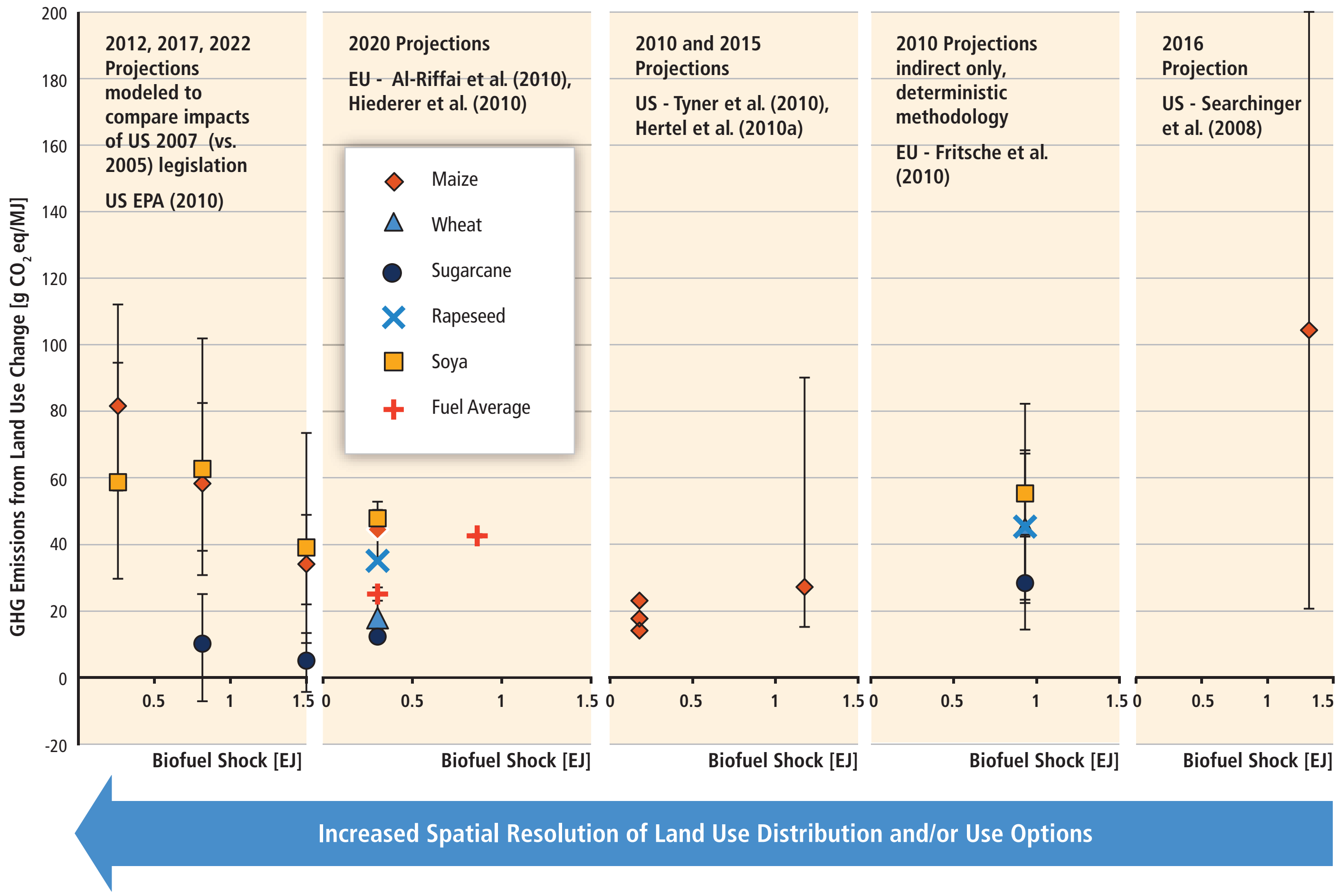


Figure 2.13 | Select model-based estimates of LUC emissions for major biofuel crops given a certain level of demand, a biofuel shock, expressed in EJ (30-year accounting framework). Mid-range values of multiple studies (g CO_2eq/MJ): 14 to 82 for US maize ethanol with high-resolution models and 100 for earlier models; 5 to 28 for sugarcane ethanol; 18 to 45 for European wheat ethanol; 40 to 63 for soy biodiesel (uncertain); and 35 to 45 for rapeseed biodiesel. Points for Tyner et al. (2010) and Hertel et al. (2010a) represent model improvements with the lowest value including feedstock yield and population increases (baseline 2006). Fritsche et al. (2010) value ranges derive from a deterministic methodology representing risk values of 25 and 75% of the theoretical worst case of LUC scenarios, such as high deforestation, to calculate iLUC.

contributed to more than 60% of output growth for EU rapeseed, Brazilian sugarcane, South American soy, and Southeast Asia oil palm. Studies report price-yield relationships; there is a weak basis for deriving these relationships (D. Keeney and Hertel, 2008) although rising oil prices and fuel tax exemptions show strong correlations for the USA and EU, respectively. Edwards et al. (2010) state that the marginal area requirement per additional unit output of a particular biofuel should increase due to decreasing productivity of additional land converted to biofuel feedstock production (also reflected in, e.g., R. Keeney and Hertel, 2005; Tabeau et al., 2006). Lywood et al. (2009b), however, state that in the case of EU cereals and US corn, there is no evidence that average yields decline as more land is used. The assumed or modelled displacement effect of process co-products used as feed can also have a strong influence on LUC values.

For European biofuels, if soy meal and cereals for feed are displaced, the net land area required to produce biofuel from EU cereal, rapeseed and sugar beet is much lower than the gross land requirement (e.g., only 6% for ethanol from feed wheat in northwestern Europe (Lywood et al., 2009a). Lywood et al. (2008) obtained large improvements in net GHG savings for European cereal ethanol and rapeseed biodiesel based on co-products displacing imported soy as animal feed, which reduces deforestation and other LUC for soy cultivation in Brazil. Conversely, increased corn cultivation at the cost of soy cultivation, in response to increasing ethanol demand in the USA, has been reported to increase soy cultivation in other countries such as Brazil (Laurance, 2007). Trade assumptions are critical and differ in the various models. In addition, marginal displacement effects of co-products may have a saturation level (McCoy, 2006; Edwards et al., 2010), although new uses may be developed, for example, to produce more biofuels (Yazdani and Gonzalez, 2007).

Bioenergy options that use lignocellulosic feedstocks are projected to have lower LUC values than those of first-generation biofuels (see, e.g., EPA, 2010; Hoefnagels et al., 2010; see Figure 9.9). As noted above, some of these feedstock sources can be used without causing LUC. Lower LUC values might be expected because of high biomass productivity, multiple products (e.g., animal feed) or avoided competition for prime cropland by using more marginal lands (Sections 2.2 and 2.3). The lower productivity of marginal lands, however, results in higher land requirements per given biomass output and presents particular challenges as discussed in Section 2.2. Also, as many lignocellulosic plants are grown under longer rotations, they should be less responsive to price increases because the average yield over a plantation lifetime can only be influenced through agronomic means (notably increased fertilizer input) and by variety selection at the time of replanting. Thus, output growth in response to increasing demand is more readily obtained by area expansion.

Depending on the atmospheric lifetime of specific GHGs, the trade-off between emitting more now and less in the future is not one-to-one in general. But the relationship for CO_2 is practically one-to-one, so that one additional (less) tonne CO_2 emitted today requires a future reduction (allows a future increase) by one tonne. This relationship is due to the close to irreversible climate effect of CO_2 emissions (Matthews and Caldeira, 2008; M. Allen et al., 2009; Matthews et al., 2009; Solomon et al., 2009).

Integrated energy-industry-land use/cover models can give insights into how an expanding bioenergy sector interacts with other sectors in society, influencing longer-term energy sector development, land use, management of biospheric carbon stocks, and global cumulative GHG emissions. In an example of early studies, Leemans et al. (1996) implemented in the IMAGE model (Integrated Model to Assess the Global Environment) the LESS (low CO_2-emitting energy supply system) scenario, which was developed for the IPCC Second Assessment Report (IPCC, 1996). This study showed that the required land use expansion to provide biomass feedstock can cause significant food-bioenergy competition and influence deforestation rates with significant consequences for environmental issues such as biodiversity, and that the outcome is sensitive to regional emissions and feedback in the carbon cycle. More recently, using linked economic and terrestrial biogeochemistry models, Melillo et al. (2009) found a similar level of cumulative CO_2 emissions associated with LUC from an expanded global cellulosic biofuels programme over the 21st century. The study concluded that iLUC was a larger source of carbon loss than dLUC; fertilizer N_2O emissions were a substantial source of global warming; and forest protection and best practices for nitrogen fertilizer use could dramatically reduce emissions associated with biofuels production.

Wise et al. (2009) also stressed the importance of limiting terrestrial carbon emissions and showed how the design of mitigation regimes can strongly influence the nature of bioenergy development and associated environmental consequences, including the net GHG savings from bioenergy. Including both fossil and LUC emissions in a carbon tax regime, instead of taxing only fossil emissions, was found to lower the cost of meeting environmental goals. However, this tax regime was also found to induce rising food crop and livestock prices and expansion of unmanaged ecosystems and forests. Improved crop productivity was proposed as a potentially important means for GHG emissions reduction, with the caution that non-CO_2 emissions (not modelled) need to be considered.

Biospheric carbon pricing as a sufficient mechanism to protect forests was proposed by Wise et al. (2009) and supported by Venter et al. (2009) and others. Persson and Azar (2010) acknowledge that pricing LUC carbon emissions could potentially make many of the current proximate causes of deforestation unprofitable (e.g., extensive cattle ranching, small-scale slash-and-burn agriculture and fuelwood use) but they question whether it will suffice to make deforestation for bioenergy production unprofitable because these bioenergy systems are highly productive according to the Wise et al. (2009) assumptions of generic feedstock productivity and biofuel conversion efficiency. A higher carbon price will increase not only the cost of forest clearing but also the revenues from certain bioenergy production systems. The upfront cost of land conversion may also be reduced if the bioenergy industry partners with the timber and pulp industries that seek access to timber revenues from clear felling forests as the first step in plantation development (Fitzherbert et al., 2008).

Three tentative conclusions are:

1. Additional, and stronger, protection measures may be needed to meet the objective of tropical forest preservation. A strict focus on the climate benefits of ecosystem preservation may put undue pressure on valuable ecosystems that have a relatively low carbon density. While this may have a small impact in terms of climate change mitigation, it may negatively impact other parts of the ecosystem, for example, biodiversity and water tables.

2. From a strict climate and cost efficiency perspective, in some places a certain level of upfront LUC emissions may be acceptable in converting forest to highly productive bioenergy plantations due to the climate benefits of subsequent continued biofuel production and fossil fuel displacement. The balance between bioenergy expansion benefits and LUC impacts on biodiversity, water and soil conservation is delicate. Climate change mitigation is just one of many rationales for ecosystem protection.

3. iLUC effects strongly (up to fully) depend on the rate of improvement in agricultural and livestock management and the rate of deployment of bioenergy production. Subsequently, implementation of bioenergy production and energy cropping schemes that follow effective sustainability frameworks and start from simultaneous improvements in agricultural management could mitigate conflicts and allow realization of positive outcomes, for example, in rural development, land amelioration and climate change mitigation including opportunities to combine adaptation measures.

2.5.4 Traditional biomass: Climate change effects

Traditional open fires and simple low-efficiency stoves have low combustion efficiency, producing large amounts of incomplete combustion products (CO, methane, particle matter, non-methane volatile organic compounds, and others) that have negative consequences for climate change and local air pollution (Smith et al., 2000; see also Box 9.4 in Section 9.3.4.2). When biomass is harvested renewably—for example, from standing trees or agricultural residues—CO_2 already emitted to the atmosphere is sequestered as biomass re-grows. Because the products of incomplete combustion also include important short-lived greenhouse pollutants and black carbon, even sustainable harvesting does not make such fuel cycles GHG neutral. Worldwide, it is estimated that household fuel combustion causes approximately 30% of the warming due to black carbon and CO emissions from human sources, about 15% of ozone-forming chemicals, and a few percent of methane and CO_2 emissions (Wilkinson et al., 2009).

Improved cookstoves (ICS) and other advanced biomass systems for cooking are cost-effective for achieving large benefits in energy use reduction and climate change mitigation. Fuel savings of 30 to 60% are reported (Berrueta et al., 2008; Jetter and Kariher, 2009). The savings in GHG emissions associated with these efficient stoves are difficult to derive because of the wide range of fuel types, stove designs, cooking practices and environmental conditions across the world. However, advanced biomass systems, such as small-scale gasifier stoves and biogas stoves, have had design improvements that increase combustion efficiency and dramatically reduce the production of short-lived GHGs by up to 90% relative to traditional stoves. Some of these new stoves even reach performance levels similar to liquid propane gas (Jetter and Kariher, 2009). Patsari improved stoves in rural Mexico save between 3 and 9 t CO_2eq/stove/yr relative to open fires, with renewable or non-renewable harvesting of biomass, respectively (M. Johnson et al., 2009).

Venkataraman et al. (2010) estimate that the dissemination of 160 million advanced ICS in India may result in the mitigation of 80 Mt CO_2eq/yr, or more than 4% of India's total estimated GHG emissions, plus a 30% reduction in India's human-caused black carbon emissions. Worldwide, with GHG mitigation per unit at 1 to 4 t CO_2eq/stove/yr compared to traditional open fires, the global mitigation potential of advanced ICS was estimated to be between 0.6 and 2.4 Gt CO_2eq/yr. This estimate does not consider the additional potential reduction in black carbon emissions. Actual figures depend on the renewability of the biomass fuel production, stove and fuel characteristics, and the actual adoption and sustained used of improved cookstoves. Reduction in fuelwood and charcoal use due to the adoption of advanced ICS may help reduce pressure on forest and agricultural areas and improve aboveground biomass stocks and soil and biodiversity conservation (Ravindranath et al., 2006; García-Frapolli et al., 2010).

2.5.5 Environmental impacts other than greenhouse gas emissions

2.5.5.1 Impacts on air quality and water resources

Air pollutant emissions from bioenergy production depend on technology, fuel properties, process conditions and installed emission reduction technologies. Compared to coal and oil stationary applications, sulphur dioxide (SO_2) and nitrous oxide (NO_x) emissions from bioenergy applications are mostly lower (see also Section 9.3.4.2). When biofuel replaces gasoline and diesel in the transport sector, SO_2 emissions are reduced, but changes in NO_x emissions depend on the substitution pattern and technology. The effects of replacing gasoline with ethanol and biodiesel also depend on engine features. Biodiesel can have higher NO_x emissions than petroleum diesel in traditional direct-injected diesel engines that are not equipped with NO_x control catalysts (e.g., Verhaeven et al., 2005; Yanowitz and McCormick, 2009).

Bioenergy production can have both positive and negative effects on water resources (see also Section 9.3.4.4). Bioenergy production generally consumes more water than gasoline production (Wu et al., 2009; Fingerman et al., 2010). However, this relationship and the water impacts of bioenergy production are highly dependent on location, the specific feedstock, production methods and the supply chain element.

Feedstock cultivation can lead to leaching and emission of nutrients that increase eutrophication of aquatic ecosystems (Millennium Ecosystem Assessment, 2005; SCBD, 2006; Spranger et al., 2008). Pesticide emissions to water bodies may also negatively impact aquatic life. Given that several types of energy crops are perennials grown in arable fields being used temporarily as a pasture for grazing animals or woody crops grown in multi-year rotations, the increasing bioenergy demand may drive land use towards systems with substantially higher water productivity. On the other hand, shifting demand to alternative—mainly lignocellulosic—bioenergy can decrease water competition. Perennial herbaceous crops and short-rotation woody crops generally require fewer agronomic inputs and have reduced impacts compared to annual crops, although large-scale production can require high levels of nutrient input (see Sections 2.2.4.2 and 2.3.1). Water impacts can also be mitigated by integrating lignocellulosic feedstocks in agricultural landscapes as vegetation filters to capture nutrients in passing water (Börjesson and Berndes, 2006). A prolonged growing season may redirect unproductive soil evaporation and runoff to plant transpiration (Berndes, 2008a,b). Crops that provide a continuous cover over the year can also conserve soil outside the growing season of annual crops by diminishing the erosion from precipitation and runoff (Berndes, 2008a,b). A number of bioenergy crops can be grown on a wide spectrum of land types that are not suitable for conventional food or feed crops. These marginal lands, pastures and grasslands could become available for feedstock production under sustainable management practices (if adverse downstream water impacts can be mitigated).

The subsequent processing of the feedstock into biofuels and electricity can increase chemical and thermal pollution loads from effluents and generate waste to aquatic systems (Martinelli and Filoso 2007, Simpson et al., 2008). These environmental impacts can be reduced if suitable equipment is installed (Wilkie et al., 2000; BNDES/CGEE, 2008).

Water demand for bioenergy can be reduced substantially through process changes and recycling (D. Keeney and Muller, 2006; BNDES/CGEE, 2008). Currently, most water is lost to the atmosphere through evapotranspiration during the production of cultivated feedstock (Berndes, 2002). Feedstock processing into fuels and electricity requires much less water (Aden et al., 2002; Berndes, 2002; D. Keeney and Muller, 2006; Phillips et al., 2007; NRC, 2008; Wang et al., 2010), but water needs to be extracted from lakes, rivers and other water bodies.

2.5.5.2 Biodiversity and habitat loss

Habitat loss is one of the major drivers of biodiversity decline globally and is projected to be the major driver of biodiversity loss and decline over the next 50 years (Sala et al., 2000; UNEP, 2008b; see Sections 9.3.4.5 and 9.3.4.6). Increased biomass output for bioenergy can directly impact wild biodiversity through conversion of natural ecosystems into bioenergy plantations or through changed forest management. Habitat and biodiversity loss may also occur indirectly, such as when productive land use displaced by energy crops is re-established by converting natural ecosystems into croplands or pastures elsewhere. Because biomass feedstocks can generally be produced most efficiently in tropical regions, there are strong economic incentives to replace tropical natural ecosystems—many of which host high biodiversity values (Doornbosch and Steenblik, 2008). However, forest clearing is mostly influenced by local social, economic, technological, biophysical, political and demographic forces (Kline and Dale, 2008).

Increasing demand for oilseed has put pressure on areas designated for conservation in some OECD member countries (Steenblik, 2007). Similarly, the rising demand for palm oil has contributed to extensive deforestation in parts of Southeast Asia (UNEP, 2008a). The palm oil plantations support significantly fewer species than the forest they replaced (Fitzherbert et al., 2008).

To the extent that bioenergy systems are based on conventional food and feed crops, biodiversity impacts from pesticide and nutrient loading can be expected from bioenergy expansion. Bioenergy production can also impact agricultural biodiversity when large-scale monocultures, based on a narrow pool of genetic material, reduce the use of traditional varieties.

Depending on a variety of factors, bioenergy expansion can also lead to positive outcomes for biodiversity. Using bioenergy to replace fossil fuels can reduce climate change, which is expected to be a major driver of habitat loss. Establishment of perennial herbaceous plants or short-rotation woody crops in agricultural landscapes has been found to improve biodiversity (Lindenmayer and Nix, 1993; Semere and Slater, 2007; Royal Society, 2008). Bioenergy plantations that are cultivated as vegetation filters can improve biodiversity by reducing the nutrient load and eutrophication in water bodies (Foley et al., 2005; Börjesson and Berndes, 2006) and providing a varied landscape.

Bioenergy plantations can be located in the agricultural landscape to provide ecological corridors through which plants and animals can move between spatially separated natural and semi-natural ecosystems. Thus, bioenergy plantations can reduce the barrier effect of agricultural lands (Firbank, 2008). However, bioenergy plantations can contribute to habitat fragmentation, as has occurred with some oil palm plantations (Danielsen et al. 2009; Fitzherbert, 2008).

Properly located biomass plantations can also protect biodiversity by reducing the pressure on nearby natural forests. A study from Orissa, India, showed that introducing village biomass plantations increased biomass consumption (as a consequence of increased availability) while decreasing pressure on the surrounding natural forests (Köhlin and Ostwald, 2001; Francis et al., 2005).

When crops are grown on degraded or abandoned land, such as previously deforested areas or degraded crop- and grasslands, the production of feedstocks for biofuels could have positive impacts on biodiversity by restoring or conserving soils, habitats and ecosystem functions (Firbank, 2008). For instance, several experiments with selected trees and intensive management on severely degraded Indian wastelands (such as alkaline, sodic or salt-affected lands) showed increases in soil carbon, nitrogen and available phosphorous within eight years (Garg, 1998).

2.5.5.3 Impacts on soil resources

The considerable soil impacts of increased biofuel production include soil carbon oxidation, changed rates of soil erosion, and nutrient leaching. However, these effects are heavily dependent on agronomic techniques and the feedstock under consideration (UNEP, 2008a). Land preparation required for feedstock production, as well as nutrient demand, varies widely across feedstocks. For instance, wheat, rapeseed and corn require significant tillage compared to oil palm, sugarcane and switchgrass (FAO, 2008a; UNEP, 2008a). In sugarcane production, soil quality benefits greatly from recycled nutrients from sugar mill and distillery wastes (IEA, 2006).

Using agricultural residues without proper management can lead to detrimental impacts on soil organic matter through increased erosion. However, this impact depends heavily on management, yield, soil type and location. In some areas, the impact of residue removal may be minimal.

Certain cultivation practices, including conservation tillage and crop rotations, can mitigate adverse impacts and in some cases improve environmental benefits of biofuel production. For example, *Jatropha* can stabilize soils and store moisture while it grows (Dufey, 2006). Other potential benefits of planting feedstocks on degraded or marginal lands include reduced nutrient leaching, increased soil productivity and increased carbon content (Berndes, 2002). If lignocellulosic energy crop plantations, which require low-intensity management and few fossil energy inputs relative to current biofuel systems, are established on abandoned agricultural or degraded land, soil carbon and soil quality could increase over time. This beneficial effect would be especially significant with perennial species.

2.5.6 Environmental health and safety implications

2.5.6.1 Feedstock issues

Currently, many crops used in fuel ethanol manufacturing are also traditional feed sources (e.g., maize, soy, canola and wheat). However, considerable efforts are focused on new crops that either enhance fuel ethanol production (e.g., high-starch corn) or that are not traditional food or feed crops (e.g., switchgrass). If the resultant distillers' grains from these new crops are used as livestock feed or could inadvertently end up in livestock feeds, pre-market assessment of their acceptability in feed prior to their use in fuel ethanol production will be necessary (Hemakanthi and Heller, 2010).

Concerns about cross-pollination, hybridization, pest resistance and disruption of ecosystem functions (FAO, 2004; FAO, 2008; IAASTD, 2009) have limited the use of genetically engineered (GE) crops in some regions. Transgene movement leading to weediness or invasiveness of the crop itself or of its wild or weedy relatives is a major reason (Warwick et al., 2009). Clarity, predictability and established risk assessment processes are literature recommendations to decrease GE crop use concerns (Warwick et al., 2009).[59] The first assessment (NRC, 2010) of the impact of GE crops in use in the USA since 1996 found that benefits to the farmer included increased worker safety from pesticide handling; indicated that water quality improves with GE crops; and acknowledged that more work needs to be done, particularly to install infrastructure to measure water quality impacts, develop weed management practices, and address the needs of farmers whose markets depend on the absence of GE traits.

Several grasses and woody species that are candidates for biofuel production have traits commonly found in invasive species (Howard and Ziller, 2008). These traits include rapid growth, high water-use efficiency and long canopy duration (Clifton-Brown et al., 2000). There are fears that if these crops are introduced, they could become invasive, displace indigenous species and decrease biodiversity. For example, *Jatropha curcas* is considered weedy in several countries, including India and many South American states (Low and Booth, 2007). Warnings have been raised about *Miscanthus* and switchgrass (*Panicum virgatum*). *Sorghum halepense* (Johnson grass), *Arundo donax* (giant reed) and *Phalaris arundinacea* (reed canary grass) are known to be invasive in the USA. A number of protocols have evolved that allow for a systematic assessment and evaluation of the inherent risk associated with species introduction (McWhorter, 1971; Randall, 1996; Molofsky et al., 1999; Dudley, 2000; Forman, 2003; Raghu et al., 2006). DiTomaso et al. (2010) address policies to keep these agro-ecosystems in check while developing desirable biofuels crops, such as preventive actions prior to and during cultivation of biofuel plants.

2.5.6.2 Biofuels production issues

Globally, most biofuels are produced with conventional production technologies (see Section 2.3) that have been used in many industries for many years (Gunderson, 2008; Abbasi and Abbasi, 2010). Hazards associated with most of these technologies are well characterized, and it is possible to limit risks to very low levels by applying existing knowledge and standards (see, e.g., Astbury, 2008; Hollebone and Yang, 2009; Marlair et al., 2009; Williams et al., 2009) and their typology is under development (Rivière and Marlair, 2009, 2010).

The literature highlights environmental health and safety areas for further evaluation as new technologies (see Section 2.6) are developed (e.g., Madsen et al., 2004; Madsen, 2006; Vinnerås et al., 2006; Narayanan et al., 2007; Gunderson, 2008; McLeod et al., 2008; Hill et al., 2009; Martens and Böhm, 2009; Moral et al., 2009; Perry, 2009; Sumner and Layde, 2009). Key areas include:

- Health risk to workers using engineered microorganisms or their metabolites.
- Potential ecosystem effects from the release of engineered microorganisms.
- Impact to workers, biofuel consumers or the environment from pesticides and mycotoxins that accumulate in processing intermediates, residues or products (e.g., spent grains, spent oil seeds).
- Risks to workers from infectious agents that can contaminate feedstocks in production facilities.
- Exposure to toxic substances, particularly for workers at biomass thermochemical processing facilities that use routes not currently practised by the fossil fuels industry.
- Fugitive air emissions and site runoff impacts on public health, air quality, water quality and ecosystems.

59 Other concerns include: reduction in crop diversity, increases in herbicide use, herbicide resistance (increased weediness), loss of farmer's sovereignty over seed, ethical concerns over transgenes origin, lack of access to intellectual property rights held by the private sector, and loss of markets owing to moratoriums on genetically modifed organisms (GMOs) (IAASTD, 2009).

- Exposure to toxic substances, particularly if production facilities become as commonplace as landfill sites or natural gas-fired electricity generating stations.
- Cumulative environmental impacts from the siting of multiple biofuel/bioenergy production facilities in the same air- and/or watershed.

2.5.7 Socioeconomic aspects

The large-scale and global development of bioenergy will be associated with a complex set of socioeconomic issues and trade-offs, ranging from local issues (e.g., income and employment generation, improved health conditions, agrarian structure, land tenure, land use competition and strengthening of regional economies) to national issues (e.g., food security, a secure energy supply and balance of trade). Participation of local stakeholders, in particular small farmers and poor households, is essential to ensure socioeconomic benefits from bioenergy projects.

2.5.7.1 Socioeconomic impact studies and sustainability criteria for bioenergy systems

The complex nature of bioenergy, with many conversion routes and the multifaceted potential socioeconomic impacts, makes the overall impact analysis difficult to conduct. Also, many impacts are not easily quantifiable in monetary or numerical terms. To overcome these problems, semi-quantitative methods based on stakeholder involvement have been used to assess social criteria such as societal product benefit and social dialogue[60] (von Geibler et al., 2006).

Regarding economic impacts, the most commonly reported variables are private production costs over the value chain, assuming a fixed set of prices for basic commodities (e.g., for fossil fuels and fertilizers). The bioenergy costs are usually compared to alternatives already on the market (fossil-based) to judge the potential competitiveness. Bioenergy systems are mostly analyzed at a micro-economic level, although interactions with other sectors cannot be ignored because of the competition for land and other resources. Opportunity costs may be calculated from food commodity prices and gross margins to account for food-bioenergy interactions. Social impact indicators include consequences for local employment, although this impact is difficult to assess because of possible offsets between fossil and bioenergy chains. Impacts at a macro-economic level include the social costs incurred because of fiscal measures (e.g., tax exemptions) to support bioenergy chains (DeLucchi, 2005). Fossil energy's negative externalities also need to be assessed (Bickel and Friedrich, 2005).

Several sustainability frameworks and certification systems have been proposed to better document and integrate the socioeconomic impacts of bioenergy systems, particularly at the project level (Bauen et al., 2009b; WBGU, 2009; van Dam et al., 2010; see also Section 2.4). Specifically, criteria and indicators related to the development of liquid biofuels have been proposed for these issues: human rights, including gender issues; working and wage conditions, including health and safety issues; local food security; rural and social development, with special regard to poverty reduction; and land rights (Table 2.12). So far, while rural and local development are included, specific economic criteria for the cost-effectiveness of the projects, level of subsidies and other financial aspects have not been included in the sustainability frameworks. Most of the frameworks are still under development. The progress of certification systems was reviewed by van Dam et al. (2008, 2010). The FAO's Bioenergy and Food Security Criteria and Indicators project has compiled bioenergy sustainability initiatives (see also Sections 2.4.5.1 and 2.4.5.2).

60 Multi Criteria Analysis methods have been applied in the bioenergy field during the past 15 years (Buchholz et al., 2009).

2.5.7.2 Socioeconomic impacts of small-scale systems

The inefficient use of biomass in traditional devices such as open fires has significant socioeconomic impacts including drudgery for getting the fuel, the cost of satisfying cooking needs, and significant health impacts from the very high levels of indoor air pollution, especially for women and children (Masera and Navia, 1997; Pimentel et al., 2001; Biran et al., 2004; Bruce et al., 2006; Romieu et al., 2009). Indoor air pollutants include respirable particles, CO, oxides of nitrogen and sulphur, benzene, formaldehyde, 1, 3-butadiene, and polyaromatic compounds such as benzo(a)pyrene (Smith et al., 2000). Wood smoke exposure can increase respiratory symptoms and problems (Thorn et al., 2001; Mishra et al., 2004; Schei et al., 2004; Boman et al., 2006). Exposures of household members have been measured to be many times higher than World Health Organization guidelines and national standards (Smith et al., 2000; Bruce et al., 2006) (see also Sections 9.3.4.3 and 9.4.4). More than 200 studies over the past two decades have assessed levels of indoor air pollutants in households using solid fuels. The burden from related diseases was estimated at 1.6 million excess deaths per year, including 900,000 children under five, and a loss of 38.6 million DALY (Disability Adjusted Life Year) per year (Smith and Haigler, 2008). This burden is similar in magnitude to the burden of disease from malaria and tuberculosis (Ezzati et al., 2002).

Properly designed and implemented ICS projects, based on the new generation of biomass stoves, have led to significant health improvements (von Schirnding et al., 2001; Ezzati et al., 2004). ICS health benefits include a 70 to 90% reduction in indoor air pollution, a 50% reduction in human exposure, and reductions in respiratory and other illnesses (Armendáriz et al., 2008; Romieu et al., 2009). Substantial health benefits can accrue even with modest reductions in exposure to indoor air pollutants. For example, in Guatemala, a 50% reduction in exposure has been shown to produce a 40% improvement in childhood pneumonia cases. In India, the health benefits from the dissemination of advanced ICS have been estimated to be potentially equivalent to eliminating nearly half the entire cancer burden in 2020. These health benefits include 240,000 averted premature deaths from acute lower respiratory infections in children younger than five years and more than 1.8 million averted premature adult deaths from ischemic heart disease and chronic obstructive pulmonary disease (Bruce et al., 2006; Wilkinson et al., 2009).

Figure 2.14 shows the cost effectiveness of treatment options for the eight major risk factors that account for 40% of the global disease burden (Glass, 2006). ICS are among the most cost-effective options in terms of the cost per avoided DALY. Overall, ICS and other small-scale biomass systems represent a very cost-effective intervention with benefits to cost ratios of 5.6:1, 20:1 and 13:1 found in Malawi, Uganda and Mexico, respectively (Frapolli et al., 2010).

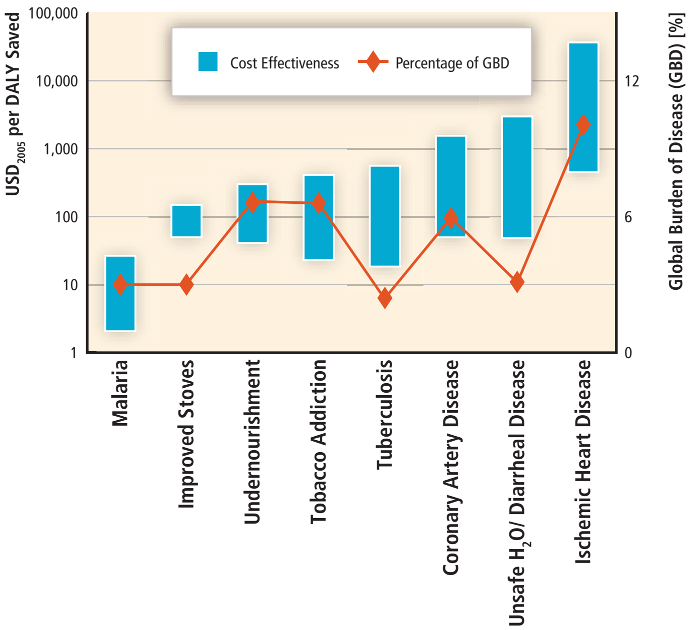


Figure 2.14 | Cost effectiveness of interventions expressed in dollars per disability adjusted life year (DALY) saved (Glass, 2006) on the left scale (logarithmic scale), and contributions to the global burden of disease (GBD) from eight major risk factors and diseases (in %, right scale). The figure shows that the dissemination of improved biomass stoves—depicted here as an intervention to reduce the health effects of indoor air pollution due to fuelwood use—compares well with the cost of interventions aimed at combating major health problems and diseases such as undernourishment, tuberculosis, heart diseases and others (Bailis et al., 2009 with permission from Elsevier B.V.).

Increased use of ICS frees up time for women to engage in income-generating activities. Reduced fuel collection times and savings in cooking time can also translate into increased time for education of rural children, especially girls (Karekezi and Majoro, 2002). ICS use fosters improvements in local living conditions, kitchens and homes, and quality of life (Masera et al., 2000). The manufacture and dissemination of ICS also represents an important source of income and employment for thousands of local small businesses around the world (Masera et al., 2005). Similar impacts were found for small-scale biogas plants, which have the added benefits of providing lighting for individual households and villages and increasing the quality of life. More efficient technologies than currently employed in small-scale industries (such as improved brick and charcoal kilns) are available that increase work productivity, quality of products and overall working conditions (FAO, 2006, 2010b).

2.5.7.3 Socioeconomic aspects of large-scale bioenergy systems

Large-scale bioenergy systems have sparked heated controversies around food security, income generation, rural development and land tenure. The controversy makes clear that there may be both advantages and disadvantages to the further development of large-scale bioenergy systems, depending on their characteristics, local conditions and the mode of implementation.

Impacts on job and income generation

Increased demand for agricultural and forestry waste materials (i.e., residues) can supplement farmers' and foresters' incomes, particularly if the wastes were previously burned or landfilled. Bioenergy can also generate jobs; in general, bioenergy generates more jobs per unit of energy delivered than other energy sources, largely due to feedstock production, especially in developing countries and rural areas (FAO, 2010b).

Wage income is a key contribution to the livelihoods of many poor rural dwellers (Ivanic and Martin, 2008). The benefits from bioenergy jobs depend on the relative labour intensity of the feedstock crop compared to the crop that was previously grown on the same land. For example, cultivation of perennial energy crops requires less labour than cereal crop cultivation, and this displacement effect should be taken into account (Thornley et al., 2009). While increased employment is an important potential benefit, highly labour-intensive operations might also reduce competitiveness (depending on the relative prices of labour and capital) (see Section 9.3.1.3).

The number of jobs created is very location-specific and varies considerably with plant size, the degree of feedstock production mechanization (Berndes and Hansson, 2007) and the contribution of imports to meeting demand (Nusser et al., 2007; Wydra, 2009). Estimates of the employment creation potential of bioenergy options differ substantially, but liquid biofuels based on traditional agricultural crops seem to provide the most employment, especially when the biofuel conversion plants are small (Berndes and Hansson, 2007). Even within liquid biofuel options, the use of different crops introduces wide differences. For ethanol, the number of direct and indirect jobs generated ranges from 45 (corn) to 2,200 (sugarcane) jobs/PJ of ethanol. For biodiesel, the number of direct and indirect jobs generated ranges from 100 (soybean) to 2,000 (oil palm) jobs/PJ of biodiesel (Dias de Moraes, 2007; Clayton et al., 2010). For electricity production, mid-scale power plants in developing countries using a low-mechanized system (25 MW) are estimated to generate approximately 400 jobs/plant or 250 jobs/PJ, of which 94% are in the production and harvesting of feedstocks. For instance, in a detailed UK study, 1.27 jobs/GWh were calculated for power generation from a 25 MW_e plant using dedicated crops (woody or *Miscanthus*). During the complete lifecycle, 4,000 to 6,000 person-year jobs are created, representing on a yearly basis 200 jobs/PJ (15, 73, and 12% at the electricity plant, feedstock production and delivery, and induced, respectively) (Thornley et al., 2008).

In Europe, if the EU25 scenario is followed, Berndes and Hansson (2007) estimate that biomass production for energy can create employment at a magnitude that is significant relative to total agricultural employment (up to 15% in selected countries) but small compared to the total industrial employment in a country. The latest analysis also shows some trade-offs—for instance, agricultural options for liquid biofuels create more employment, but forest-based options for electricity and heat production produce more climate benefits. In Brazil, the biofuel sector accounted for about one million jobs in rural areas in 2001, mostly for unskilled labour related to manual harvesting after field burning of sugarcane (Moreira, 2006). Indeed, mechanization, already ongoing in about 50% of the Center South production (responsible for 90% of the country's harvest), reduces demand for unskilled labour for manual harvest but produces an environmental benefit. Meanwhile, worker productivity continues to grow and part of the workforce is retrained for the skilled higher-paying jobs required for mechanized operations (Oliveira, 2009).

2.5.7.4 Risks to food security

Unless the feedstocks are grown on abandoned land or use residues that previously had no economic value, liquid biofuel production creates additional demand for food and agricultural commodities that places additional pressure on natural resources such as land and water and thus raises food commodity prices (Chakravorty et al., 2009; B. Wright, 2009). Lignocellulosic biofuels, because they can be grown more easily on land that is not suitable for food production, can reduce but not eliminate competition (Chakravorty et al., 2009). To the extent that domestic food markets are linked to international food markets, even countries that do not produce bioenergy may be affected by the higher prices.

Commodity prices are determined by a complex set of factors, of which biofuels is only one, and projections of future prices are highly uncertain. Nevertheless, several studies have examined the contribution of increased biofuels production to the surge in food prices that occurred in the mid-2000s. These studies use different analytical methods and report their results in different ways (for a comprehensive review of these studies, see DEFRA, 2009). For example, the OECD-FAO Agricultural Outlook (OECD-FAO, 2008) model found that if biofuel production were frozen at 2007 levels, coarse grains prices would be 12% lower and vegetable oil prices 15% lower in 2017 compared with a situation where biofuels production continues to increase as expected. Rosegrant et al. (2008) estimated that world maize prices would be 26% higher under a scenario of continued biofuel expansion according to the existing national development plans and more than 70% higher under a drastic biofuel expansion scenario where biofuel demand is double that under the first scenario (these scenarios are relative to a baseline of modest biofuel development where biofuel production remains constant at 2010 levels in most countries). IFPRI (2008) estimated that 30% of the weighted average increase in world cereal prices was attributable to biofuels between 2000 and 2007. Elobeid and Hart (2007) compared two modelled scenarios, with and without biofuel utilization barriers, and found that removing utilization barriers doubled the projected increases in corn and food basket prices. These studies generally agree that increased biofuels production played some role in increased food prices, but there is no consensus about the size of this contribution (FAO, 2008a; Mitchell, 2008; DEFRA, 2009; Baffes and Haniotis, 2010). Other factors include the weak US dollar, increased energy costs, increased agricultural production costs, speculation on commodities, and adverse weather conditions (Headey and Fan, 2008; Mitchell, 2008; DEFRA, 2009; Baffes and Haniotis, 2010). The eventual impact of biofuels on prices will depend, among other factors, on the specific technology used, the strength of government mandates for biofuel use, the design of trade policies that favour inefficient methods of biofuel production, and oil prices.

The impact of higher prices on the welfare of the poor depends on whether the poor are net sellers of food (benefit from higher prices) or net buyers of food (harmed by higher prices). On balance, the evidence indicates that higher prices will adversely affect poverty and food security in developing countries, even after taking into account the benefits of higher prices for farmers (Ivanic and Martin, 2008; Zezza et al., 2008). A major FAO study on the socioeconomic impacts of the expansion of liquid biofuels (FAO, 2008a) indicates that poor urban consumers and poor net food buyers in rural areas are particularly at risk. Rosegrant et al. (2008) estimated that the number of malnourished children would double under the two scenarios mentioned above.

A significant increase in the cultivation of crops for bioenergy indicates a close coupling of the markets for energy and food (Schmidhuber, 2008), and an analysis by the World Bank (2009) confirmed a strong association between food and energy prices when oil prices are above USD_{2005} 45 per barrel. Thus, if energy prices increase, there may be spillovers into food markets that increase food insecurity.

Meeting the food demands of the world's growing population will require a 70% increase in global food production by 2050 (Bruinsma, 2009). At the same time, FAO (2008b) estimates that the increase in arable land between 2005 and 2050 will be just 5% (Alexandratos et al., 2009). This limited increase indicates that economically exploitable arable land is scarce. Because biomass production is land-intensive, there could be significant competition between food and fuel for the use of agricultural land (Chakravorty et al., 2009). Increased biofuels production could also reduce water availability for food production, as more water is diverted to production of biofuel feedstocks (Chakravorty et al., 2009; Hoekstra et al., 2010).

2.5.7.5 Impacts on rural and social development

Growing demand for biofuels and the resulting rise in agricultural commodity prices can present an opportunity for promoting agricultural growth and rural development in developing countries (Schmidhuber, 2008). The development potential critically depends on whether the bioenergy market is economically sustainable without government subsidies. If long-term subsidies are required, fewer government funds will be available for the wide range of other public goods that are essential for economic and social development, such as agricultural research, rural roads, and education. Even short-term subsidies need to be considered very carefully, as once subsidies are implemented they can be difficult to remove. Latin American experience shows that governments that use agricultural budgets for investment in public goods experience faster growth and alleviate poverty and environmental degradation more rapidly than those that apply them for subsidies (López and Galinato, 2007).

Bioenergy may reduce dependence on fossil fuel imports and increase energy supply security. In many cases these benefits are not likely to be large, although the contribution could be substantial for countries with large amounts of arable land per person (FAO, 2008a). Recent analyses of the use of indigenous resources implies that much of the expenditure on energy is retained locally and recirculated within the local or regional economy, but there are trade-offs to consider. For example, the increased use of biomass for electricity production and the corresponding increase in demand for some types of biomass (e.g., pellets) could cause a temporary lack of biomass supply during periods of high demand. Households are particularly vulnerable to this market distortion.

The biofuels production technologies and institutions will also be an important determinant of rural development outcomes. In some instances, private investors will look to establish biofuel plantations to ensure security of supply. If plantations are established on non-productive land without harming the environment, there should be benefits to the economy. It is essential not to overlook the uses of land that are important to the poor. Governments may need to establish clear criteria for determining whether land is marginal or productive, and these criteria must protect vulnerable communities and female farmers who may have less secure land rights (FAO, 2008a). Research in Mozambique shows that, compared with a more capital-intensive plantation approach, an out-grower approach to producing biofuels helps to reduce poverty due to the greater use of unskilled labour and accrual of land rents to smallholders (Arndt et al., 2010).

Increased investment in rural areas will be crucial for making biofuels a positive development force. If governments rely exclusively on short-term farm-level supply side economic response, the negative effects of higher food prices will predominate. If higher prices motivate greater public and private investment in agriculture (e.g., rural roads and education, R&D), there is tremendous potential for sparking medium- and long-term rural development (De La Torre Ugarte and Hellwinckel, 2010). As one example, proposed biofuel investments in Mozambique could increase annual economic growth by 0.6% and reduce the incidence of poverty by about 6% over a 12-year period between 2003 and 2015 (Arndt et al., 2010).

2.5.7.6 Trade-offs between social and environmental aspects

Some important trade-offs between environmental and social criteria exist and need to be considered in future bioenergy developments. In the case of sugarcane, the environmental sustainability criteria promoted by certification frameworks (such as the Roundtable for Sustainable Biofuels) favour mechanical harvesting due to the avoided emissions from sugarcane field burning required in manual systems. Several other organizations are concerned about the large number of workers that will be displaced by these new systems. Also, the mechanized model tends to favour further concentration of land ownership, potentially excluding small- and medium-scale farmers and reducing employment opportunities for rural workers (Huertas et al., 2010).

Strategies for addressing such concerns can include providing support for small- and medium-size stakeholders that lack the capacity to meet the certification system requirements and/or developing alternative income possibilities for the seasonal workers that presently earn a substantial part of their annual income by cutting sugarcane (Huertas et al., 2010). Retraining workers from manual to skilled labour, such as truck driving, is already taking place in Center South Brazil (Oliveira, 2009).

2.5.8 Synthesis

As a component of the much larger agriculture and forestry systems of the world, traditional and modern biomass affects social and environmental issues ranging from health and poverty to biodiversity and water quality. Land and water resources need to be properly managed in concert with each specific region's economic development situation and suitable types of bioenergy. Bioenergy has the opportunity to contribute positively to climate change mitigation, secure energy supply and diversity goals, and economic development in developed and developing countries alike. However, the effects of bioenergy on environmental sustainability may also be negative depending upon local conditions, how criteria are defined, and how actual projects are designed and implemented, among many other factors.

- Climate change and biomass production can be influenced by interactions and feedbacks among land and water use, energy and climate at scales that range from micro through macro (see Figure 2.15). Social and environmental trade-offs may be present but can be minimized to a large extent with appropriate project design and implementation.

- Although crops grown as biofuels feedstocks currently use less than 1% of the world's agricultural land, the expansion of large-scale bioenergy systems raises several important socioeconomic issues including food security, income generation, rural development, land tenure and water scarcity in specific regions.

- Estimates of LUC effects require value judgments about the temporal scale of analysis, the land use under the assumed 'no action' scenario, the expected uses in the longer term, and the allocation of impacts among different uses over time. Regardless, a system that ensures consistent and accurate inventory of and reporting on carbon stocks is considered an important first step towards LUC carbon accounting.

- Emissions of pollutants, like SO_2 and NO_x, are generally lower for bioenergy than for coal, gasoline and diesel, though the NO_x results for biodiesel are more variable. Thus, bioenergy can reduce negative impacts on air quality. Bioenergy impacts on water resources can be positive or negative, depending on the particular feedstock, supply chain element and processing methodologies. Bioenergy systems similar to conventional food and feed crop systems can contribute to loss of habitat and biodiversity, but bioenergy plantations can be designed to provide filters for nutrient loss, to function as ecological corridors, to reduce pressure on natural forests and to restore degraded or abandoned land. Genetically engineered and potentially invasive bioenergy crops have raised concerns. More research and protocols are needed to monitor and evaluate the introduction of new or modified species.

- Advanced ICS for traditional biomass use can provide large and cost-effective mitigation of GHG emissions (GHG mitigation potential of 0.6 to 2.4 Gt CO_2eq/yr) with substantial co-benefits in health and living conditions, particularly for the poorest 2.7 billion people in the world. Efficient technologies for cooking are cost-effective and comparable to major health interventions such as those for tobacco addiction, undernourishment or tuberculosis.

- Biofuel production has contributed to increases in food prices, but additional factors affect food prices, including weather conditions, changes in food demand and increasing energy costs. Even considering the benefit of increased prices to poor farmers, increased food prices have adversely affected poverty, food security and malnourishment of children. On the other hand, biofuels can also

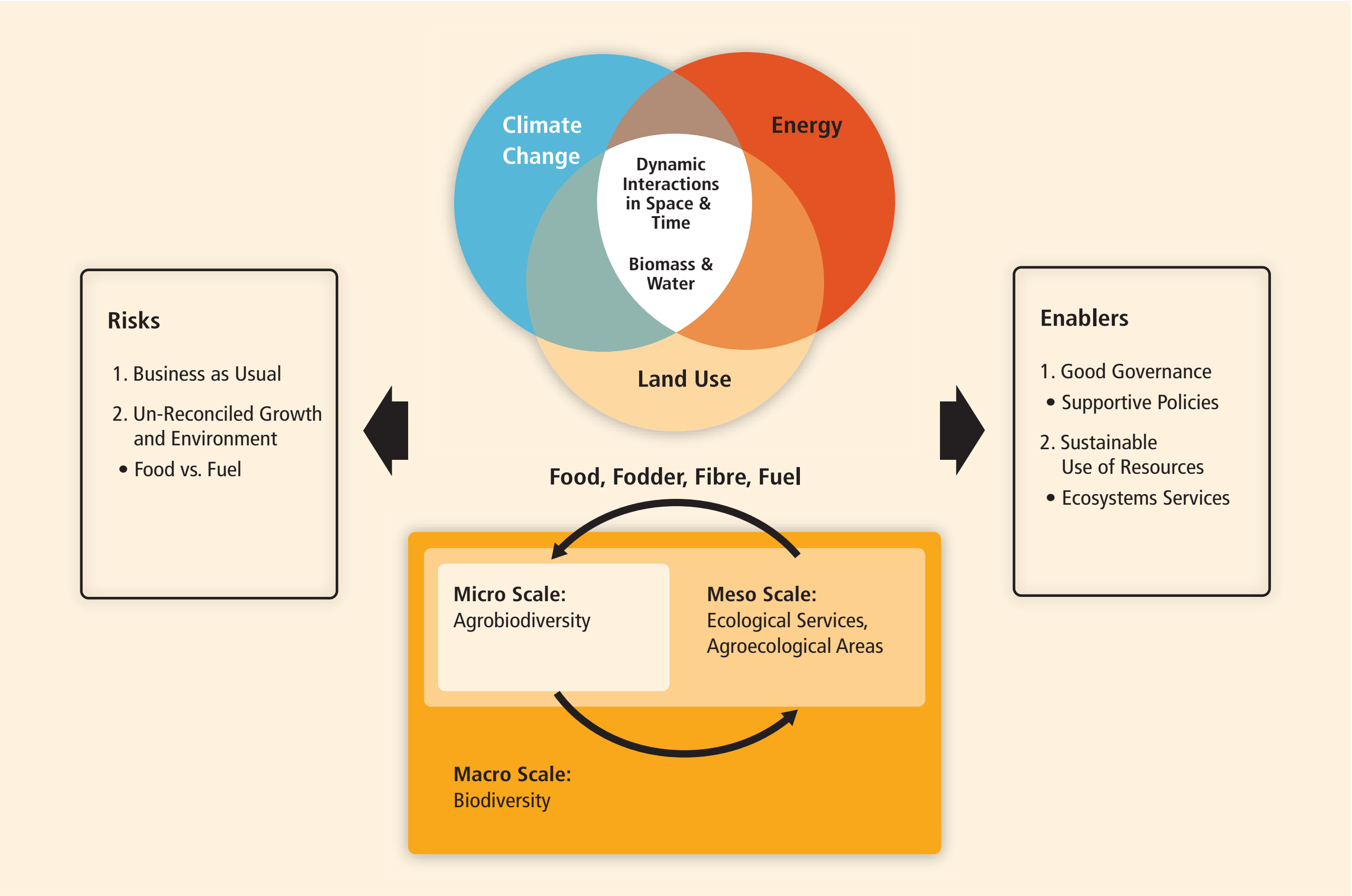


Figure 2.15 | Bioenergy's complex, dynamic interactions among society, energy and the environment include climate change feedbacks, biomass production and land use with direct and indirect impacts at various spatial and temporal scales on all resource uses for food, fodder, fibre and energy (Dale et al., 2011). Biomass resources need to be produced in sustainable ways as their impacts can be felt from micro to macro scales (van Dam et al., 2010). Risks are maintenance of business-as-usual approaches with uncoordinated production of food and fuel. Opportunities are many and include good governance and sustainability frameworks that generate effective policies that also lead to sustainable ecosystem services.

provide opportunities for developing countries to make progress in rural development and agricultural growth, especially when this growth is economically sustainable. Proper design, implementation, monitoring and adherence to sustainability frameworks may help minimize negative socioeconomic impacts and maximize benefits, particularly for local people.

- These social and environmental impacts should be compared with those of the energy systems they replace. Many lifecycle assessments that characterize the amount of RE provided relative to fossil energy used in biofuel production and compare that with the reference system show GHG emission savings for biofuels. These studies can be expanded to use multiple indicators and more comprehensively analyze the whole chain from feedstock to final energy use.

2.6 Prospects for technology improvement and innovation[61]

This section provides a literature overview of the sets of developing technologies, their performance characteristics and projections of cost performance for biomass feedstocks, logistics and supply chains, and conversion routes to a variety of biofuels alone or in combination with heat and power or with other bio-based products. Advanced power routes are also discussed. As illustrated in Figure 2.2 and Table 2.5, many such advanced biomass energy chains are commercial or in development at various stages ranging from small-scale R&D through near commercialization for each component of the chain, including some examples of integrated systems. Linkages are made with the various applications, with the suppliers of feedstocks, which can be residues from urban or rural areas, and with the existing and developing biomass conversion industry to products. The integration of biomass energy and related products into the electricity, natural gas, heating (residential and district, commercial and public services), industrial and fossil liquid fuels systems for transport is discussed more thoroughly in Chapter 8. The structure of this section parallels that of Section 2.3, following the bioenergy supply chain from feedstocks (Section 2.6.1) to logistics (Section 2.6.2) to end products (e.g., various advanced secondary energy carriers in gaseous or liquid states) made by various conversion technologies (Section 2.6.3).

2.6.1 Improvements in feedstocks

2.6.1.1 Yield gains

Increasing land productivity, whether for food or energy purposes, is a crucial prerequisite for realizing large-scale future deployment of biomass for energy because it would make more land available for growing biomass and reduce the associated demand for land. Much of the increase in agricultural productivity over the past 50 years came about through plant breeding and improved agricultural management practices including irrigation, fertilizer and pesticide use. The adoption of these techniques in the developing world is most advanced in Asia, where productivity grew strongly during the past 50 years, and also in Brazil, with sugarcane. Considerable potential exists for extending the same kind of gains to other regions, particularly sub-Saharan Africa, Latin America, Eastern Europe and Central Asia, where adoption of these techniques has been slower (Evenson and Gollin, 2003; FAO, 2008a). A recent long-term forecast by the FAO expects global agricultural production to rise by 1.5% per year for the next three decades, still significantly faster than projected population growth (World Bank, 2009). For the major food staple crops, maximum attainable yields may increase by more than 30% by switching from rain-fed to irrigated and optimal rainwater use production (Rost et al., 2009), while moving from intermediate- to high-input technology may result in 50% increases in tropical regions and 40% increases in subtropical and temperate regions. The yield increase when moving from low- to intermediate-input levels can reach 100% for wheat, 50% for rice and 60% for maize (Table 2.14), due to better pest control and adequate nutrient supply. However, important environmental trade-offs may be involved with agricultural intensification, and avenues for more sustainable management practices may need exploration and adoption (IAASTD, 2009).

Biotechnologies or conventional plant breeding could improve biomass production by focusing on traits relevant to energy production such as biomass per hectare, increased oil or fermentable sugar yields, or other characteristics that facilitate their conversion to energy end-products (e.g., Sannigrahi et al., 2010). Also, considerable genetic improvement is still possible for drought-tolerant plants (Nelson et al., 2007; Castiglioni et al., 2008; FAO, 2008b).

The projected increases in productivity reflect present knowledge and technology (Duvick and Cassman, 1999; Fischer and Schrattenholzer, 2001) and vary across the regions of the world (FAO, 2008a). In developed countries where cropping systems are already highly input-intensive, productivity increases will be more limited. Also, projections do not always account for the strong environmental limitations in many regions, such as water or temperature (Nelson et al., 2007; Castiglioni et al., 2008; FAO, 2008b).

Doubling the current yields of perennial grasses appears achievable through genetic manipulation such as marker-assisted breeding (Turhollow, 1994; Eaton et al., 2008; Tobias et al., 2008; Okada et al., 2010). Shifts to sustainable farming practices and large improvements in crop and residue yield could increase the outputs of residues from arable crops (Paustian et al., 2006).

Future feedstock production cost projections are scant because of their connections with food markets (which are, as all commodities, volatile and uncertain) and because many candidate feedstock types are still in the R&D phase. Cost figures for growing these feedstock species in commercial farms are not well understood yet but will likely reduce over time

61 Section 10.5 offers a complementary perspective on drivers and trends of technological progress across RE technologies.

Table 2.14 | Prospects for yield improvements by 2030 relative to 2007 to 2009 data from Table 2.4.

Feedstock type	Regions	Yield trend (%/yr)	Potential yield increase by 2030 (%)	Improvement routes	Ref.
DEDICATED CROPS					
Wheat	Temperate	0.7	20-50	New energy-oriented varieties	1,10
	Subtropics		30-100	Higher input rates, irrigation	
Maize	N America	0.7	20-35	New varieties, GMOs, higher plantation density, reduced tillage Higher input rates, irrigation	
	Subtropics		20-60		
	Tropics		50		
Soybean	USA	0.7	15-35	Breeding	2,3,10
	Brazil	1.0	20-60		
Oil palm	World	1.0	30	Breeding, mechanization	3
Sugarcane	Brazil	1.5	20-40	Breeding, GMOs, irrigation inputs	2,3,8,10
SR Willow	Temperate	—	50	Breeding, GMOs	3
SR Poplar	Temperate	—	45		
Miscanthus	World	—	100	Breeding for minimal input, improved management	
Switchgrass	Temperate	—	100	Genetic manipulation	
Planted forest	Europe Canada	1.3	20 20	Species choice, breeding, fertilization, shorter rotations, increased rooting depth	4,9 11
PRIMARY RESIDUES					
Cereal straw	World	—	15	Improved collection equipment, breeding for higher residue-to-grain ratios (soybean)	5,6
Soybean straw	N America	—	50		
Forest residues	Europe	1.0	25	Ash recycling, cutting increases, increased roundwood, productivity	4,7

Abbreviations: SR = short rotation; GMO = genetically modified organism.

References: 1. Fischer and Schrattenholzer (2001); 2. Bauen et al. (2009a); 3. WWI (2006); 4. Nabuurs et al. (2002); 5. Paustian et al. (2006); 6. Perlack et al. (2005); 7. EEA (2007); 8. Matsuoka et al. (2009); 9. Loustau et al. (2005); 10. Jaggard et al. (2010). 11. APEC (2003).

as farmers descend the learning curves, as past experience has shown in Brazil (van den Wall Bake et al., 2009).

Under temperate conditions, the expenses for the farm- or forest-gate supply of lignocellulosic biomass from perennial grasses or short-rotation coppice are expected to fall to less than USD_{2005} 2.5/GJ by 2020 (WWI, 2006) from a USD_{2005} 3 to 16/GJ range today (Table 2.6, without land rental cost). However, these are marginal costs, which do not account for the competition for land with other sectors and markets that would increase unit costs as the demand for biomass increases. This is reflected in supply curves (see Section 2.2 and Figure 2.5(b)). Recent studies in Northern Europe that include such land-related costs thus report somewhat higher projections, in a USD_{2005} 2 to 7.5/GJ range for herbaceous grasses and USD_{2005} 1.5 to 6/GJ range for woody biomass (Ericsson et al., 2009; de Wit and Faaij, 2010). For perennial species, the transaction costs required to secure a supply of energy feedstock from farmers may increase the production costs by 15% (Ericsson et al., 2009). Delivered prices for herbaceous crops are shown in Figure 2.5(d) for the USA and about 8 EJ could be delivered at USD_{2005} 5/GJ to the conversion facility.

In recent decades, forest productivity has increased more than 1% per year in temperate and boreal regions due to higher CO_2 concentrations and nitrogen deposition or fertilization rates (Table 2.14). This trend is projected to continue until 2030 when productivity might plateau due to increased stand ages and increased respiration rates in response to warmer temperatures (Nabuurs et al., 2002). However, yield trends vary across climatic zones at a finer scale. Water limitations in Mediterranean/semi-arid environments lead to zero or even negative variations in biomass yield increments by 2030 (Loustau et al., 2005). This may be counteracted by adaptive measures such as choosing species more tolerant to water stress or using appropriate thinning regimes (Loustau et al., 2005). Where water is non-limiting, productivity may be maximized by more intensive silvicultural practices, including shorter rotations, optimum row spacing, fertilization and improved breeding stock (Loustau et al., 2005; Feng et al., 2006). Increased roundwood extraction would also generate extra logging residues and carbon sequestration in forest soils as a co-benefit, outweighing several-fold the GHG emissions generated by management practices (Markewitz, 2006).

2.6.1.2 Aquatic biomass

Aquatic phototrophic organisms dominate the world's oceans, producing 350 to 500 billion tonnes of biomass annually and include 'algae', both microalgae (such as *Chlorella* and *Spirulina*) and macroalgae (i.e., seaweeds) and cyanobacteria (also called 'blue-green algae') (Garrison, 2008). Oleaginous microalgae such as *Schizochytrium* and *Nannochloropsis* can accumulate neutral lipids, analogous to seed oil triacylglycerides, at greater than 50% of their dry cell weight (Chisti, 2007). Weyer et al. (2009) reported yields of 40 x 10^3 to 50 x 10^3 litres/ha/yr (0.04 to 0.05 litres/m^2/yr) in unrefined algal oil from biomass grown in the Equator region and containing 50% oil. Assuming a neutral lipid yield ranging from 30 to 50%, algae productivity can be several-fold higher than palm oil productivity at 4.7 x 10^3 litres/ha/yr (0.0047 litres/m^2/yr). Photosynthetic cyanobacteria used to produce nutraceuticals at commercial scales (J. Lee, 1997; Colla et al., 2007) could also directly produce fuels such as H_2 (Hu et al., 2008; Sections 3.3.5 and 3.7.5).

Macroalgae do not accumulate lipids like microalgae do. Instead, they synthesize polysaccharides from which various fuels could be made (see Figure 2.6). Uncultivated macroalgae can have polysaccharide yields higher than those of terrestrial plants (per unit area) (Zemke-White and Ohno, 1999; Ross et al., 2009) and can live in marine environments. Halophiles, another group of phototrophic organisms, live in environments with high salt concentration.

Microalgae can photoproduce chemicals, fuels or materials in non-agricultural land such as brackish waters and highly saline soils. Hundreds of microalgae species, out of hundreds of thousands of species, have been tested or used for industrial purposes. Understanding the genetic potential, lipid productivity, growth rates and control, and use of genetic engineering allows broader use of land and decreases the LUC impacts of biofuels production (Hu et al., 2008). Microalgae can be cultivated in open ponds and closed photobioreactors (PBRs) (Sheehan et al., 1998a; van Iersel et al., 2009) but scale-up can involve logistical challenges, can require high cost to produce the biomass, and requires water consumption minimization (Borowitzka et al., 1999; Molina Grima et al., 2003). Production costs using low- to high-productivity scenarios currently range approximately from USD_{2005} 30 to 80/GJ for open ponds and from USD_{2005} 50 to 140/GJ for PBR (EPA, 2010).

Macroalgae are typically grown in offshore cultivation systems (Ross et al., 2009; van Iersel et al., 2009) that require shallow waters for light penetration (Towle and Pearse, 1973). The impact of biofuel production on competing uses (fisheries, leisure) and on marine ecosystems needs assessment. Using aquatic biomass harvested from algal blooms may provide multiple benefits (Wilkie and Evans, 2010).

The bioenergy potential from aquatic plants is usually excluded from resource potential determinations because of insufficient data available for such an assessment. However, the potential may be substantial compared to conventional energy crops, considering the high yield potential of cultivated microalgae production (up to 150 dry t/ha/yr, 0.015 t/m^2/yr) (Kheshgi et al., 2000; Smeets et al., 2007). With the large number of diverse algal species in the world, upper range productivity potentials of up to several hundred EJ for microalgae and up to several thousand EJ for macroalgae (Sheehan et al., 1998a; van Iersel et al., 2009) have been reported. Figure 2.10 shows very approximate ranges for GHG reductions relative to the fossil fuel replaced. Comparable or increased emission reductions relative to crop biodiesel could be achieved with successful RD&D and commercialization (EPA, 2010).

Some key conclusions from current efforts (US DOE, 2009; IEA Bioenergy, 2010; Darzins et al., 2010) are the following: (1) Microalgae can offer productivity levels above those possible with terrestrial plants. (2) There are currently several significant barriers to widespread deployment and many information gaps and opportunities for improvement and breakthroughs. (3) Various systems suited to different types of algal organisms, climatic conditions, and products are still being considered. (4) Basic information related to genomics, industrial design and performance is still needed. (5) Cost estimates for algal biofuels production vary widely, but the best estimates are promising at this early stage of technology development. (6) The cost of processing algae solely for fuel production is still too high. Producing a range of products for the food, fodder and fuel markets offers opportunities for economical operation of algal biorefineries. (7) Lifecycle assessments are needed to guide future developments of sustainable fuel production systems.

2.6.2 Improvements in biomass logistics and supply chains

Optimization of supply chains includes achieving economies of scale in transport, in pretreatment and in conversion technologies. Relevant factors include spatial distribution and seasonal supply patterns of the biomass resources, transportation, storage, handling and pretreatment costs, and economies of scale benefiting from large centralized plants (Dornburg and Faaij, 2001; Nagatomi et al., 2008). Smart utilization of a combination of biomass resources over time can help conversion plants gain economies of scale through year-round supplies of biomass and thus efficiently utilize the investment cost (Junginger et al., 2001; McKeough et al., 2005; Nishi et al., 2005; Ileleji et al., 2010; Kang et al., 2010) and technology transfer (Asikainen et al., 2010).

Over time the lower-cost biomass residue resources are increasingly depleted and more expensive (e.g., cultivated) biomass needs to cover the growing demand for bioenergy. Part of this growing demand may be met by learning and optimization, but, for example, future heat generation from pellets in the UK may be more costly (2020) than it is today due to a shift from local to imported feedstocks (E4tech, 2010). Similar effects are found in scenarios for large-scale deployment of biofuels in Europe (Londo et al., 2010).

Learning and optimization in the past one to two decades in Europe (Scandinavia and the Baltic in particular), North America, Brazil and also in various developing countries have shown steady progress in market development and cost reduction of biomass supplies (Section 2.7.2; Junginger et al., 2006). Well-working international biomass markets and substantial investments in logistics capacity are key prerequisites to achieve this (see also Section 2.4).

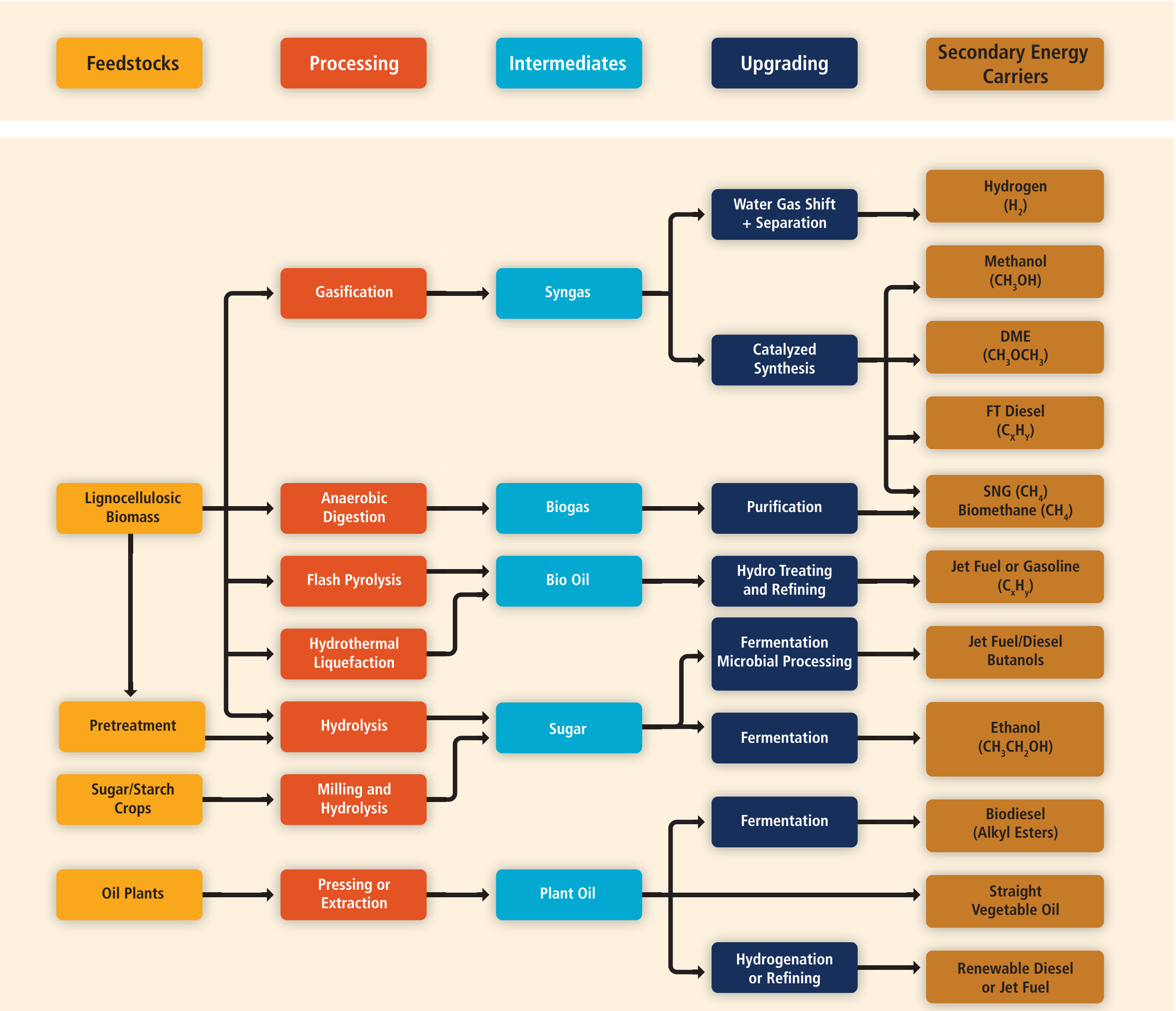


Figure 2.16 | Overview of lignocellulosic biomass, sugar/starch crops and oil plants (feedstocks) and the processing routes to key intermediates, which can be upgraded through various routes to secondary energy carriers, such as liquid and gaseous biofuels. Fuel product examples are (1) oxygenated biofuels to blend with current gasoline and diesel fuels or to use in pure form, such as ethanol, butanols, methanol, liquid ethers, biodiesel, and gaseous DME (dimethyl ether); (2) hydrocarbon biofuels such as Fischer Tropsch (FT) liquids, renewable diesel and some microbial fuels (which are compatible with the current infrastructure of liquid fuels because their chemical composition is similar to that of gasoline, diesel, and jet fuels (see Table 2.15.C)), or the simplest hydrocarbon methane for natural gas replacement (SNG) from gasification or biomethane from anaerobic digestion; and (3) H_2 for future transportation (adapted from Hamelinck and Faaij, 2006 and reproduced with permission from Elsevier B.V.).

Notes: Microbial fuels include hydrocarbons derived from isoprene, the component of natural rubber; a variety of non-fermentative alcohols with three to six carbon atoms including butanols (four carbons); and fatty acids which can be processed as plant oils to hydrocarbons (Rude and Schirmer, 2009).[1] For sugar and starch crops the sugar box indicates six-carbon sugars, while for lignocellulosic biomass this box is more complex and has mixtures of six- and five-carbon sugars, with proportions dependent on the feedstock type. Hardwoods and agricultural residues contain xylan and other polymers of five-carbon sugars in addition to cellulose that yield glucose, a six-carbon sugar.

1. Not shown are the aquatic plants (see Section 2.6.1.2) that can utilize the same types of processing shown for their vegetable oil and carbohydrate fractions.

Pretreatment technologies

Torrefied wood is manufactured by heating wood in a process similar to charcoal production. At temperatures up to 160°C, wood loses water, but it keeps its physical and mechanical properties and typically maintains 70% of its initial weight and 90% of the original energy content (D. Bradley et al., 2009). Torrefied wood only absorbs 1 to 6% moisture (Uslu et al., 2008). Torrefaction can produce uniform quality feedstock, which eliminates inefficient and expensive methods designed to handle feedstock variations and thus makes conversion more efficient (Badger, 2000) and more predictable.

Pyrolysis processes convert solid biomass to liquid bio-oil, a complex mixture of oxidized hydrocarbons. Although this liquid product is toxic and needs stabilization for longer-term storage, bio-oil is relatively easy to transport. Pyrolysis oil production is more expensive and less efficient per unit of energy delivered compared to torrefaction of wood pellets. Section 2.3.4 discusses the cost data for multiple countries based on Bain (2007); McKeough et al. (2005) arrive at similar figures of USD_{2005} 6.2 to 7.0/GJ. The process allows for separation of a solid fraction (biochar) that contains the bulk of the nutrients of the biomass. With proper handling, such biochars could be used to improve soil quality and productivity, recycle nutrients and possibly store carbon in the soil for long periods of time (Laird, 2008; Laird et al., 2009; Woolf et al., 2010).

2.6.3 Improvements in conversion technologies for secondary energy carriers from modern biomass

Different conversion technologies (or combinations) including mechanical, thermochemical, biochemical and chemical steps, as shown in Figure 2.2, are needed to transform the variety of potential feedstocks into a broader range of secondary energy carriers. In addition to electricity and heat as products, a variety of liquid and gaseous fuels or products can be made from biomass as illustrated in Figure 2.16, where key chemical intermediates that could make identical, similar or new products as energy carriers, chemicals and materials are highlighted (see Section 2.6.3.4 for further detail):

- **Sugars**, mixtures of five- and six-carbon sugars from lignocellulosic materials, are converted primarily through biochemical or chemical processes into liquid or gaseous fuels and a variety of chemical products.

- **Syngas** from thermochemical gasification processes, which can be converted in integrated gasification combined cycle (IGCC) systems to electricity, through a variety of thermal/catalytic processes to gaseous or liquid fuels, or through biological processes at low temperature to H_2 or polymers.

- **Oils** from pyrolysis or hydrothermal treatment, which can be upgraded into a variety of fuels and chemicals.

- **Lipids** from plant oils, seeds or microalgae, which can be converted into a wide variety of fuels, such as diesel or jet fuels, and chemicals.

- **Biogas** is a mixture of methane and CO_2 released from anaerobic degradation of organic materials with a lower heat content than its upgraded form, mostly methane, called biomethane. If upgraded, it can be added to natural gas grids or used for transport.

Table 2.15 contains process efficiency and projected improvements along with cost information expressed in USD_{2005}/GJ for several bioenergy systems and chains, in various stages of development, from various studies from multiple sources. Part A details processes for alcohols; Part B summarizes microalgal fuels; Part C details hydrocarbon fuels; and Part D includes gaseous fuels and electricity from IGCC. Financial assumptions are provided at the end of the table; some groups of references use the same assumptions but not all. First-of-a-kind plants are more expensive as there are technical uncertainties in the chemical, biochemical, thermochemical or mechanical component steps in a route, as shown by Kazi et al. (2010) and Swanson et al. (2010) compared to Bauen et al. (2009a) or Foust et al. (2009). Such combination of steps is often significantly more complex than a similar petroleum industry process because of the characteristics of solid biomass. Scaling up is conducted after initial bench-scale experimentation and encouraging initial techno-economic evaluation. As experience in operating the process and correcting design or operating parameters is gained, cost evaluations are conducted and the plant is operated until costs decrease at a slower pace. At this point, the technical and economic risks of the plant have decreased and the production costs have reached so-called nth plant status. The uncertainties in these studies are variable and higher for the least-developed concepts (Bauen et al., 2009a).

An overview of advanced pilot, demonstration and commercial-scale bioenergy projects in 33 countries is provided by Bacovsky et al. (2010a,b), including the site at Kalundborg, Denmark, where a wheat straw ethanol is made in the pilot plant and sold to a gasoline distributor in 2010.[62] The number of actual projects moving to pilot and demonstration scale is probably larger. The reference contains descriptions of most of the development projects listed in Table 2.15. See also the IEA (Renewable Energy Division, 2010) report on global sustainable second-generation technologies and future perspectives in the context of the transport sector and the recently published technology roadmap for biofuels (IEA, 2011).

This section focuses on bioenergy products to avoid repetition of technology descriptions provided in Section 2.3—for instance, a thermochemical technology such as gasification can produce multiple fuels and electricity. Similarly, a variety of end products can be made from sugars.

An initial meta-analysis of advanced conversion routes (Hamelinck and Faaij, 2006) for methanol, H_2, Fischer-Tropsch liquids and biochemical ethanol produced from lignocellulosic biomass under comparable financial assumptions suggests that these systems compare favourably with starch-based biofuels and offer more competitive fuel prices and opportunities in the longer term because of their inherently lower feedstock costs and because of the variety of sources of lignocellulosic biomass, including agricultural residues from cereal crop production, and forest residues. The feedstock cost range used in this meta-analysis is in line with costs highlighted in Section 2.6.1.1 and the low range of the supply curves shown in Figure 2.5. In the EU study, Northern Europe projected production costs are in the USD_{2005} 2 to 7.5/GJ range for herbaceous grasses and USD_{2005} 1.5 to 6/GJ for woody biomass (land-related costs included). For perennial species, transaction costs may need to increase by 15% to secure a supply of energy feedstock from farmers. This additional cost (e.g., transport to the conversion plant and payment to secure the feedstock) is already built into the prices of the US supply

62 An interactive website with this information is maintained by the IEA Bioenergy Task 39: biofuels.abc-energy.at/demoplants.

Table 2.15 | Summary of developing technologies costs projected for 2030 biofuel production and their 2010 industrial development level. Using today's performance for a pioneer plant built in the near term increases costs, and the majority of the references assumes that technology learning will occur upon development, referred to as nth plant costs. Costs expressed in USD_{2005}.

A: Fuels – Alcohols by Biochemical and Gasification Processes

Process	Feedstock	Efficiency and process economics. Eff. = Energy product/biomass energy Component costs in USD_{2005}/GJ	% GHG reduction from fossil reference	Potential technical advances and challenges	Production cost by 2030 (USD_{2005}/GJ)	Industrial development (see Bacovsky et al., 2010a,b)
Consolidated bioprocessing (CBP)	Lignocellulosic	Eff. ~49% for wood and 42% for straw (ethanol) + 5% power.[19]	Scenarios analyzed[30]	Lignin engineering cellulose access.[7] Develop CBP organisms.[44]	15.5[19] future	Demonstration and pilots. Reduce enzyme and pretreatment costs. Several pilots in many countries. First commercial plants. Lignin residues co-firing.[32]
Separate hydrolysis/ co-fermentation		Eff. ~39% (ethanol) + 10% power.[1]		Efficient 5-carbon sugar conversion.[2,3] R&D investment.[5] Advanced enzyme.[6]	25[1]–27[19] 28–35[48]	
Simultaneous saccharification/ co- fermentation	Barley straw	Steam explosion, enzyme hydrolysis, ethanol fermentation.[9] High solids 15%.	N/A	System integration, high solids, decrease toxicity for fermentation.	30[9] (Finland) from pilot data	
Simultaneous saccharification and fermentation	Corn stover	Dilute acid hydrolysis, 260 million L/yr; FC: 6.6, CC*: 10.1, CR: 1.1 for ethanol.[24]	83–88 Depending on co-product credit method[25]	Pretreatment, process integration, enzyme costs.[24]	15.5 (US) nth plant, future[24]	
	Lignocellulosic Various Eff. 35% ethanol + 4% power.[1]	Generic; 90 million L/yr; FC:14; CC*:14. At 360 million L/yr; FC:14; CC*:10; CR:0.5.[45]		Meta-analysis conditions.[45]	28 (2015)[45] 23.5 (2022)[45]	
		Eff. kg/L ethanol (poplar, *Miscanthus*, switchgrass, corn stover, wheat: 3.7, 3.2, 2.6, 2.6, 2.4). Plant sizes 1,500 to 1,000 t/day. FC 50% of total.[10]		Process integration—capital costs per installed litre of product USD 0.9 to 1.3 for plants of 150 to 380 million litres/yr (2020 estimates). Project a 25% operating cost reduction by 2025 and a 40% operating cost reduction by 2035.[10]	18–22[10] (2020) breakeven USD 100/barrel; + CCS USD 95/ barrel; USD 50/t CO_2	
	Bagasse	Standalone plant[35] 370 L/t dry (ethanol) + 0.56 kWh/L ethanol (elec.).	86 Advanced CHP: 120% (replace NG peak power).[36]	Mechanical harvest improvements sugarcane residues (occurring).[35,36]	6[35]–15[35] w/o and w FC	
Gasification/catalytic synthesis ethanol	Lignocellulosic	170 million L per year plant (varies in size).[18] By-product propanol/butanols.	90[38]	Improvements in catalyst development and syngas cleaning.	12[49]–15[18] 14.5[24]	RD&D, pilot.
Fermentation; product compatible with gasoline infrastructure to butanols, in particular biobutanol	Sugar/starch	Development of an integrated biobutanol production and removal systems using the solvent-producing bacteria *Clostridia* improved by genetic engineering.[29] Initial acetone, butanol, and ethanol (ABE) fermentation is costly.	5–31 Depending on co-product credit method.[29]	For high selectivity to biobutanol: (1) mutated strain of *Clostridium beijernekei* BA101, or protein engineering in *E. coli* to increase selectivity/lower cost to biobutanol.[15,16] (2) dual fermentation to butyric acid and reduction to butanols.	29.6 for ABE;[18] 25.2 for mutated *Clostridia*[17] or 21.6 for dual process[17]	Large and small venture companies in different routes, including yeast host. Hydrocarbon precursor.
Gasification to butanols	Lignocellulosic	Catalytic process for synthesis of predominantly butanols.	N/A	Estimated production costs include return on capital.[17]	13[17]	N/A
Gasification/synthesis to methanol for fuel and/or power	Lignocellulosic	Eff. 55% fuel only[19] Eff. 48% fuel and 12% power.[19]	90[27]	Methanol (and dimethyl ether) production possible in various configurations that co-produce power.	12–18 (fuel)[19] 7.1–9.5 (fuel and power)[19]	Pilots, demos, and first commercial.

Continued next Page →

curves based on county-level data; the projected price of delivery to the conversion facility for forest and related residues is USD_{2005} 1 to 3/GJ up to about 1.5 EJ, and for woody and herbaceous plants and sorghum delivered to the conversion facility the projected price is USD_{2005} 2 to 4/GJ up to about 5 EJ (or more at higher price).

2.6.3.1 Liquid fuels

Alcohols. Estimated production costs for various fuel processes are assembled in Part A of Table 2.15, and they range from USD_{2005} 13 to 30/GJ.

B: Fuels – Algae

Process	Feedstock	Efficiency and process economics Eff. = Energy product/biomass energy Component costs in USD_{2005}/GJ	% GHG reduction from fossil reference	Potential technical advances and challenges	Production cost by 2030 (USD_{2005}/GJ)	Industrial development
Lipid production, extraction, and conversion of microalgae neutral lipids to biodiesel or renewable diesel. Remainder of algal mass digested or used in other process	Microalgae lipids; see Section 2.6.1.2	Assuming biomass production capacity of 10,000 t/yr, cost of production per kg is USD 0.47 and 0.60 for photobioreactors (PBR) and raceways, respectively.[23]	28–76 Scenarios for open pond and bioreactor[34]	Assuming[34] biomass contains 30% oil by weight, cost of biomass for providing a litre of oil would be USD 1 to 3 and USD 1.5 to 5 for algae of low productivity = 2.5 g/m²/day or high productivity = 10 g/m²/day in open ponds or photobiological reactors.	Preliminary Results 95 or more[23] 30–80[34] for open ponds 50–140[34] for PBR going from low to high productivity	Active R&D by companies small and large including pilots pursuing jet and diesel fuel substitutes.

C: Fuels – Hydrocarbons by Gasification, Pyrolysis, Hydrogenation and Isomerization of Vegetable Oils and Wastes

Process	Feedstock	Efficiency and process economics Eff. = Energy product/biomass energy Component costs in USD_{2005}/GJ	% GHG reduction from fossil reference	Potential technical advances and challenges	Production cost by 2030 (USD_{2005}/GJ)	Industrial development
Gasification to syndiesel followed by FT (Fischer-Tropsch) process. Known as biomass to liquids. With and without CCS. Process makes hydrocarbons fuels (number of carbon atoms) for gasoline (5–10); kerosene (jet fuel) (10–15); diesel (15–20); fuel oil (20–30)	Lignocellulosic	Eff. = 0.42 fuel only; 0.45 fuel + power.[19]	91[27] (EU)	CCS for CO_2 from processing.	14–20 (fuel only) 8–11 (fuel/power)[19] 15.2-18.6[43]	One first commercial plant (wood) under way. Many worldwide demonstration and pilot processes under way.
		80 million L/yr; FC:12, CC*17 (2015); 280 million L/yr; FC:12, CC*8 (2022).[45]		Meta-analysis conditions.[45]	20–29.5[45]	
		Eff. = 0.52 w/o CCS and 0.5 w/ CCS + 35 and 24 MW_e. 4000 t/day switchgrass. Plant cost ~ USD 650 Mi.[10]	90[26] (US)	Gas clean-up costs and scale/volume. Breakeven with barrel of crude oil of USD 122 (USD 113 with CCS and USD 50/t CO_2).[10]	25[10] (w/o CCS US) 30[10] (w/ CCS US) see[38] for cost breakdown (2020)	
		Eff. = 0.52 + 22 MW_e. Capital USD 500 million; wide range of densified feeds imported into EU for processing.[39]	Detailed Well-to-Wheel EU[39] US[14] scenarios	Breakeven with barrel of crude oil of USD 75. Mixture of 50% biomass and coal is climate neutral.	16–22.5[39]	
		Coal and biomass co-gasification.	See Fig. 2.10	Switchgrass and mixed prairie grasses.	29[38]	
Hydrogenation to renewable diesel	Plant oils, animal fat, waste	Technology well known. Cost of feedstock is the barrier.	63–130[26] Depending on the co-product treatment method	Feedstock costs drive this process. Process is standard in petrochemical operations.	17–18[34]	One large and few small commercial (see, e.g., footnote 68 in the main text); many demos.
Biomass pyrolysis[4] and catalytic upgrading to diesel/jet fuel; vegetable oils processed directly into a refinery [33]	Biomass/ wastes, plant oils, animal fat, waste oils	Developing pyrolysis[8,13] process (also from hydrothermal processing)[46] to a blendstock for a refinery,[33] for direct coupled firing in a boiler (e.g., with coal)[32] or a final product.		Catalyst development, process yield improvements with biomass.	14–24[47] for pyrolysis oils to refinery blendstocks	Demos and fuel product tests in USA, Brazil, EU. Test flights using biojet fuels from plant oils conducted.[33]

Continued next Page →

While some methanol, butanols and other alcohol production processes from biomass exist in various stages of technical development, the most predominant alcohol production pathways have ethanol as their finished product. Lignocellulosic ethanol technologies have many possible process chains (e.g., Sánchez and Cardona, 2008; Sims et al., 2010). Those with the highest sugar yields and with low environmental impact were considered more promising (Wooley et al., 1999) and involve chemical/biochemical, mechanical/chemical/biochemical, and biological/chemical/biochemical processing steps. Most of these chains involve a pretreatment step to overcome the recalcitrance of the plant cell wall, with separate and partial hydrolysis of the cellulose and hemicelluloses fibres to release the complex streams of five- and six-carbon sugars for fermentation. Simultaneous saccharification and fermentation (SSF), simultaneous saccharification and co-fermentation (SSCF) and consolidated bioprocessing

D: Gaseous Fuels, Power and Heat from Gasification

Process	Feedstock	Efficiency and process economics Eff. = product energy/biomass energy Component costs in USD_{2005}/GJ	% GHG reduction from fossil reference	Potential technical advances and challenges	Production cost by 2030 (USD_{2005}/GJ)	Industrial development
Gasification/syngas processing of H_2 to fuel and power	Lignocellulosic	Eff. 60% (fuel only). Needs 0.19 GJ of elect. per GJ H_2 for liquid estimated at USD 11–14/GJ (long term), wood USD 2.4/GJ, USD 568/kW_{th} capital.[19]	88[30]	Co-production H_2 and power (55% fuel efficiency, 5% power) in the longer term.[19] USD 426/kW_{th} capital.[19]	4–5[19] (longer) 6[20]–12[12] 5.5–7.7[41]	R&D stage.
Gasification/methanation to methane for fuel, heat and/or power	Lignocellulosic	Eff. ~60% (or higher for dry feed).[42] Combined fuel and power production possible.	98[27]	RD&D on gas clean up and methanation catalysts. For wet feedstocks wet gasification developing.[46]	10.6–11.5[42] wood USD 2.8/GJ	RD&D stage.
Anaerobic digestion, upgrading of gas, liquefaction	Organic wastes, sludges	Eff. ~20 to 30%; includes mixtures of animal and agriculture residues.		Improve technology robustness with new metagenomic tools, reduce costs.	15–16[21]	
Integrated gasification combined cycle for CHP	Lignocellulosic	District heating; power-to-heat ratio 0.8 to 1.2; power production efficiency 40 to 45%; total efficiency 85 to 90%. Investment USD 1,200/kW_{th}. Wood residues in Finland.[22]	96[31]	Gas cleaning, increased efficiency cycles, cost reductions.	8–11[11]	Demos at 5 to 10 MW projected cost at USD 29–38/GJ or US cents 10–13.5/kWh.[45]
				IGCC at 30 to 300 MW[45] with a capital cost of USD 1,150 to 2,300/kW_e, at 10% discount rate, 20 year plant life, and USD 3/GJ. Meta-analysis conditions.	13–19[45] or US cents 4.5–6.9/kWh	

Notes: Abbreviations: *Conversion costs (CC) include investment costs and operating expenses; CR = Co-product Revenue; FC = feedstock cost; CC = conversion cost. All CC, CR, FC costs are given in USD_{2005}/GJ.

System Boundaries: Many references use a 10% discount rate, 20-yr plant life referred to as meta-analysis conditions. 17. Production costs include return on capital; 24.10% IRR (Internal Rate of Return), 39% tax rate, 20-yr plant life, Double-declining-balance depreciation method, 100% equity, nth plant, for the biochemical pathway costs are FC: 6, CC*: 10.6, CR: 1.1 and for thermochemical pathway costs are FC: 6.7, CC*: 10, CR: 2.5; 3012% IRR, 39% tax rate, 25-yr plant life, Modified Accelerated Cost Recovery System depreciation method (MACRS dep.), 65/35 equity/debt, 7% debt interest, nth plant, FC: 8.2, CC*: 16.9, CR: 2.6; 37. Pioneer (first-of-a-kind) plant example: 10% IRR, 39% tax rate, 20-yr plant life, MACRS dep., 100% equity, FC: 12.2–20.7, CC*: 27.3–38, CR: 0–6; 38. 7% discount rate, 39% tax rate, 20-yr plant life, MACRS dep., 45/55 equity/debt, 4.4% debt interest, nth plant, FC w/ CCS: 16, FC w/o CCS: 8.8, CC* w/ CCS: 14.7, CC* w/o CSS: 15.7, CR w/ CCS: 2, CR w/o CCS: 2.1; 39.10% discount rate, 10-yr plant life; 40. Pioneer plant example: 10% IRR, 39% tax rate, 20-yr plant life, MACRS dep, 100% equity, FC: 9.5, CC*: 24.5, CR: 1.1; 41.10% IRR, 15-yr plant life.

References: 1. Hamelinck et al. (2005a); 2. Jeffries (2006); 3. Jeffries et al. (2007); 4. Balat et al. (2009) and see IEA Bioenergy Pyrolosis Task (www.pyne.co.uk); 5. Sims et al. (2008); 6. Himmel et al. (2010); 7. Sannigrahi et al. (2010); 8. Bain (2007); 9. von Weyman (2007); 10. NRC (2009a); 11. IEA Bioenergy (2007); 12. Kinchin and Bain (2009); 13. McKeough et al 2005; 14. Wu et al. (2005); 15. Ezeji et al. (2007a); 16. Ezeji et al. (2007b); 17. Cascone (2008); 18. Tao and Aden (2009); 19. Hamelinck and Faaij (2006); 20. Hoogwijk (2004); 21. Sustainable Transport Solutions (2006); 22. Helynen et al. (2002); 23. Chisti (2007); 24. Foust et al. (2009); 25. Wang et al. (2010); 26. Kalnes et al. (2009); 27. Edwards et al. (2008); 28. Huo et al. (2009); 29. Wu et al. (2008); 30. Laser et al. (2009); 31. Daugherty (2001); 32. Cremers (2009) (see IEA co-firing database at www.ieabcc.nl/database/cofiring.php); 33. IATA (2009); 34. EPA (2010); 35. Seabra et al. (2010); 36. Macedo et al. (2008); 37. Kazi et al. (2010); 38. Larson et al. (2009); 39. van Vliet et al. (2009); 40. Swanson et al. (2010); 41. Hamelinck and Faaij (2002); 42. Mozaffarian et al. (2004); 43. Hamelinck et al. (2004); 44. van Zyl et al. (2007); 45. Bauen et al. (2009a); 46. Elliott (2008); 47. Holmgren et al. (2008); 48. Dutta et al. (2010); 49. Phillips et al. (2007).

(CBP), which combines all of the hydrolysis, fermentation and enzyme production steps into one, were defined as short-, medium- and longer-term approaches, respectively. For CBP, efficiencies and yields are expected to increase and costs to decrease by 35 and 66% relative to SSF and SSCF, respectively (Hamelinck et al., 2005a, and see Table 2.15).

Pretreatment is one of the key technical barriers causing high costs, and a multitude of possible options exist. So far, no 'best' technology has been identified (da Costa Sousa et al., 2009; Sims et al., 2010). Pretreatment overcomes the recalcitrance of the cell wall of woody, herbaceous or agricultural residues and makes carbohydrate polymers accessible to hydrolysis (e.g., by enzymes) and in some cases liberates a portion of the sugars for fermentation to ethanol (or butanols) and the lignin for process heat or electricity. Alternatively, multiple steps (including pretreatment) can be combined with other downstream conversion steps and material can be bioprocessed with multiple organisms simultaneously. To evaluate pretreatment options,[63] the use of common

63 The areas of biomass pretreatment and low-cost ethanol emerged as essential in 2009 with fourteen core papers establishing a biology/biochemistry/biomass chemical analysis concentration area (sciencewatch.com/dr/tt/2009/09-octtt-BIO/). Included were coordinated pretreatment research in multiple US and Canadian institutions, investigating common samples and analytical methodology and conducting periodic joint evaluation of technical and economic performance of these processes.

feedstocks and common analytical methodology (Wyman et al., 2005) is needed to differentiate between the performance of the many chains and combinations. For corn stover, among the evaluated options of ammonia fibre expansion (AFEX), dilute acid and hot water pretreatments, dilute acid pretreatment had the lowest cost and the hot water process cost was the highest by 25%. This ranking, however, does not hold for other feedstocks (Elander et al., 2009). On-site enzyme preparation increased the cost of the dilute acid pretreatment by 4.5% (Kazi et al., 2010). Apart from pretreatment, enzymes are another key variable cost and are the focus of major global efforts in RD&D and cost reduction (e.g., Himmel et al., 2010; Sims et al., 2010). Finally, all of the key individual conversion steps (e.g., pretreatment, enzymatic hydrolysis and fermentation) are highly interdependent. Therefore, process integration is another very important focus area, as many steps are either not yet optimized or have not been optimized in a fully integrated process.

The US National Academies analyzed liquid transport fuels from biomass (NRC, 2009a), and their cost analysis found the breakeven point for cellulosic ethanol with crude oil to be USD_{2005} 100/barrel (USD_{2005} 0.64/litre) in 2020, which translates to USD_{2005} 18 to 22/GJ. This projection is similar[64] to the USD_{2005} 23.5/GJ projected by Bauen et al. (2009a) for 2022. The National Research Council (NRC, 2009a) projects that by 2035, process improvements could reduce the plant-related costs by up to 40%, or to within USD_{2005} 12 to 15/GJ, in line with estimates for nth plant costs of USD_{2005} 15.5/GJ (Foust et al., 2009). Further cost reductions in some of the processing pathways may come from converting bagasse to ethanol, as the feedstock is already at the conversion facility, and the bagasse has the potential to produce an additional 30 to 40% yield of ethanol per unit land area in Brazil (Seabra et al., 2010). A similar strategy is currently being employed in the USA, where the coupling of crop residue collection and collocation of the second-generation (residue) and first-generation (corn) ethanol facilities are being pursued by two of the first commercial cellulosic ethanol plant developments by the U.S. Department of Energy.[65]

Several strains of microorganisms have been selected or genetically modified to increase the enzyme production efficiency (FAO, 2008b) for SSF (Himmel et al., 2010), for SSCF (e.g., Dutta et al., 2010) and for CPB (van Zyl et al., 2007; Himmel et al., 2010). Many of the current commercially available enzymes are produced in closed fermenters from genetically modified (GM) microorganisms. The final enzyme product does not contain GM microorganisms (Royal Society, 2008), which facilitates acceptance of the routes (FAO, 2008b).

64 See Table 2.15 for financial assumptions that are not identical; Bauen et al. (2009a) and Foust et al. (2009) are close.

65 Impact Assessment of first-of-a-kind commercial ethanol from corn stover and cobs collocated with grain ethanol facilities is provided by the Integrated Bioenergy Projects. U.S. DOE Golden Field Office web site: www.eere.energy.gov/golden/Reading_Room.aspx; www.eere.energy.gov/golden/PDFs/ReadingRoom/NEPA/Final_Range_Fuels_EA_10122007.pdf; www.eere.energy.gov/golden/PDFs/ReadingRoom/NEPA/POET_Project_LIBERTY_Final_EA.pdf; and www.biorefineryprojecteis-abengoa.com/Home_Page.html.

Microbial fuels. Industrial microorganisms[66] with imported genes to accelerate bioprocessing functions (Rude and Schirmer, 2009) can make hydrocarbon fuels, higher alcohols, lipids and chemicals from sugars. Researchers in synthetic biology have imported pathways, and more recently used artificial biology to design alternative biological paths into microorganisms, which may lead to increased efficiency of fuels and chemicals production (Keasling and Chou, 2008; S. Lee et al., 2008). Another route is to alter microorganisms' existing functions with metabolic engineering tools. Detailed production costs are not available in the literature but Regalbuto (2009) and E4tech (2009) summarize some data.[67] Additionally, some microalgae can metabolize sugars in the absence of light (heterotrophically) to make lipids (similar to plant oils) that are easily converted downstream to biodiesel and/or renewable diesel or jet fuel. With additional genetic engineering, the microorganisms can excrete lipids, leading to a decrease in production costs. Microbial biofuels and chemicals are under active development (Alper and Stephanopoulos, 2009; Rude and Schirmer, 2009).

Gasification-derived products (see Table 2.15.A and B)

Gasification of biomass to syngas (CO and H_2) followed by catalytic upgrading to either ethanol or butanols has estimated production costs (USD_{2005} 12 to 20/GJ) comparable to the biochemical chains discussed above. The lowest-cost liquid fuel is methanol (produced in combination with power) at USD_{2005} 7 to 10/GJ (USD_{2005} 12 to 18/GJ for fuel only). Further reduction in production costs of fuels derived from gasification will depend on significant development of IGCC (currently at the 5 to 10 MW_e demonstration phase) to obtain practical experience and reduce technical risks. Costs are projected to be USD_{2005} 13 to 19/GJ (US $cents_{2005}$ 4.6 to 6.9/kWh) for 30 to 300 MW_e plants (see Table 2.15; Bauen et al., 2009a). Although process reliability is still an issue for some designs, niche markets have begun to develop (Kirkels and Verbong, 2011).

Even though the cost bases are not entirely comparable, the recent estimates for Fischer-Tropsch (FT) syndiesel from Bauen et al. (2009a), van Vliet et al. (2009), the NRC (2009a) and Larson et al. (2009) are (in USD_{2005}/GJ), respectively: 20 to 29.5, 16 to 22, 25 to 30, and 28 (coal and biomass). The breakeven point would occur around USD_{2005} 80 to 120/barrel (USD_{2005} 0.51 to 0.74/litre). High efficiency gains are expected, especially in the case of polygeneration with FT fuels (Hamelinck and Faaij, 2006; Laser et al., 2009; Williams et al., 2009).

Process intensification is the combination of multiple unit operations conducted in a chemical plant into one thus reducing its footprint and

66 E.g., *Escherichia coli* and *Saccharomyces cerevisiae* have well-established genetic tools and industrial use.

67 Rude and Schimer (2009) report stoichiometric data, for example, per tonne of glucose the number of litres is 297 of farnesene (for diesel), and 384 of microbial biocrude oil (for jet fuel) compared with 648 of ethanol (for gasoline). Metabolic mass yields are 25 and 30% for farnesene and biocrude, respectively, compared to 51% for ethanol. The routes grow the intermediate cell mass that then starts producing biofuels or intermediates—these steps are usually aerobic and require air and agitation that reduce the overall energy efficiency.

capital costs and enabling plants to operate more cost effectively at smaller scale. Therefore chemical/thermal processing that previously could only be conducted at very large scale could now be downsized to match the supply of biomass cost effectively. Efficient heat and mass transfer in micro-channel reactors has been explored to compact reactors by 1-2 orders of magnitude in water-gas-shift, steam reforming and FT processes for conventional natural gas or coal gasification streams (Nehlsen et al., 2007) and significantly reduce capital costs (Schouten et al., 2002; Sharma, 2002; Tonkovich et al., 2004). Such intensification could lead to distributed biomass to liquids (BTL) production, as capital requirements would be significantly reduced (as they would be for coal to liquids (CTL) or gas to liquids (GTL) (Shah, 2007). Methanol/DME synthesis could be intensified as well. Additionally, combined biomass/coal gasification options could capture some of the economies of scale while taking advantage of biomass' favourable CO_2 mitigation potential.

Other intermediates: vegetable or pyrolysis/ hydrothermal processing oils

For **diesel substitution**, hydrogenation technologies are already commercially producing direct hydrocarbon diesel substitutes from hydrogenation of vegetable oils to renewable diesel in 2011.[68] Costs depend on the vegetable oil prices and subsidies (see Table 2.15.C and Section 2.3.4). Lignocellulosic residues from vegetable oil production could provide the energy for standalone hydrogenation. The downstream processing of the lipids/plant oils to finished fuels is often conducted in conjunction with a petroleum refinery, in which case jet fuel and other products can be made.

Fast **pyrolysis** processes or **hydrothermal liquefaction** processing of biomass make low-cost intermediate oil products (Bain, 2007; Barth and Kleinert, 2008; Section 2.7.1). Holmgren et al. (2008) estimated production costs for lignocellulose pyrolysis upgrading to a blendstock (component that can be blended with gasoline at a refinery) as USD_{2005} 14 to 24/GJ, from bench scale data.

Under mild conditions of **aqueous phase reforming** and in the presence of multifunctional supported metal catalysts, biomass-derived sugars and other oxygenated organics can be combined and chemically rearranged (with retention of carbon and hydrogenation) to make hydrocarbon fuels. These processes can also make hydrogen at moderate temperature and pressure (Cortright et al., 2002; Huber et al., 2004, 2005, 2006; Davda et al., 2005; Gurbuz et al., 2010). These developments have reached the pilot and demonstration phase (Regalbuto, 2009).

From carbon dioxide, water and light energy with photosynthetic algae (Table 2.15.B)

Microalgal lipids (microalgal oil) are at an early stage of R&D and currently have significant feedstock production and processing costs, ranging from USD_{2005} 30 to 140/GJ (EPA, 2010). Exploring the biodiversity of microbial organisms for their chemical composition and their innate microbial pathways can lead to use of highly saline lands, brackish waters or industrial waste waters, avoiding competition with land for food crops but the potential of microalgae is highly uncertain.

Prospects. In the near to medium term, the biofuel industry, encompassing first- and second-generation technologies that meet agreed-upon environmental and economic sustainability and policy goals, will grow at a steady rate. It is expected that the transition to an integrated first- and second-generation biofuel landscape will likely require another decade or two (Sims et al., 2008, 2010; NRC, 2009a; Darzins et al., 2010).

2.6.3.2 Gaseous fuels

Part D of Table 2.15 compares estimated production costs for the production of gaseous fuels from lignocellulosic biomass and various waste streams:

Anaerobic digestion. Production of methane from a variety of waste streams, alone or combined with agricultural residues, is being used throughout the world at various levels of performance. The estimated production costs depend strongly on the application: USD_{2005} 1 to 2/GJ for landfill gas, USD_{2005} 15 to 20/GJ for natural gas or transport applications, USD_{2005} 50 to 60/GJ for on-farm digesters/small engines and USD_{2005} 100 to 120/GJ for distributed electricity generation (see Tables 2.6 and 2.15). The reliability, predictability and cost of individual technologies and assembled systems could be decreased using advanced metagenomics tools[69] and microbial morphology and population structure (Cirne et al., 2007). Also, control and automation technologies and improved gas clean-up and upgrading and quality standards are needed to permit injection into natural gas lines, which could result in more widespread application. Avoided methane emissions provide a significant climate benefit with simultaneous generation of energy and other products.

Synthesis gas-derived methane (a substitute for natural gas), methanol-dimethyl ether (DME), and H_2 are gaseous products from biomass gasification that are projected to be produced in the USD_{2005} 5 to 18/GJ range. After suitable gas cleaning and tar removal, the syngas is converted in a catalytic synthesis reactor into other products by designing catalysts and types of reactors used (e.g., nickel/magnesium catalysts will lead to SNG, while copper/zinc oxide will preferentially make methanol and DME). Processes developed for use with multiple feedstocks in various proportions can decrease investment risks by ensuring continuous feedstock availability throughout the year and decreasing vulnerability to weather and climate. Methanol synthesis from natural gas (and coal) is practised commercially, and synthesis from biomass is being developed at demonstration and first commercial plants. H_2 production has the lowest potential costs, but more developed infrastructure

68 Renewable Diesel is currently produced by Neste Oil in Singapore from Malaysian palm oil and then shipped to Germany (see biofuelsdigest.com/bdigest/2011/03/11/neste-oil-opens-giant-renewable-diesel-plant-in-singapore/). The development of the process took about 10 years from proof of principle as described in www.climatechange.ca.gov/events/2006-06-27+28_symposium/presentations/CalHodge_handout_NESTE_OIL.PDF (nesteoil.com/).

69 See, for instance, www.jgi.doe.gov/sequencing/why/99203.html.

is needed for transportation applications (Kirkels and Verbong, 2011). DME is another product from gasification and upgrading (jointly produced with methanol). It can be made from wood residues and black liquor and is being pursued as a transportation fuel. Sweden considered scenarios for multiple bioenergy products, including a substantial replacement of diesel fuel and gasoline with DME and methanol (Gustavsson et al., 2007).

Microbial fuel cells using organic matter as a source of energy are being developed for direct generation of electricity. Electricity is generated through what may be called a microbiologically mediated oxidation reaction, which implies that overall conversion efficiencies are potentially higher for microbial fuel cells compared to other biofuel processes (Rabaey and Verstraete, 2005). Microbial fuel cells could be applied for the treatment of liquid waste streams and initial pilot winery wastewater treatment is described by Cusick et al. (2011).

2.6.3.3 Biomass with carbon capture and storage: long-term removal of greenhouse gases from the atmosphere

Bioenergy technologies coupled with CCS (Obersteiner et al., 2001; Möllersten et al., 2003; Yamashita and Barreto, 2004; IPCC, 2005; Rhodes and Keith, 2008; Pacca and Moreira, 2009) could substantially increase the role of biomass-based GHG mitigation if the geological technologies of CCS can be developed, demonstrated and verified to maintain the stored CO_2 over time. These technologies may become a cost-effective indirect mitigation, for instance, through offsets of emission sources that are expensive to mitigate directly (IPCC, 2005; Rhodes and Keith, 2008; Azar et al., 2010; Edenhofer et al., 2010; van Vuuren et al., 2010).

Corn ethanol manufacturers in the USA supply CO_2 for carbonated beverages, flash freezing meat and to enhance oil recovery in depleted fields, but due to the low commercial value of CO_2 markets and requirements for regional proximity, the majority of the ethanol plants vent it into the air. CO_2 capture from sugar fermentation to ethanol is thus possible (Möllersten et al., 2003) and may now be used for carbon sequestration. Demonstrations of these technologies are proceeding.[70] The impact of this technology was projected to reduce the lifecycle GHG emissions of a natural gas-fired ethanol plant from 39 to 70% relative to the fossil fuel ethanol replaced, while the energy balance is degraded by only 3.5% (see Table 2.13 for performance in different functional units) ((S&T)^2 Consultants, 2009).

Similarly, van Vliet et al. (2009) estimated that a net neutral climate change impact could be achieved by combining 50% BTL and 50% coal FTL fuels with CCS, if biomass gasification and CCS can be made to work at an industrial scale and the feedstock is obtained in a climate-neutral manner (see Figure 2.10). Perhaps additional removal could be achieved by using crops that increase soil carbon content (e.g., on degraded lands) as indicated by Larson et al. (2009).

2.6.3.4 Biorefineries

The concept of biorefining is analogous to petroleum refining in that a wide array of products including liquid fuels, chemicals and other products (Kamm et al., 2006) can be produced. Even today's first generation biorefineries are making a variety of products (see Table 2.7), many of which are associated with food and fodder production. For example, sugarcane ethanol biorefineries produce multiple energy products (EPE, 2008, 2010). Sustainable lignocellulosic biorefineries can also enhance the integration of energy and material flows (e.g., Cherubini and Strohman 2010). These biorefineries optimize the use of biomass and resources in general (including water and nutrients) while mitigating GHG emissions (Ragauskas et al., 2006). The World Economic Forum (King et al., 2010) projects that biorefinery revenue potentials with existing policies along the entire value chain could be significant and could reach about USD_{2005} 295 billion by 2020.[71]

2.6.3.5 Bio-based products

Bio-based products are defined as non-food products derived from biomass. The term is typically used for new non-food products and materials such as bio-based plastics, lubricants, surfactants, solvents and chemical building blocks. Plastics represent 73% of the total petrochemical product mix, followed by synthetic fibres, solvents, detergents and synthetic rubber (2007 data; Gielen et al., 2008). Bio-based products can therefore be expected to play a pivotal role in these product categories, in particular plastics and fibres.

The four principal ways of producing polymers and other organic chemicals from biomass are: (1) direct use of several naturally occurring polymers, usually modified with some thermal treatment, chemical transformation or blending; (2) thermochemical conversion (e.g., pyrolysis or gasification) followed by synthesis and further processing; (3) fermentation (for most bulk products) or enzymatic conversion (mainly for specialty and fine chemicals) of biomass-derived sugars or other intermediates; and (4) bioproduction of polymers or precursors in genetically modified field crops such as potatoes or *Miscanthus.*

Worldwide production of recently emerging bio-based plastics is expected to grow from less than 0.4 Mt in 2007 to 3.45 Mt in 2020 (Shen et al., 2009). Cost-effective bio-based products with properties superior to those in conventional materials, not just renewability, are

70 See sequestration.org/report.htm and www.netl.doe.gov/technologies/carbon_seq/database/index.html. In the USA, through the Midwest Geological Sequestration Consortium, a coal-fired wet-milled ethanol plant is planning over three years to inject 1 Mt of CO_2 into the Mount Simon sandstone saline formation in central Illinois at a depth of about 2 km in a verification phase test project including monitoring, verification and accounting, which is in the characterization phase (June 2010).

71 Approximate values (USD_{2005} billion by 2020) of business potential for the various parts of the value chain were estimated as: agricultural inputs (15), biomass production (89), biomass trading (30), biorefining inputs (10), biorefining fuels (80), biorefining chemicals and products (6), and biomass power and heat (65).

projected to penetrate the markets (King et al., 2010). For synthetic organic materials production, scenario studies indicate that at a productivity of 0.15 ha/t, an area of 75 million hectares globally could supply the equivalent of 15 to 30 EJ of value-added products (Patel et al., 2006).

Given the early stage of development, the GHG abatement costs differ substantially. The current abatement costs for polylactic acid are estimated at USD_{2005} 100 to 200/t of abated CO_2. Today's abatement costs for bio-based polyethylene, if produced from sugarcane-based ethanol, may be of the order of USD_{2005} 100/t CO_2 or lower. For all processes, technological progress in chemical and biochemical conversion and the combined production of bioenergy is likely to reduce abatement costs by USD_{2005} 50 to 100/t CO_2 in the medium term (Patel et al., 2006).

2.6.4 Synthesis

Lignocellulosic feedstocks offer significant promise because they (1) do not compete directly with food production; (2) can be bred specifically for energy purposes (or energy-specific products), enabling higher production per unit land area, and have a very large market for the products; (3) can be harvested as residues from crop production and other systems that increase land use efficiency; and (4) allow the integration of waste management operations with a variety of other industries offering prospects for industrial symbiosis at the local level.

Drivers and challenges for converting biomass to fuels, power, heat and multiple products are economic growth and development, environmental awareness, social needs, and energy and climate security. The estimated revenue potential along the entire value chain could be of the order of USD_{2005} 295 billion in 2020 with current policies (King et al., 2010).

Residues from crop harvests and from planted forests are projected to increase on average by about 20% by 2030 to 2050 in comparison to 2007 to 2009. Production costs of bioenergy from perennial grasses or short rotation coppice are expected to fall to under USD_{2005} 2.5/GJ by 2020 (WWI, 2006), from a range of USD_{2005} 3 to 16/GJ today. Supply curves projecting the costs and quantities available at specific sites are needed, and they should also consider competing uses as shown in examples in Figure 2.5. For example, EU and US lignocellulosic supply curves show more than 20 EJ at reasonable delivered costs by 2025 to 2030.

A new generation of aquatic feedstocks that use sunlight to produce algal lipids for diesel, jet fuels or higher-value products from CO_2 and water can provide strategies for lowering land use impacts because they enable use of lands with brackish waters or industrial waste water. Today's estimated production costs are very uncertain and range from USD_{2005} 30 to 140/GJ in open ponds and engineered reactors.

Many microbes could become microscopic factories to produce specific products, fuels or materials that decrease society's dependence on fossil energy sources.

Although significant technical progress has been made, the more complex processing required by lignocellulosic biomass and the integration of a number of new steps take time and support to bring development through the 'Valley of Death' in demonstration plants, first-of-a kind plants and early commercialization. Projected costs from a wide range of sources and process variables are very sensitive to feedstock cost and range from USD_{2005} 10 to 30/GJ. The US National Academies project a 40% reduction in operating costs for biochemical routes by 2035.

Cost projections for pilot integrated gasification combined cycle plants in many countries are USD_{2005} 13 to 19/GJ (US $cents_{2005}$ 4.6 to 6.9/kWh at USD_{2005} 3/GJ feedstock cost). In addition to providing power, syngas can be used to produce a wide range of fuels or can be used in a combined power and fuels approach. Estimated projected costs are in the range of USD_{2005} 12 to 25/GJ for methanol, ethanol, butanols and syndiesel. Biomass to liquids technology uses a commercial process already developed for fossil fuel feedstocks. Gaseous products (H_2, methane, SNG) have lower estimated production costs (USD_{2005} 6 to 12/GJ) and are in an early commercialization phase.

The production of biogas from a variety of waste streams and its upgrading to biomethane is already penetrating small markets for multiple applications, including transport in Sweden and heat and power in Nordic and European countries. A key factor is the combination of waste streams with agriculture residues. Improved upgrading and further cost reductions are still needed.

Pyrolysis oil/hydrothermal oils are low-cost transportable oils (see Sections 2.3.4 and 2.7.2) that could become a feedstock for upgrading either in standalone facilities or coupled to a petrochemical refinery. Pyrolysis oils have low estimated production costs of about USD_{2005} 7/GJ and provide options for electricity, heat and chemicals production. Pyrolysis-oil stabilization and subsequent upgrading still require cost reductions and are active areas of research.

Many bioenergy/biofuels routes enable CCS with significant opportunities for removal of GHGs from the atmosphere. As CCS technologies are further developed and verified, coupling concentrated CO_2 streams from fermentation or IGCC for electricity or biomass and coal to liquids through Fischer-Tropsch processes with CCS offer opportunities to achieve carbon-neutral fuels, and in some cases carbon-negative fuels, within the next 35 years. Achieving this goal will be facilitated by well-designed systems that span biomass selection, feedstock supply systems, conversion technologies to secondary energy carriers, and integration of these carriers into the existing energy systems of today and tomorrow.

2.7 Cost trends[72]

2.7.1 Determining factors

Determining the production costs of energy (or materials) from biomass is complex because of the regional variability in the costs of feedstock production and supply and the wide variety of deployed and possible biomass conversion technology combinations. Key factors that affect the costs of bioenergy production are:

- For crop production: the cost of land and labour, crop yields, prices of various inputs (such as fertilizer), water supply and the management system (e.g., mechanized versus manual harvesting) (Sections 2.3.1 and 2.6.1; see Wiskerke et al., 2010 for a local specific example).
- For delivering biomass to a conversion facility: spatial distribution of biomass resources, transport distance, mode of transport and the deployment (and timing) of pretreatment technologies in the chain. Supply chains range from onsite use (e.g., fuelwood or use of bagasse in the sugar industry, or biomass residues in other conversion facilities) all the way to international supply chains with shipped pellets or liquid fuels such as ethanol (Sections 2.3.2 and 2.6.2); see Dornburg and Faaij (2001) on regional transport for power; Hamelinck et al. (2005b) on international supply chains.
- For final conversion to energy carriers (or biomaterials): the scale of conversion, financing mechanisms, load factors, production and value of co-products and ultimate conversion costs (in the production facility). These key factors vary between technologies and locations. The type of energy carrier used in the conversion process influences the climate mitigation potential (Wang et al., 2011).

The analyses of Hoogwijk et al. (2009) provide a global and long-term outlook for potential biomass production costs (focused on perennial cropping systems) of different IPCC SRES scenarios (IPCC, 2000) discussed in Sections 2.8.4 and 2.8.5 (see Table 2.16 and Figure 2.17). Land rental/lease costs, although a smaller cost factor in most world regions, are dependent on intensity of land use in the underlying scenarios. Capital costs vary due to different levels of mechanization. Based on these analyses, a sizeable part (100 to 300 EJ) of the long-range technical potentials based on perennial cropping systems could cost around USD_{2005} 2.3/GJ. The cost range depends on the assumed scenario conditions, and is shown in Figure 10.23 (Hoogwijk et al., 2009; see also cost supply curves and potentials shown in Figure 2.5 for near-term production). More details on costs of both annual and perennial energy crop production are described in Sections 2.3.1 and 2.6.1.

Biomass supplies are, as with any commodity, subject to complex pricing mechanisms. Biomass supplies are strongly affected by fossil fuel prices (OECD-FAO, 2008; Schmidhuber, 2008; Tyner and Taheripour, 2008) and by agricultural commodity and forest product markets. In an ideal situation, demand and supply will balance and price levels will provide a good measure of actual production and supply costs (see also Section 2.5.3 for discussions on LUC). At present, market dynamics determine the costs of the most important biofuel feedstocks, such as corn, rapeseed, palm oil and sugarcane. For wood pellets, another important internationally traded feedstock for modern bioenergy production, prices have been strongly influenced by oil prices, because wood pellets partly replace heating oil, and by supportive measures to stimulate green electricity production, such as FITs for co-firing (Section 2.4; Junginger et al., 2008). In addition, prices of solid and liquid biofuels are determined by national settings, and specific policies and the market value of biomass residues for which there may be alternative applications is often determined by price mechanisms of other markets influenced by national policies (see Junginger et al., 2001 for a specific example for Thailand).

2.7.1.1 Recent levelized costs of electricity, heat and fuels for selected commercial systems

The factors discussed above make it clear that it is difficult to generate generic cost information for bioenergy that is valid worldwide. Nonetheless, this section provides estimates for the recent levelized cost of electricity (LCOE), heat (LCOH) and fuels (LCOF) typical of selected commercial bioenergy systems, some of which are described in more technological detail in Section 2.3.4.[73] The methodology for calculating levelized cost is described in Annex II. Data and assumptions used to produce these figures are provided in Annex III, with those assumptions derived in part from the literature summarized earlier.

The results of the LCOE, LCOH and LCOF calculations for a selected set of commercially available bioenergy options, and based on recent costs, are summarized in Figure 2.18 and discussed below.

To calculate the LCOE for electricity generation, a standardized range of feedstock cost of USD_{2005} 1.25 to 5/GJ was assumed (based on High Heating Value, HHV). To calculate the LCOE of CHP plants where both electricity and heat are produced, the heat was counted as a co-product with revenue that depended on the assumed quality and application of the heat. For large-scale CHP plants, where steam is generated for process heat, the co-product revenue was set at USD_{2005} 5/GJ. For small-scale CHP plants, on the other hand, the revenue was effectively set according to the cost of hot water, or USD_{2005} 13/GJ (applicable, e.g., in Nordic countries and Europe).

The LCOH for heating systems illustrated in the light blue bars of Figure 2.18 is less certain due to a more limited set of available literature. For

72 Discussion of costs in this section is largely limited to the perspective of private investors producing secondary energy carriers. Chapters 1 and 8 to 11 offer complementary perspectives on cost issues covering e.g. costs of integration, external costs and benefits, economy-wide costs and costs of policies.

73 The levelized cost of energy represents the cost of an energy generating system over its lifetime; it is calculated as the per-unit price at which energy must be generated from a specific source over its lifetime to break even. It usually includes all private costs that accrue upstream in the value chain, but does not include the downstream cost of delivery to the final customer the cost of integration or external environmental or other costs. Subsidies and tax credits are also not included.

Table 2.16 | Estimated regional technical potential of energy crops for 2050 (in EJ) on abandoned agricultural land and rest of land at various cut-off costs (in USD_{2005}/GJ biomass harvested, including local transport) for the two extreme SRES land use scenarios A1 and A2 (Hoogwijk et al., 2009; reproduced with permission from Elsevier B.V.).

Region	A1: high crop growth intensity and maximum international trade in 2050			A2: low crop growth intensity and minimum trade and low technology development in 2050		
cut-off cost	<1.15 USD/GJ	<2.3 USD/GJ	<4.6 USD/GJ	<1.15 USD/GJ	<2.3 USD/GJ	<4.6 USD/GJ
Canada	0	11.4	14.3	0.0	7.9	9.4
USA	0	17.8	34.0	0.0	6.9	18.7
C America	0	7.0	13.0	0.0	2.0	2.9
S America	0	11.7	73.5	0.0	5.3	14.8
N Africa	0	0.9	2.0	0.0	0.7	1.3
W Africa	6.6	26.4	28.5	7.9	14.6	15.5
E Africa	8.1	23.8	24.4	3.6	6.2	6.4
S Africa	0	12.5	16.6	0.1	0.3	0.7
W Europe	0	3.0	11.5	0.0	5.6	12.5
E Europe	0	6.8	8.9	0.0	6.2	6.3
Former USSR	0	78.6	84.9	0.8	41.9	46.6
Middle East	0	0.1	3.0	0.0	0.0	1.3
South Asia	0.1	12.1	15.3	0.6	8.2	9.8
East Asia	0	16.3	63.6	0.0	0.0	5.8
SE Asia	0	8.8	9.7	0.0	6.9	7.0
Oceania	0.7	33.4	35.2	1.6	16.6	18.0
Japan	0	0.0	0.1	0.0	0.0	0.0
Global	**15.5**	**271**	**438**	**14.6**	**129**	**177**

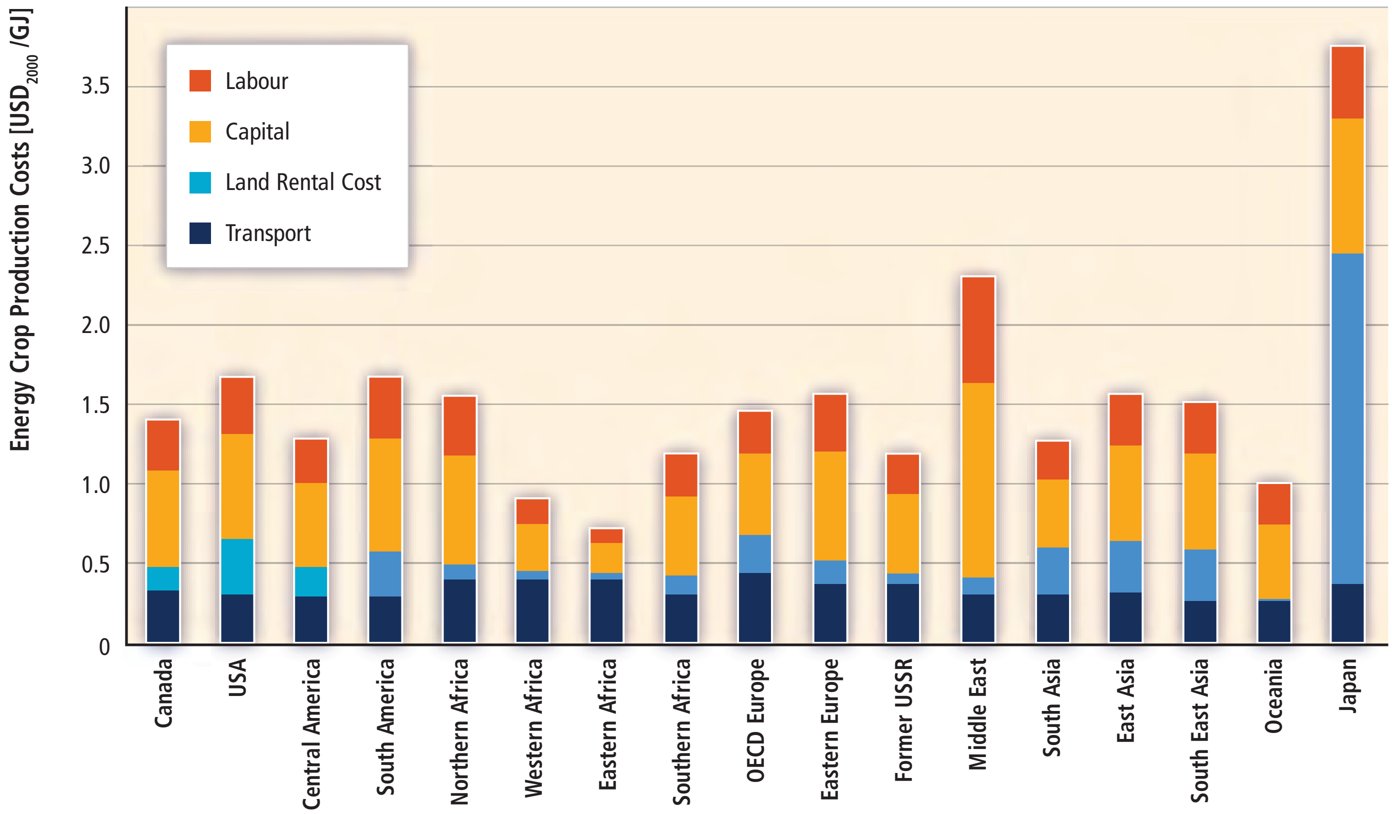


Figure 2.17 | Cost breakdown for energy crop production costs in the grid cells with the lowest production costs within each region for the SRES A1 scenario (IPCC, 2000) in 2050 (in USD_{2000} instead of USD_{2005})(Hoogwijk et al., 2009; reproduced with permission from Elsevier B.V.).

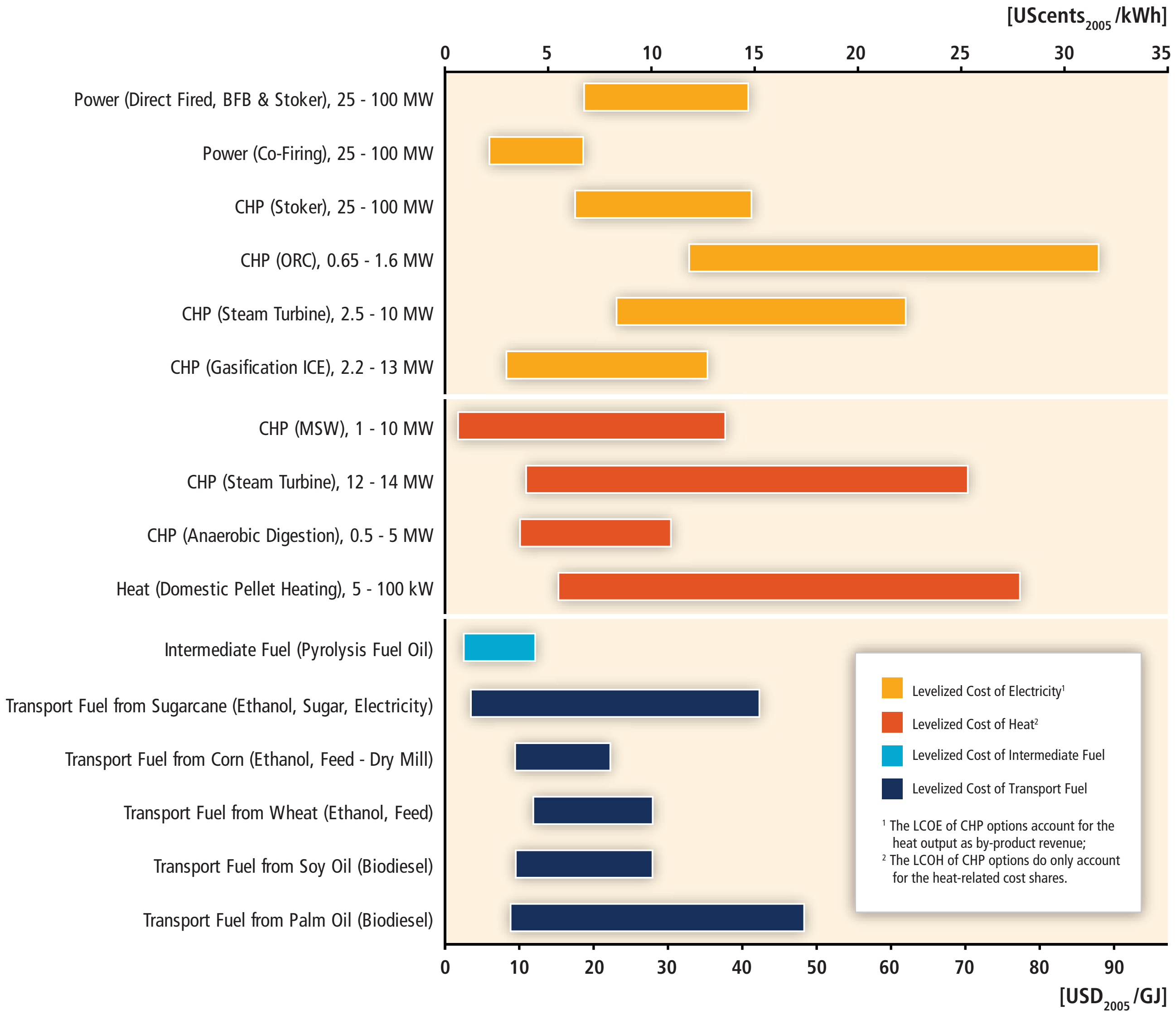


Figure 2.18 | Typical recent levelized cost of energy service from commercially available bioenergy systems at 7% discount rate. Feedstock cost ranges differ between technologies. For levelized cost at other discount rates (3 and 10%) see Annex III and Section 10.5. For biofuels, the range of LCOF represents production in a wide range of countries whereas LCOE and LCOH are given only for major user markets of the technologies for which data were available. The underlying cost and performance assumptions used in the calculations are summarized in Annex III. Calculations are based on HHV.

Abbreviations: BFB: Bubbling fluidized bed; ORC: Organic Rankine cycle; ICE: Internal combustion engine.

heating applications, investment cost assumptions came principally from literature from European and Nordic countries, which are major users of these applications (see Figure 2.8). Feedstock cost ranges came from the same literature and therefore may not be representative of other world regions: feedstock costs were assumed to be USD_{2005} 0 to 3.0/GJ for MSW and low-cost residues, USD_{2005} 2.5 to 3.7/GJ for anaerobic digestion, USD_{2005} 3.7 to 6.2/GJ for steam turbine and USD_{2005} 10 to 20/GJ for pellets. The LCOH figures presented here are therefore most representative of European systems.

LCOF estimates were derived from a techno-economic evaluation of the production of biofuels in multiple countries (Bain, 2007).[74] Underlying feedstock cost assumptions represent the maximum and minimum recent feedstock cost in the respective regions, and are provided in Annex III. All routes for biofuel production take into account sometimes multiple co-product revenues, which were subtracted from expenditures to calculate the LCOF. In the case of ethanol from sugarcane, for example,

74 The study was done in conjunction with a preliminary economic characterization of feedstock supply curves for the Americas, China and India (Kline et al., 2007) described in Section 2.2.3. The biomass market potential associated with these calculations (Alfstad, 2008) is shown in Figure 2.5(c) (45 EJ, 25 EJ and 8 EJ respectively for the high-growth, baseline and low-growth cases for these countries).

the revenue from sugar was set at USD_{2005} 4.3/GJ_{feed}, though this value varies with sugar market prices and can go up to about USD_{2005} 5.6/GJ_{feed}. For the LCOF calculations, however, average by-product revenues were assumed. Along with ethanol and sugar (and potentially other biomaterials in the future), the third co-product is electricity, revenues for which were also assumed to be deducted in calculating the LCOF. A similar approach was used for other biofuel pathways (see Annex III). This single example, however, illustrates the complexity of biofuel production cost assessments.

Finally, the levelized cost of pyrolysis oil as an intermediate fuel, a densified energy carrier, was also assessed, because pyrolysis oils are already used for heating and CHP applications and are also being investigated for stationary power and transport applications (see Sections 2.3.3.2, 2.6.2 and 2.6.3.1).

Figure 2.18 presents a broad range of values, driven by variations not only in feedstock costs but also investment costs, efficiencies, plant lifetimes and other factors. Feedstock costs, however, not only vary substantially by region but also represent a sizable fraction of the total levelized cost of many bioenergy applications. The effect of different feedstock cost levels on the LCOE of the electricity generation technologies considered here is shown more clearly in Figure 2.19, where variations are also shown for investment costs and capacity factors.[75] Similar effects are shown for the levelized cost of biofuels (LCOF) in Figure 2.20. (Though a figure is not shown for heating systems, a similar relationship would

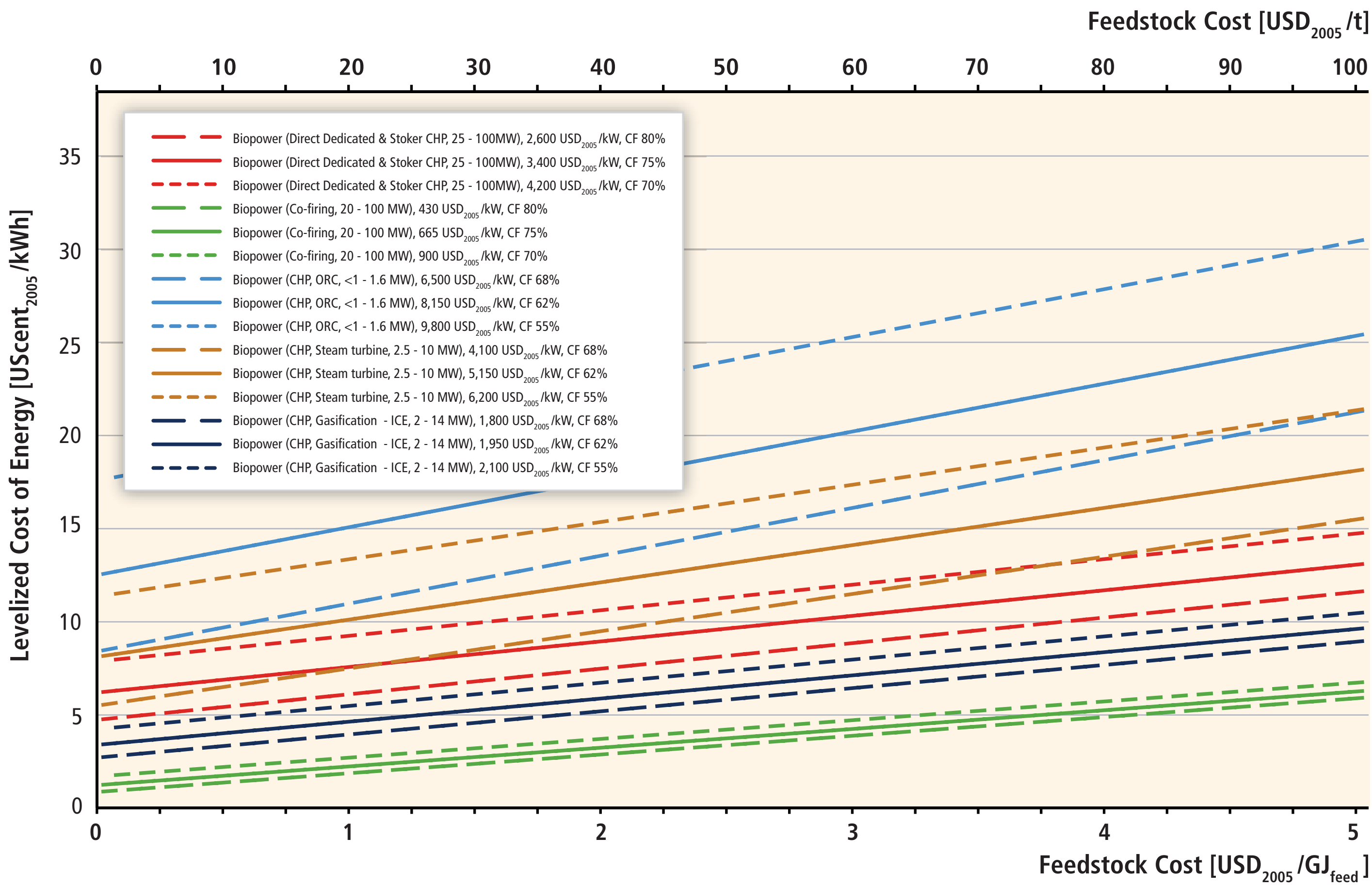


Figure 2.19 | Sensitivity of LCOE with respect to feedstock cost for a variety of investment costs and plant capacity factors (CF). LCOE is based on a 7% discount rate, the mid-value of the operations and maintenance (O&M) cost range, and the mid-value of the lifetime range (see Annex III). Calculations are based on HHV.

References: DeMeo and Galdo (1997); Bain et al. (2003); EIA (2009); Obernberger and Thek (2004); Sims (2007); McGowin (2008); Obernberger et al. (2008); EIA (2010b); Rauch (2010); Skjoldborg (2010); Bain (2011); OANDA (2011).

75 Note that large-scale power only and CHP technologies have been aggregated in Figure 2.18, while they are shown separately in Figure 2.19.

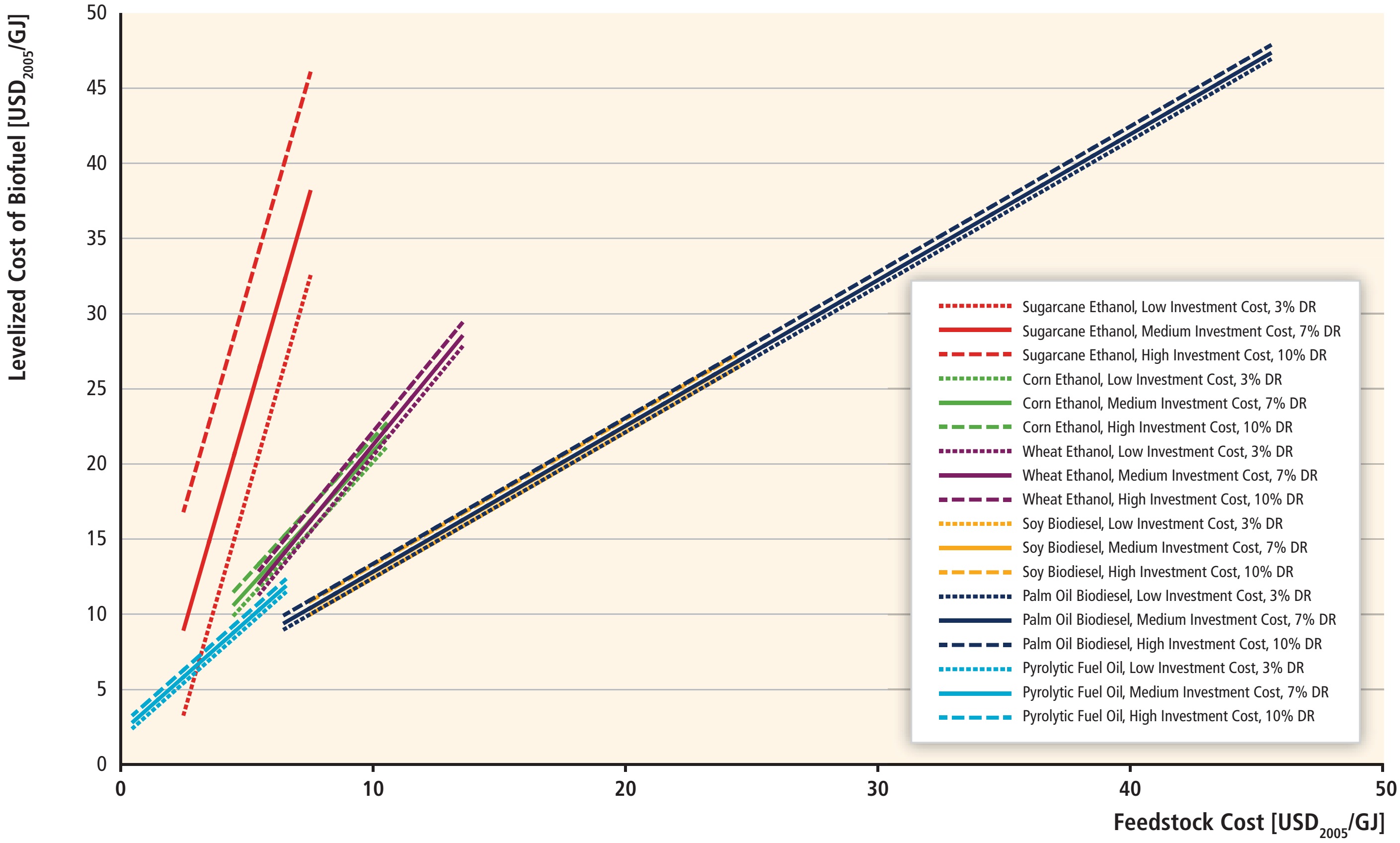


Figure 2.20 | Sensitivity of LCOF with respect to feedstock cost for different discount rates and the mid-values of other cost components from multiple countries (see Annex III). Calculations are based on HHV.

References: Delta-T Corporation (1997); Sheehan et al. (1998b); McAloon et al. (2000); Rosillo-Calle et al. (2000); McDonald and Schrattenholzer (2001); Ibsen et al. (2005); Jechura (2005); Bohlmann (2006); CBOT (2006); Haas et al. (2006); Oliverio (2006); Oliverio and Ribeiro (2006); Ringer et al. (2006); Shapouri and Salassi (2006); USDA (2006); Bain (2007); Kline et al. (2007); USDA (2007); Alfstad (2008); RFA (2011); University of Illinois (2011).

exist.) References used to generate the cost data are assembled in notes to the figures.

2.7.2 Technological learning in bioenergy systems

Cost trends and technological learning in bioenergy systems are not as well described as those for solar or wind energy technologies. Recent literature, however, gives more detailed insights into the learning curves of various bioenergy systems. Table 2.17 and Figure 2.21 summarize a number of analyses that have quantified learning, expressed by learning rates (LR) and learning (or experience) curves, for three commercial biomass systems:

1. Sugarcane-based ethanol production (van den Wall Bake et al., 2009),
2. Corn-based ethanol production (Hettinga et al., 2009),
3. Wood fuel chips and CHP in Scandinavia (Junginger et al., 2005 and a number of other sources).

The LR is the rate of a unit cost decline associated with each doubling of cumulative production (see Section 10.2.5 for a more detailed discussion). For example, a LR of 20% implies that after one doubling of cumulative production, unit costs decreased by 20% of the original costs. The definition of the 'unit' depends on the study variable.

Learning curve studies have accuracy limitations (Junginger et al., 2008; see also Section 10.5.3). Yet, there are a number of general factors that drive cost reductions that can be identified: For biomass feedstocks for ethanol production such as sugar crops (sugarcane) and starch crops (corn), increasing crop yields have been the driving force behind cost reductions.

- For sugarcane, cost reductions have come from R&D efforts to develop varieties with increased sucrose content and thus ethanol yield, increasing the number of harvests from the crop ratoon (from shoots) before replanting the field, increasingly efficient manual harvesting and the use of larger trucks for transportation. More recently, mechanical harvesting of sugarcane is replacing manual harvest, increasing the amount of residues for electricity production (van den Wall Bake et al., 2009; Seabra et al., 2010).

- For the production of corn, the highest cost decline occurred in costs for capital, land and fertilizer until 2005. Additional drivers behind cost reductions were increased plant sizes through cooperatives that

Table 2.17 | Experience curves for major components of bioenergy systems and final energy carriers expressed as reduction (%) in cost (or price) per doubling of cumulative production.

Learning system	LR (%)	Time frame	Region	N	R^2
Feedstock production					
Sugarcane (tonnes sugarcane)[1]	32±1	1975–2005	Brazil	2.9	0.81
Corn (tonnes corn)[2]	45±1.5	1975–2005	USA	1.6	0.87
Logistic chains					
Forest wood chips (Sweden)[3]	12–15	1975–2003	Sweden/Finland	9	0.87–0.93
Investment and O&M costs					
CHP plants[3]	19–25	1983–2002	Sweden	2.3	0.17–0.18
Biogas plants[4]	12	1984–1998		6	0.69
Ethanol production from sugarcane[1]	19±0.5	1975–2003	Brazil	4.6	0.80
Ethanol production from corn (only O&M costs)[2]	13±0.15	1983–2005	USA	6.4	0.88
Final energy carriers					
Ethanol from sugarcane[5]	7 29	1970–1985 1985–2002	Brazil	~6.1	n.a.
Ethanol from sugarcane[1]	20±0.5	1975–2003	Brazil	4.6	0.84
Ethanol from corn[2]	18±0.2	1983–2005	USA	7.2	0.96
Electricity from biomass CHP[4]	8–9	1990–2002	Sweden	~9	0.85–0.88
Electricity from biomass[6]	15	Unknown	OECD	n.a.	n.a.
Biogas[4]	0–15	1984–2001	Denmark	~10	0.97

Notes: Abbreviations: LR: Learning Rate, N: Number of doublings of cumulative production, R^2: Correlation coefficient of the statistical data.

References: 1. van den Wall Bake et al. (2009); 2. Hettinga et al. (2009); 3. Junginger et al. (2005); 4. Junginger et al. (2006); 5. Goldemberg et al. (2004); 6. IEA (2000).

enabled higher production volumes, efficient feedstock collection, decreased investment risk through government loans and the introduction of improved efficiency natural gas-fired ethanol plants, which are responsible for nearly 90% of ethanol production in the USA (Hettinga et al., 2009). Higher yields were achieved from corn hybrids genetically modified to have higher pest resistance and increased adoption of no-till practices that improved water quality (NRC, 2010). While it is difficult to quantify the effects of these factors, it seems clear that R&D efforts (realizing better plant varieties), technology improvements and learning by doing (e.g., more efficient harvesting) played important roles.

For ethanol production, industrial costs from both sugarcane and corn mainly decreased because of increasing scales of the ethanol plants.

- Cost breakdowns of the sugarcane production process showed reductions of around 60% within all sub processes from 1975 to 2005. Ethanol production costs (excluding feedstock costs) declined by a factor of three between 1975 and 2005 (in real terms, i.e., corrected for inflation). Investment and operation and maintenance costs declined mainly due to economies of scale. Other fixed costs, such as administrative costs and taxes, did not fall dramatically, but cost reductions can be ascribed to automated administration systems. Decreased costs can be primarily ascribed to increased scales and load factors (van den Wall Bake et al., 2009).

- For ethanol from corn, the conversion costs (without costs for corn) declined by 45% from USD_{2005} 240/ m^3 in the early 1980s to USD_{2005} 130/m^3 in 2005. Costs for energy, labour and enzymes contributed in particular to the overall decline in costs. Additional drivers behind these reductions are higher ethanol yields, the introduction of automation and control technologies that require less energy and labour and the up-scaling of average dry grind plants (Hettinga et al., 2009).

2.7.3 Future scenarios of cost reduction potentials

2.7.3.1 Future cost trends of commercial bioenergy systems

For the production of ethanol from sugarcane and corn, future production cost scenarios based on direct experience curve analysis were found in the literature:

For Brazilian sugarcane ethanol (van den Wall Bake et al., 2009), total production costs in 2005 were approximately USD_{2005} 340/m^3 (USD_{2005} 16/GJ). Based on the experience curves for the cost components shown in Figure 2.21 (feedstock and ethanol without feedstock costs), total ethanol production costs in 2020 are estimated between USD_{2005} 200 and 260/m^3 (USD_{2005} 9.2 to 12.2/GJ). These costs compare well with those in Table 2.7 for Brazil with a current production cost estimate of USD_{2005} 14.8/GJ and projected 2020 cost of USD_{2005} 9 to 10/GJ. Ethanol production costs without feedstocks are in a range of USD_{2005} 139 to 183/m^3 (USD_{2005} 6.5 to 8.6/GJ) in 2005 and could reach about USD_{2005}113/m^3 (USD_{2005} 6.6/GJ) by 2020, assuming a constant 82 m^3 hydrous ethanol per t of sugarcane.

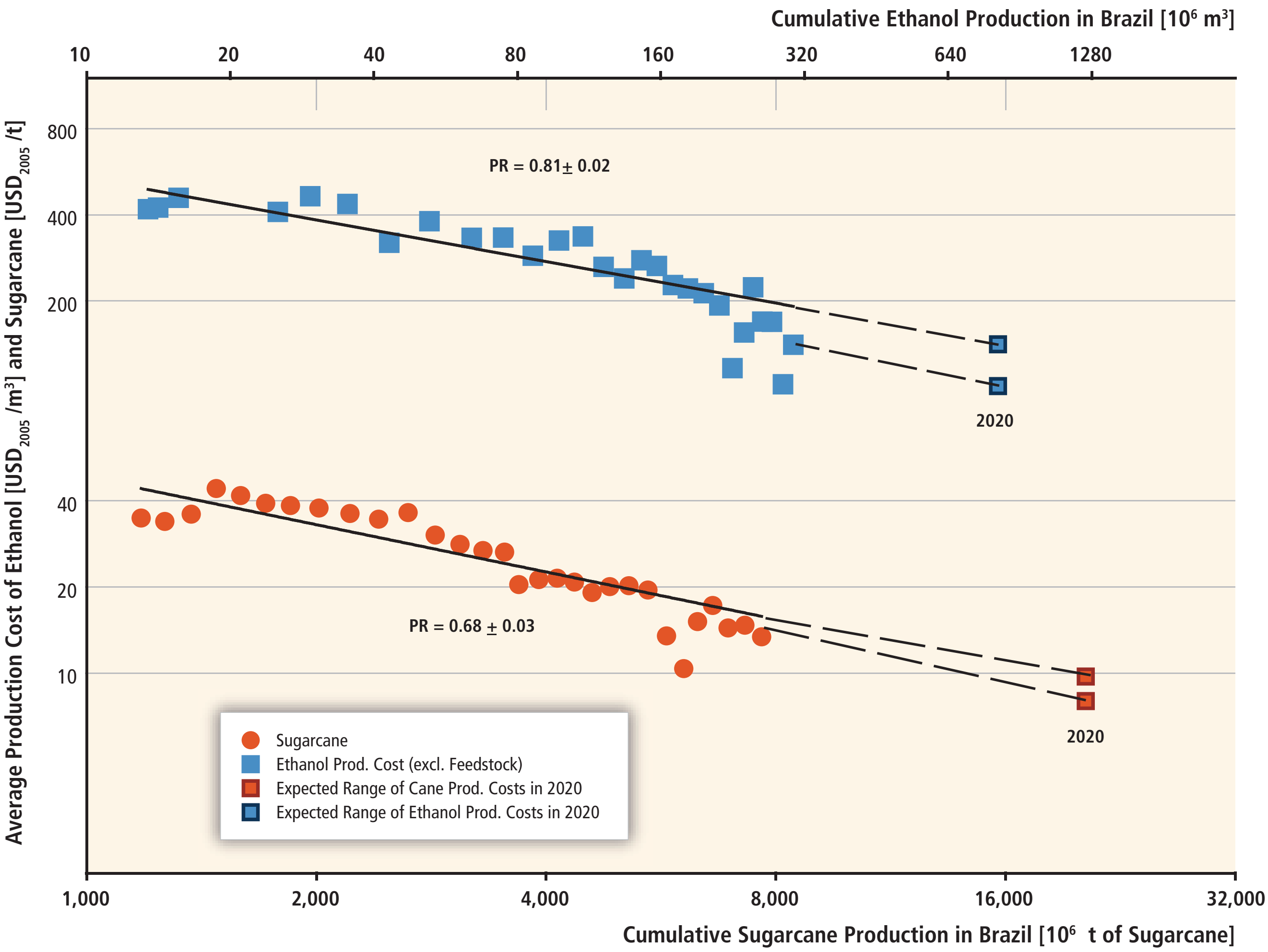


Figure 2.21 | Brazilian sugarcane and ethanol production cost learning curves for between 1975 and 2005 and extrapolated to 2020 (in USD_{2005}). Progress ratio (PR=1-LR) is obtained by best fit to data (van den Wall Bake et al., 2009; reproduced with permission from Elsevier B.V.).

For US ethanol from corn (Hettinga et al., 2009), costs of corn production and ethanol processing are estimated respectively as USD_{2005} 75/t and USD_{2005} 60 to 77/m^3 by 2020. Overall ethanol production costs could decline from a current level of USD_{2005} 310/m^3 to USD_{2005} 248/m^3 (USD_{2005} 14.7 to 11.7/GJ) by 2020. This estimate excludes the investment costs and the effect of future corn prices. The EPA (2010) Regulatory Impact Analysis of the Renewable Fuel Standard 2 modelled the current corn ethanol industry in detail and projected a decrease in total production cost from USD_{2005} 17.5 to 16/GJ by 2022 by taking into account both feedstock and process improvements listed in Table 2.7 and the anticipated co-product revenue.

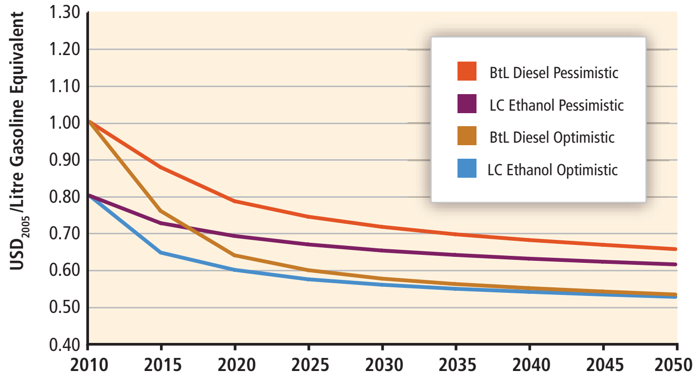
Confirming the trend and supporting the projections to 2020, Table 2.13 illustrates key indicators for environmental performance of a North American corn dry-grind natural gas-fired mill and the Brazilian sugarcane benchmark of 44 mills in terms of GHG emissions per carbon content of the biomass feedstock (displacement factor), emissions reductions relative to the reference fossil fuel in the production region (GHG savings), and a land use efficiency (volume of production per unit area) indicator. The commercial North American system's performance improved with time; for instance, using the relative GHG savings, which were 26% in 1995 and 39% in 2005, and the projected efficiency improvements through application of commercial CHP systems alone or in combination with CCS, would lead to 55 and 72% emissions savings by 2015, respectively. Similarly, the Brazilian sugarcane ethanol/electricity/sugar mill would go from 79 to 120 and 160% in relative GHG savings for the 2005-2006 baseline and the CHP and CCS scenarios, respectively.

In the Renewable Fuels for Europe project that focused on deployment of biofuels in Europe (de Wit et al., 2010; Londo et al., 2010), specific attention was paid to the effects of learning for lignocellulosic biofuels technologies on projections of future costs. The analyses showed two key points:

- Lignocellulosic biofuels have considerable potential for improvement in the areas of crop production, supply systems and the conversion technology. For conversion in particular, economies of scale are a very important element of the future cost reduction potential as specific capital costs can be reduced (partly due to improved conversion efficiency). Biomass resources may become somewhat more expensive due to a reduced share of (less costly) residues over time. It was estimated that lignocellulosic biofuel production cost could compete with gasoline and diesel from oil at USD_{2005} 60 to 70/barrel by 2030 (USD_{2005} 0.38 to 0.44/litre) (Hamelinck and Faaij, 2006).

- The penetration of lignocellulosic biofuel options depends considerably on the rate of learning. This rate is in turn dependent on increased market penetration (which allows for producing with larger production facilities), which makes the LR partly dependent on market support or mandates in earlier phases of market penetration.

The IEA Energy Technology Perspectives report (IEA, 2008a) and the WEO (IEA, 2009b) project a rapid increase in production of lignocellulosic biofuels, especially between 2020 and 2030, accounting for all incremental biomass increases after 2020. The biofuels analysis projects an almost complete phase-out of cereal- and corn-based ethanol production and edible oilseed-based biodiesel after 2030. The potential cost reductions from current demonstration projects to future commercial-scale facilities for production of specific lignocellulosic biofuels are shown in Figure 2.22. Such potential cost reductions are also quantified in Hamelinck and Faaij (2006) and van Vliet et al. (2009).



Note: BtL = Biomass-to-Liquids; LC = Lignocellulose

Figure 2.22 | Cost projections for lignocellulosic ethanol and BTL diesel (*Energy Technology Perspectives 2008*, © OECD/IEA, Figure 9.11, p. 335 in IEA (2008a); for additional future cost considerations see also Sims et al. (2008), IEA Renewable Energy Division (2010) and IEA (2011)).

2.7.3.2 Future cost trends for pre-commercial bioenergy systems

A number of bioenergy systems are evolving, as shown in Figure 2.2 and discussed in Section 2.6. The key intermediates that enable generation of bioenergy from modern biomass include syngas, sugars, vegetable oils/lipids, thermochemical oils derived from biomass (pyrolysis or other thermal treatments), and biogas. These intermediates can produce higher efficiency electricity and heat, a wider range of liquid hydrocarbon fuels, alcohols (including some with higher energy density), ethers, and chemical products and polymers (bio-based materials) in the developing biorefineries that are discussed in Section 2.6. Initial R&D on producing hydrocarbon fuels is starting with sugar and starch crops and covering the range of gasoline, diesel and higher-energy content transport fuels such as jet fuels and chemicals. Both improved first-generation crops, perennial sugarcane-derived, in particular, and second-generation plants have the potential to provide a variety of energy products suited to specific geographic regions, and high-volume chemicals and materials traditionally derived from the petrochemical industry, maximizing the outputs of end products per unit of feedstock.

Table 2.18 presents projected ranges of production costs for developing technologies such as integrated gasification combined cycle for the production of higher efficiency electricity and gasification-(syngas) derived fuels, including diesel, jet fuel, and H_2, methane, dimethyl ether and other oxygenated fuels through catalytic upgrading of the syngas. The sugar intermediates, lignocellulosic for instance, can be converted through biochemical routes to a variety of fuels with the properties of petroleum-based fuels. Similarly, pyrolysis oil-based hydrocarbon fuels are under development. Oilseed crop and tree seed oil development could also expand the range of fuel products with properties of petroleum fuels because they are readily upgraded to hydrocarbons. Finally, algae for biomass production are photosynthetic, using CO_2, water, and sunlight to biologically produce a variety of carbohydrates, lipids, plastics, chemicals or fuels like H_2, along with oxygen. In addition, heterotrophic microbes, such as certain algae are engineered to metabolize sugars and excrete lipids in the dark. Microorganisms or their consortia can consolidate various processing steps; genetically engineered yeasts or bacteria can make specific fuel products, including hydrocarbons and lipids, developed either with tools from synthetic biology or through metabolic engineering (see also IEA, 2011).

2.7.4 Synthesis

Despite the complexities of determining the economic performance and regional specificities of bioenergy systems, several key conclusions can be drawn from available experiences and literature:

- Several important bioenergy systems today can be deployed competitively, most notably sugarcane-based ethanol and heat and power generation from residues and waste.

- Although not all bioenergy options discussed in this chapter have been investigated in detail with respect to technological learning, several important bioenergy systems have reduced their cost and improved environmental performance over time. These systems still

Table 2.18 | Projected production cost ranges estimated for developing technologies (see Section 2.6.3).

Selected Bioenergy Technologies	Energy Sector (Electricity, Thermal, Transport)*	2020-2030 Projected Production Costs (USD_{2005}/GJ)
IGCC [1]	Electricity and/or transport	12.8–19.1 (4.6–6.9 cents/kWh)
Oil plant-based renewable diesel and jet fuel	Transport and electricity	15–30
Lignocellulose sugar-based biofuels[2]	Transport	6–30
Lignocellulose syngas-based biofuels[3]		12–25
Lignocellulose pyrolysis-based biofuels[4]		14–24 (fuel blend components)
Gaseous biofuels[5]	Thermal and transport	6–12
Aquatic plant-derived fuels, chemicals	Transport	30–140

Notes: 1. Feed cost USD_{2005} 3.1/GJ, IGCC (future) 30 to 300 MW, 20-yr life, 10% discount rate; 2. ethanol, butanols, microbial hydrocarbons from sugar or starch crops or lignocellulose sugars; 3. syndiesel, methanol and gasoline, etc.; syngas fermentation routes to ethanol; 4. biomass pyrolysis (or other thermal treatment) and catalytic upgrading to gasoline and diesel fuel blend components or to jet fuels; 5. synfuel to SNG, methane, dimethyl ether, or H_2 from biomass thermochemical and anaerobic digestion (larger scale). *Several applications could be coupled with CCS when these technologies, including CCS, are mature and thus could remove GHGs from the atmosphere.

require government subsidies that are put in place for economic development, poverty reduction, a secure and diverse energy supply, and other reasons.

- There is clear evidence that further improvements in power generation technologies, production of perennial cropping systems and development of supply systems can bring the costs of power (and heat) generation from biomass down to attractive cost levels in many regions. With the deployment of carbon taxes of up to USD_{2005} 50/t, biomass can, in many cases, also be competitive with coal-based power generation. Nevertheless, the competitive production of bio-electricity depends also on the performance of alternatives such as wind and solar energy, CCS coupled with coal, and nuclear energy (see Section 10.2.2.4 and Chapter 8).

- Bioenergy systems for ethanol and biopower production show technological learning and related cost reductions with LRs comparable to those of other RE technologies. This applies to cropping systems (following progress in agricultural management of annual crops), supply systems and logistics (as clearly observed in Scandinavia, as well as international logistics) and in conversion (ethanol production, power generation and biogas).

- With respect to lignocellulosic biofuels, recent analyses have indicated that the improvement potential is large enough to make them competitive with oil prices of USD_{2005} 60 to 70/barrel (USD 0.38 to 0.44/litre). Currently available scenario analyses indicate that if shorter-term R&D and market support are strong, technological progress could allow for commercialization around 2020 (depending on oil price developments and level of carbon pricing). Some scenarios also indicate that this would mean a major shift in the deployment of biomass for energy, because competitive production would decouple deployment from policy targets (mandates) and demand for biomass would move away from food crops to biomass residues, forest biomass and perennial cropping systems. The implications of such a (rapid) shift have not been studied.

- Data about the production of biomaterials and cost estimates for chemicals from biomass are rare in peer-reviewed literature. Future projections and LRs are even rarer, because successful bio-based products are just now entering the market place. Two examples are as partial components of otherwise fossil-derived products (e.g., poly(1,3)-propylene terephthalates based on 1,2-propanediol derived from sugar fermentation) or as fully new synthetic polymers such as polylactides based on lactic acid derived from sugar fermentation. This is also the case for biomass conversion coupled with CCS (see Section 2.6.3.3) concepts, which are not developed at present and for which cost trends are not available in literature. CO_2 from ethanol fermentation is commercially sold to carbonate beverages, flash freeze meats or enhance oil recovery, and demonstrations of CCS are ongoing (see Section 2.6.3.3). Nevertheless, recent scenario analyses indicate that advanced biomaterials (and cascaded use of biomass) as well as other biomass conversion coupled to CCS may become attractive medium-term mitigation options. It is therefore important to gain experience so that more detailed analyses on those options can be conducted in the future.

2.8 Potential Deployment[76]

2.8.1 Current deployment of bioenergy

Modern biomass use (for electricity and CHP for the power sector; modern residential, commercial, and public buildings heating; or transport fuels) already provides a significant contribution of about 11.3 EJ (see Table 2.1; IEA, 2010a,b) out of the 2008 TPES from biomass of 50.3 EJ. Between 60 and 70% of the total biomass supply is used in rural areas and relates to charcoal, wood, agricultural residues and manure used for cooking, lighting and space heating, generally by the poorer part of the population in developing countries. From 1990 to 2008, the

76 Complementary perspectives on potential deployment based on a comprehensive assessment of numerous model-based scenarios of the energy system are presented in Sections 10.2 and 10.3 of this report.

average annual growth rate of solid biomass use for bioenergy was 1.5%, while the average annual growth rate of modern liquid and gaseous biofuels use was 12.1 and 15.4%, respectively, during the same period (IEA, 2010c). As a result, biofuels' share of global road transport fuels was about 2% in 2008; and nearly 3% of global road transport fuels in 2009, as oil demand decreased for the first time since 1980 (IEA, 2010b). Government policies in various countries fostered the five-fold increase in global biofuels production from 2000 to 2008. Biomass and renewable waste power generation was 259 TWh (0.93 EJ) in 2007 and 267 TWh (0.96 EJ) in 2008, representing 1% of the world's electricity and a doubling since 1990 (from 131 TWh, 0.47 EJ) (Section 2.4.1). Modern bioenergy heating applications, including space and hot water heating systems such as for district heating, account for 3.4 EJ (see Table 2.1 and Section 2.4.1).

International trade in biomass and biofuels has also become much more important over the recent years, with roughly 6% (reaching levels of up to 9% in 2008) of biofuels (ethanol and biodiesel only) traded internationally and one-third of pellet production dedicated to energy use in 2009 (Figures 2.8 and 2.9; Junginger et al., 2010; Lamers et al., 2010; Sikkema et al., 2011). The latter has proven to be an important facilitating factor in both increased utilization of biomass in regions where supplies are constrained and mobilizing resources from areas where demand is lacking.

The policy context for bioenergy and particularly biofuels has changed rapidly and dramatically since the mid-2000s in many countries. The food versus fuel debate and growing concerns about other conflicts created a strong push for the development and implementation of sustainability criteria and frameworks and changes in temporization of targets for bioenergy and biofuels. Furthermore, the support for advanced biorefinery and second-generation biofuel options drives bioenergy in more sustainable directions.

Nations like Brazil, Sweden, Finland and the USA have shown that persistent and stable policy support is a key factor in building biomass production capacity and working markets, required competitive infrastructure and conversion capacity (see also Section 2.4) and results in considerable economic activity.

2.8.2 Near-term forecasts

Countries differ in their priorities, approaches, technology choices and support schemes for bioenergy development. Although on the one hand complex for the market, this is also a reflection of the many aspects that affect bioenergy deployment: agriculture and land use; forestry and industry development; energy policy and security; rural development; and environmental policies. Priorities, the stage of technology development, and access to, availability of and cost of resources differ widely from country to country and in different settings.

The near-term forecasts reflect that the policies already in place, as shown in Table 2.11, are driving current forecasts. For instance, the WEO (IEA, 2010b) projects that the bioenergy industry will continue the growth observed in the past five years and reach about 60 EJ by 2020 in the Current Policies scenario (which replaces the former Reference scenario), with slightly higher levels of up to 63 EJ in the more ambitious New Policies and 450-ppm CO_2 scenarios (Section 2.4.1). Considering the 2008 starting point at 50 EJ/yr, this represents a 10 to 13 EJ increase in bioenergy consumption over 10 years. Much of the increase happens in the transport sector, with biofuel consumption starting from 2.1 EJ in 2009 and increasing to 4.5 to 5.1 EJ in 2020 in the three presented scenarios. Most of this growth is therefore already expected due to existing policies, and additional growth relying on new policies is expected to only foster an additional 10% increase. The global primary biomass supply (efficiency of about 65% for first-generation biofuels) needed to deliver this amount of biofuels ranges between 7.4 and 8.4 EJ. The increase at the global level goes along with further regional diversification of biofuels adoption. While the currently dominant biofuels markets in Brazil, the USA and the EU are projected to roughly double consumption by 2020, many other regions with very little or no biofuels consumption currently are expected to adopt biofuel policies, resulting in significant growth, most notably in Asia. Electricity generation increases by 85% from 265 TWh/yr (0.96 EJ/yr) in 2008 to 493 TWh/yr (1.8 EJ/yr) in the Current Policies scenario, again with relatively modest additional growth (20%) in the more ambitious policy scenarios (up to 594 TWh/yr or 2.1 EJ/yr) (Table 2.10).

2.8.3 Long-term deployment in the context of carbon mitigation

The AR4 (IPCC, 2007d) demand projections for primary biomass for production of transportation fuel were largely based on WEO (IEA, 2006) global projections, with a relatively wide range of about 14 to 40 EJ of primary biomass, or 8 to 25 EJ of biofuels in 2030. However, higher estimates were also included, in the range of 45 to 85 EJ of demand for primary biomass for electricity generation in 2030 (equivalent to roughly 30 to 50 EJ of biofuel). Demand for biomass for heat and power was stated to be strongly influenced by (availability and introduction of) competing technologies such as CCS, nuclear power and non-biomass RE. The demand in 2030 for biomass was estimated in the AR4 to be around 28 to 43 EJ. These estimates focus on electricity generation. Heat was not explicitly modelled or estimated in the WEO (on which the AR4 was based); therefore it underestimates total demand for biomass. Also, potential future demand for biomass in industry (especially new uses such as biochemicals, but also expansion of charcoal use for iron and steel production) and the built environment (heating as well as increased use of biomass as building material) was highlighted as important, but no quantitative projections were included in potential demand for biomass at the medium or longer term.

A summary of the literature on the possible future contribution of RE supplies in meeting global energy needs under a range of GHG stabilization scenarios is provided in Chapter 10. Focussing specifically on bioenergy, Figure 2.23 presents modelling results for global primary energy supply from biomass (a) and global biofuels production in secondary energy terms (b). Between about 100 and 140 different long-term scenarios underlie Figure 2.23 (Section 10.2). These scenario results derive from a diversity of modelling teams and cover a wide range of assumptions about—among other variables—energy demand growth, the cost and availability of competing low-carbon technologies and the cost and availability of RE technologies (including bioenergy). A description of the literature from which the scenarios have been taken (Section 10.2.2) and how changes in some of these variables impact RE deployment outcomes are displayed in Figure 10.9.

in most scenarios, which means that modern use of biomass as liquid biofuels, biogas, and electricity and H_2 produced from biomass tends to increase even more strongly than suggested by the above primary energy numbers. This trend is also illustrated by the example of liquid biofuels production shown in the right panel of Figure 2.23(b). With increasingly ambitious GHG concentration stabilization levels, bioenergy supply increases, indicating that bioenergy could play a significant long-term role in reducing global GHG emissions. The median levels of biomass deployment for energy in the most stringent mitigation categories I and II (<440 ppm atmospheric CO_2 concentration by 2100) increase significantly compared to the baseline levels to 63, 85 and 155 EJ/yr by 2020, 2030 and 2050, respectively.

Despite these robust trends, there is by no means an agreement about

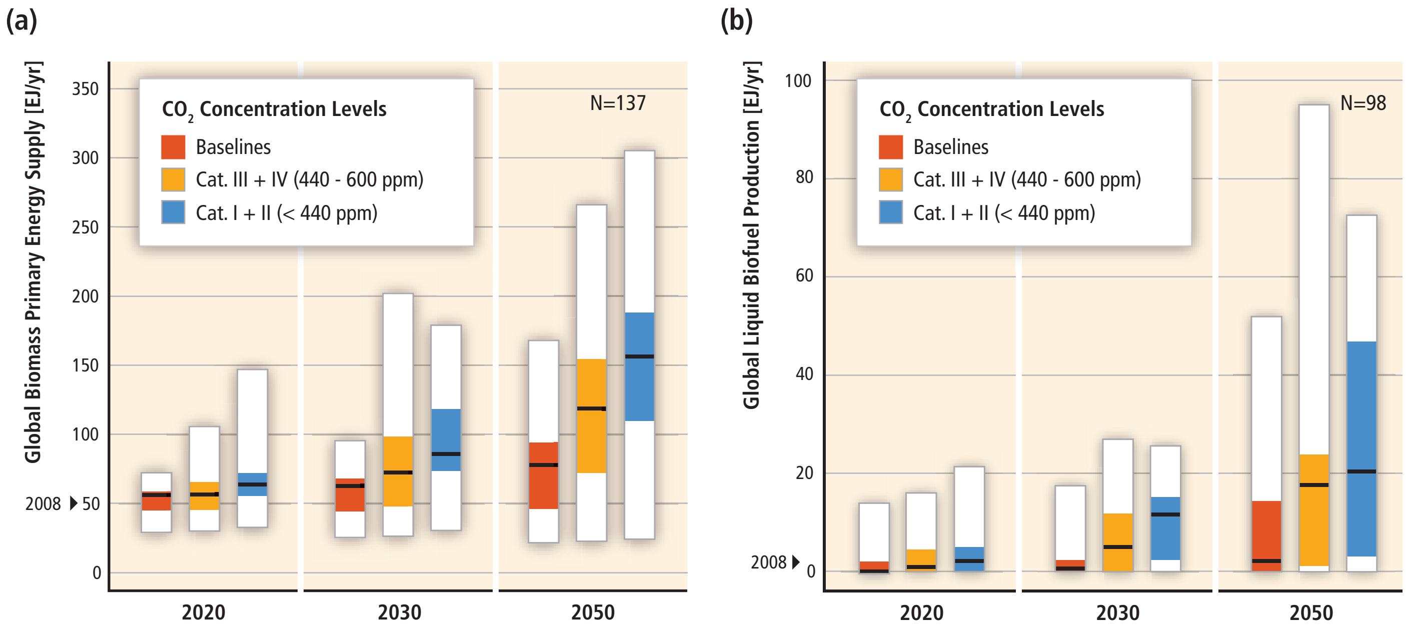
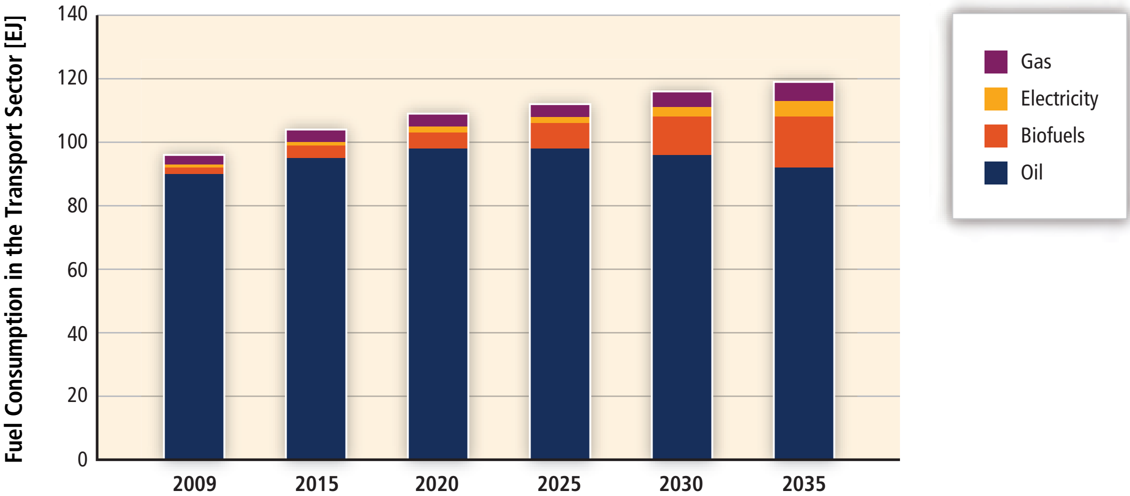


Figure 2.23 | (a) The global primary energy supply from biomass in long-term scenarios; (b) global biofuels production in long-term scenarios reported in secondary energy terms of the delivered product (median, 25th to 75th percentile range and full range of scenario results; colour coding is based on categories of atmospheric CO_2 concentration levels in 2100; the number of scenarios underlying the figure is indicated in the right upper corner) (adapted from Krey and Clarke, 2011). For comparison, the historic levels in 2008 are indicated by the small black arrows on the left axis.

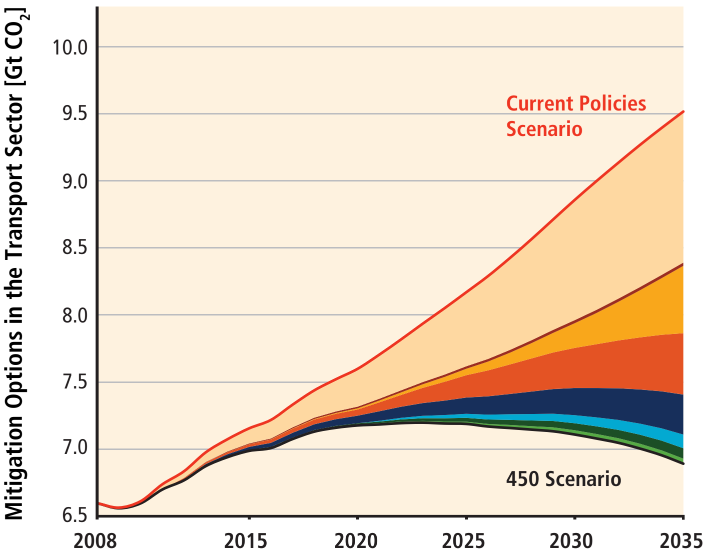
In Figure 2.23, the results for biomass deployment for energy under these scenarios for 2020, 2030 and 2050 are presented for three GHG stabilization ranges based on the AR4: Categories I and II (<440 ppm CO_2), Categories III and IV (440-600 ppm CO_2) and Baselines (>600 ppm CO_2) all by 2100. Results are presented for the median scenario, the 25th to 75th percentile range among the scenarios, and the minimum and maximum scenario results. Figure 2.23(a) shows a clear increase in global primary energy supply from biomass over time in the baseline scenarios, that is, absent climate policies, reaching about 55, 62 and 77 EJ/yr in the median cases by 2020, 2030 and 2050, respectively. At the same time, traditional use of solid biomass is projected to decline

the precise future role of bioenergy across the scenarios, leading to fairly wide deployment ranges in the different GHG stabilization categories. For 2030, primary biomass supply estimates for energy vary (rounded) between 30 and 200 EJ for the full range of results obtained. The 25th to 75th percentiles cover a range of 45 to 120 EJ, with a comparatively narrower range of 44 to 67 EJ/yr in the baselines and much wider ranges of 47 to 98 EJ/yr in the 440 to 600 ppm stabilization category and 73 to 120 EJ/yr in the <440 ppm category. By 2050, the contribution of biomass to primary energy supply in the two GHG stabilization categories ranges from 70 to 120 EJ/yr at the 25th percentile to about 150 to 190 EJ/yr at the 75th percentile, and to about 265-300 EJ/yr in the highest ranges. It should be noted that the net GHG mitigation impact of

(a)



(b)



	Abatement 2020	Abatement 2030	Abatement 2035
Road	83%	80%	80%
Increased Efficiency	67%	51%	43%
Switch to Gas	3%	1%	1%
Switch to Electricity	2%	11%	19%
Switch to Biofuels	11%	17%	17%
Aviation	14%	15%	15%
Increase Efficiency	14%	12%	11%
Switch to Biofuels	0%	3%	4%
Navigation	2%	3%	3%
Other Transport	2%	2%	1%
Total [Gt CO_2]	0.4	1.7	2.6

Figure 2.24 | (a) Evolution of fuel consumption in the transport sector including biofuels (*World Energy Outlook 2010*, © OECD/IEA, figure 14.12, page 429 in IEA (2010b)) and (b) shares of carbon mitigation by various technologies including biofuels for road and aviation transport from current policies baseline (upper red line) to the 450 ppm bottom curve of the mitigation scenario. (*World Energy Outlook 2010*, © OECD/IEA, figure 14.14, page 432 in IEA (2010b))

bioenergy deployment is not straightforward because different options result in different GHG savings, and savings depend on how land use is managed, which is a central reason for the wide ranges in the stabilization scenarios.

The sector-level penetration of bioenergy is best explained using a model with detailed transport sector representation such as the WEO (IEA, 2010b) that is also modelling both traditional and modern biomass applications, and includes second-generation biofuels evolution. Additionally, the WEO model takes into account anticipated industrial and government investments and goals. It projects very significant increases in modern bioenergy and a decrease in traditional biomass use, in qualitative agreement with the results from Chapter 10. By 2030, for the 450-ppm mitigation scenario, the model projects that 11% of global transport fuels will be provided by biofuels with second-generation biofuels contributing 60% of the projected 12 EJ, and half of this production is projected to be supplied owing to continuation of current policies (see Table 2.9). Biomass and renewable wastes would supply 5% of the world's electricity generation, or 1,380 TWh/yr (5 EJ/yr) of which 555 TWh/yr (2 EJ/yr) result from the 450 ppm strategy by 2030 (see Table 2.10). Biomass industrial heating applications for process steam and space and hot water heating for buildings would each double in absolute terms from 2008 levels. However, the total heating demand is projected to decrease because of assumed traditional biomass decline. Heating is seen as a key area for continued modern bioenergy growth.

The evolution of biofuels in the transport sector is shown in Figure 2.24a. Biofuels penetration is projected to be significant in both in global road transport and in air transport. Second-generation technologies are projected to provide 66% of the biofuels by 2035 and 14% of world transport energy demand in the 450-ppm scenario (see Figure 2.24a and Table 2.9). Figure 2.24b shows the projected GHG emissions mitigation of biofuels relative to projected road and air transport applications from the current policies to the 450 ppm scenario. For instance, by 2030, 17% of road transport emissions and 3% of air transport emissions could be mitigated by biofuels in the 450-ppm stabilization scenario. A biofuels technology roadmap was recently developed (IEA, 2011).

The potential demand of biomass for materials is not explicitly addressed by many of the scenarios, but it could become significant and add up to several dozens of EJ (Section 2.6.3.5; Hoogwijk et al., 2003).

The expected deployment of biomass for energy in the 2020 to 2050 time frame differs considerably between studies, also due to varying detail in bioenergy system representation in the relevant models. A key message from the review of available insights is that large-scale biomass deployment strongly depends on sustainable development of the resource base, governance of land use, development of infrastructure and cost reduction of key technologies, for example, efficient and complete use of primary biomass for energy from the most promising first-generation feedstocks and second-generation lignocellulosic biomass. The results discussed above are consistent with the *Energy Technology Perspectives* report (IEA, 2008a), which projects a rapid penetration of second-generation biofuels after 2010 and an almost complete phase-out of cereal- and corn-based ethanol production and oilseed-based biodiesel after 2030.[77]

2.8.4 Conditions and policies: Synthesis of resource potentials, technology and economics, and environmental and social impacts of bioenergy

2.8.4.1 Resource potentials

The inherent complexity of biomass resources makes the assessment of their combined technical potential controversial and difficult to characterize. Literature studies range from zero (no biomass potential available as energy) to around 1,500 EJ, the theoretical potential for terrestrial biomass based on modelling studies exploring the widest potential ranges of favourable conditions (Smeets et al., 2007).

Figure 2.25 presents a summary of technical potential found in major studies, including potential deployment data from the scenario analysis of Chapter 10 compared to global TPES (projections). To put technical potential in perspective, because global biomass used for energy currently amounts to approximately 50 EJ/yr, and all harvested biomass used for food, fodder, fibre and forest products, when expressed in equivalent heat content, equals 219 EJ/yr (2000 data, Krausmann et al., 2008), the entire current global biomass harvest would be required to achieve a 200 EJ/yr deployment level of bioenergy by 2050 (Section 2.2.1).

From a detailed assessment, the upper-bound technical potential of biomass was about 500 EJ with a minimum of about 50 EJ in the case that even residues had significant competition with other uses. The assessment of each contributing category performed by Dornburg et al. (2008, 2010) was based on literature up to 2007 (stacked bar of Figure 2.25) and is roughly in line with the conditions sketched in the IPCC SRES A1 and B1 storylines (IPCC, 2000), assuming sustainability and policy frameworks to secure good governance of land use and major improvements in agricultural management (summarized in Figure 2.26). The resources used are:

- Residues originating from forestry, agriculture and organic wastes (including the organic fraction of MSW, dung, process residues etc.) were estimated at around 100 EJ/yr. This part of the technical potential of biomass supply is relatively certain, but competing applications may push net availability for energy applications to the lower end of the range.

- Surplus forestry other than from forestry residues had an additional technical potential of about 60 to 100 EJ/yr.

- Biomass produced via cropping systems had a lower range estimate for energy crop production on possible surplus good quality agricultural and pasture lands of 120 EJ/yr. The potential contribution of water-scarce, marginal and degraded lands could amount to an additional 70 EJ/yr, corresponding to a large area where water scarcity provides limitations and soil degradation is more severe. Assuming strong learning in agricultural technology leading to improvements in agricultural and livestock management would add 140 EJ/yr.

Adding these categories together leads to a technical potential of up to about 500 EJ in 2050, with temporal data on the development of biomass potential ramping from 290 to 320 EJ/yr in 2020 to 330 to 400 EJ/yr in 2030 (Hoogwijk et al., 2005, 2009; Dornburg et al., 2008, 2010).

From the expert review of available scientific literature in this chapter, *potential deployment levels of biomass for energy by 2050 could be in the range of 100 to 300 EJ* (Sections 2.2.1, 2.2.2, and 2.2.5).

Values in this range are described in van Vuuren et al. (2009), which focused on an intermediate development scenario within the SRES scenario family. The lower estimates of Smeets et al. (2007) and Hoogwijk et al. (2005, 2009) are in line with those figures, and further confirmation for such a range is given by Beringer et al. (2011), who report a 26 to 116 EJ range for energy crops alone in 2050 without irrigation (and 52 to 174 EJ with irrigation), and Haberl et al. (2010), who report 160 to 270 EJ/yr in 2050 across all biomass categories. Krewitt et al. (2009), following Seidenberger et al. (2008), also estimated the technical potential to be 184 EJ/yr in 2050 using strong sustainability

77 Contrast these projections with the 2007 and 2008 WEO studies (IEA, 2007b, 2008b), where second-generation biofuels were excluded from the scenario analysis and thus biofuels at large played a marginal role in the 2030 projections.

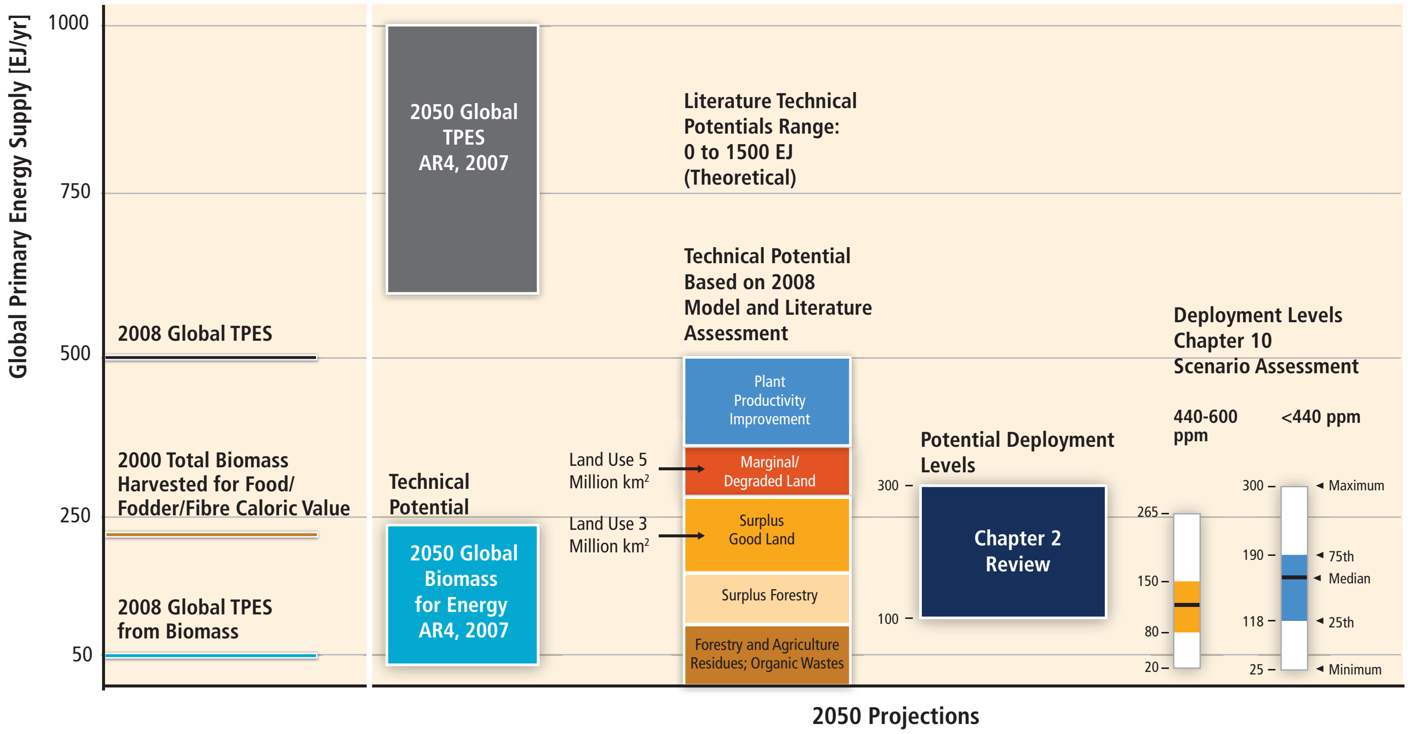


Figure 2.25 | On the left-hand side, the lines represent the 2008 global primary energy supply from biomass, the primary energy supply, and the equivalent energy of the world's total harvest for food, fodder and fibre in 2000. A summary of major global 2050 projections of primary energy supply from biomass is shown from left to right: (1) The global AR4 (IPCC, 2007d) estimates for primary energy supply and technical potential for primary biomass for energy; (2) the theoretical primary biomass potential for energy and the upper bound of biomass technical potential based on integrated global assessment studies using five resource categories indicated on the stacked bar chart and limitations and criteria with respect to biodiversity protection, water limitations, and soil degradation, assuming policy frameworks that secure good governance of land use (Dornburg et al., 2010, reproduced with permission from the Royal Society of Chemistry); (3) from the expert review of available scientific literature, potential deployment levels of terrestrial biomass for energy by 2050 could be in the range of 100 to 300 EJ; and (4) deployment levels of biomass for energy from long-term scenarios assessed in Chapter 10 in two cases of climate mitigation levels (CO_2 concentrations by 2100 of 440 to 600 ppm (orange) or <440 ppm (blue) bars or lines, see Figure 2.23(a)). Biomass deployment levels for energy from model studies described in (4) are consistent with the expert review of potential biomass deployment levels for energy depicted in (3).The most likely range is 80 to 190 EJ/yr with upper levels in the range of 265 to 300 EJ/yr.

criteria and including 88 EJ/yr from residues. They project a ramping-up to this potential from around 100 EJ/yr in 2020 and 130 EJ/yr in 2030.

The expert review conclusions based on available scientific literature (Sections 2.2.2 through 2.2.5) are:

- Important uncertainties include:
  - Population and economic/technology development; food, fodder and fibre demand (including diets); and development in agriculture and forestry;
  - Climate change impacts on future land use including its adaptation capability (IPCC, 2007a; Lobell et al., 2008; Fischer et al., 2009); and
  - Extent of land degradation, water scarcity, and biodiversity and nature conservation requirements (Molden, 2007; Bai et al., 2008; Berndes, 2008a,b; WBGU, 2009; Dornburg et al., 2010; Beringer et al., 2011).
- Residue flows in agriculture and forestry and unused (or extensively used thus becoming marginal/degraded) agricultural land are important sources for expansion of biomass production for energy, both in the near and longer term. Biodiversity-induced limitations and the need to ensure maintenance of healthy ecosystems and avoid soil degradation set limits on residue extraction in agriculture and forestry (Lal, 2008; Blanco-Canqui and Lal, 2009; WBGU, 2009).
- The cultivation of suitable (especially perennial) crops and woody species can lead to higher technical potential. These crops can produce bioenergy on lands less suited for the cultivation of conventional food crops that would also lead to larger soil carbon emissions than perennial crops and woody species. Multi-functional land use systems with bioenergy production integrated into agriculture and forestry systems could contribute to biodiversity conservation and help restore/maintain soil productivity and healthy ecosystems (Hoogwijk et al., 2005; Berndes et al., 2008; Folke et al., 2009; IAASTD, 2009; Malézieux et al., 2009; Dornburg et al., 2010).

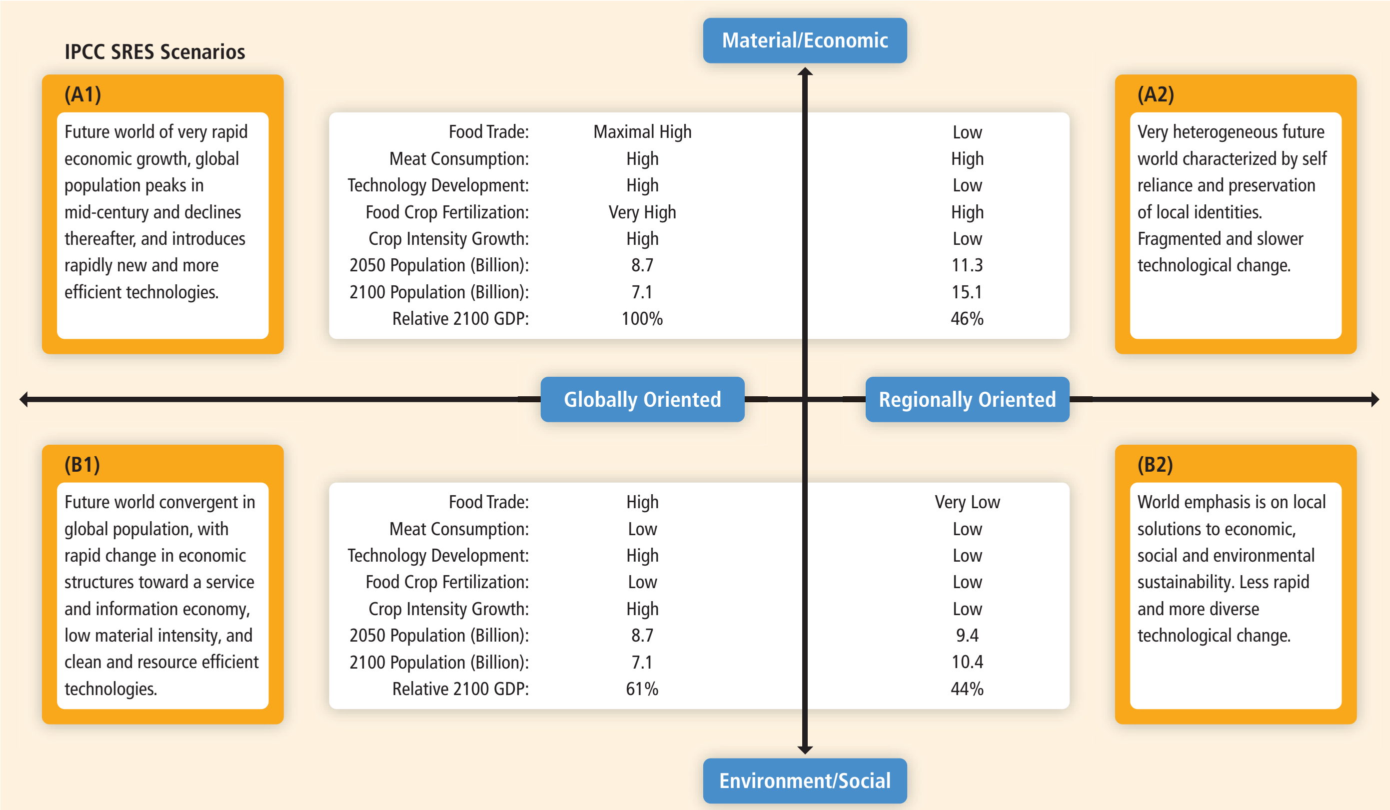


Figure 2.26 | Storylines for the key scenario variables of the IPCC SRES (IPCC, 2000) used to model biomass and bioenergy by Hoogwijk et al. (2005, reproduced with permission from Elsevier B.V.), the basis for the 2050 sketches adapted for this report and used to derive the stacked bar showing the upper bound of the biomass technical potential for energy in Figure 2.25.

- Regions experiencing water scarcity may have limited production. The possibility that conversion of lands to biomass plantations reduces downstream water availability needs to be considered. The use of suitable energy crops that are drought tolerant can help adaptation in water-scarce situations. Assessments of biomass resource potentials need to more carefully consider constraints and opportunities in relation to water availability and competing uses (Jackson et al., 2005; Zomer et al., 2006; Berndes et al., 2008; de Fraiture and Berndes, 2009).

To reach the *upper range of the deployment level* of 300 EJ/yr shown in Figure 2.25 would require major policy efforts, especially targeting improvements and efficiency increases in the agricultural sector and good governance, such as zoning, of land use.

Review scenario studies (as included in Dornburg et al., 2008) that calculate the amount of biomass used if energy demands are supplied cost-efficiently for different carbon tax regimes estimate that in 2050, between about 50 and 250 EJ/yr of biomass are used (cf. Figure 2.25). This is roughly in line with the scenarios reviewed in Chapter 10 (see Figure 2.23, which shows that the maximum demand is 300 EJ and the median value is about 155 EJ; note that the high end is only reached under the stringent mitigation scenarios of Categories I+II (<440 ppm CO_2) only).

2.8.4.2 Bioenergy technologies, supply chains and economics

A wide array of technologies and bioenergy systems exist to produce heat, electricity and fuels for transport, at commercial or development stages. Furthermore, biomass conversion to energy can be integrated with the production of biomaterials and biochemicals in cascading schemes that maximize the outputs of end products per unit input feedstock and land used.

The key currently commercial technologies are heat production at scales ranging from home cooking to district heating; power generation from biomass via combustion, CHP, or co-firing of biomass and fossil fuels; and first-generation liquid biofuels from oil crops (biodiesel) and sugar and starch crops (ethanol).

Modern biomass systems involve a wide range of feedstock types, including dedicated crops or trees, residues from agriculture and forestry, and various organic waste streams. Existing bioenergy systems rely mostly on wood, residues and waste for heat and power production and agricultural crops for liquid biofuels. The economics and yields of feedstocks vary widely across world regions and feedstock types. Energy yields per unit area range from 16 to 200 GJ/ha (1.6 to 20.0 TJ/km^2) for crops and oil seeds (biofuel feedstocks), from 80 to 415 GJ/ha (8.0 to 41.5 TJ/km^2) for lignocellulosic biomass, and from 2 to 155 GJ/ha

(0.2 to 15.5 TJ/km[2]) for residues, while costs range from USD_{2005} 0.9 to 16/GJ (data from 2005 to 2007). Feedstock production competes with the forestry and food sectors, but integrated production systems such as agro-forestry or mixed cropping may provide synergies along with additional environmental services.

Handling and transport of biomass from production sites to conversion plants may contribute 20 to up to 50% of the total costs of biomass production. Factors such as scale increase, technological innovations and increased competition contributed to decrease the economic and energy costs of supply chains by more than 50%. Densification via pelletization or briquetting is required for transportation distances over 50 km. Charcoal made from biomass is a major fuel in developing countries, and it should benefit from the adoption of higher-efficiency kilns.

Different end-use applications require that biomass be processed through a variety of conversion steps depending on the physical nature and the chemical composition of feedstocks. Costs vary by world regions, feedstock types, feedstock supply costs for conversion processes, the scale of bioenergy production, and production time during the year. Examples of estimated commercial bioenergy levelized cost ranges are roughly USD 2 to 48/GJ for liquid and gaseous biofuels; roughly US $cents_{2005}$ 3.5 to 25/kWh (USD_{2005} 10 to 50/GJ) for electricity or CHP systems larger than about 2 MW (with feedstock costs of USD_{2005} 3/GJ based on high heating value and a heat value of USD_{2005} 5/GJ (steam) or USD_{2005} 12/GJ (hot water)); and roughly USD_{2005} 2 to 77/GJ for domestic or district heating systems with feedstock costs in the range of USD_{2005} 0 to 20/GJ (solid waste to wood pellets). These calculations refer to 2005 to 2008 data and are expressed in USD_{2005} at a 7% discount rate. Several bioenergy systems have deployed competitively, most notably sugarcane ethanol and heat and power generation from wastes and residues. Other biofuels have also undergone cost and environmental impact reductions but still require government subsidies.

In the medium term, the performance of existing bioenergy technologies can still be improved considerably, while new technologies offer the prospect of more efficient and competitive deployment of biomass for energy (as well as materials). Bioenergy systems, namely for ethanol and biopower production, show rates of technological learning and related cost reductions with learning comparable to those of other RE technologies. This applies to cropping systems (following progress in agricultural management when annual crops are concerned), to supply systems and logistics (as clearly observed in Scandinavia, as well as international logistics) and in conversion (e.g., ethanol production, power generation and biogas). Although not all bioenergy options discussed in this chapter have been investigated in detail with respect to technological learning, several important bioenergy systems have reduced their cost and improved environmental performance (Sections 2.3.4.2 and 2.7.2; Table 2.13). However, they usually still require government subsidies provided for economic development, poverty reduction and a secure energy supply or other country-specific reasons.

There is clear evidence that further improvements in power generation technologies (e.g., via biomass IGCC technology), supply systems for biomass, and production of perennial cropping systems can bring the costs of power (and heat or fuels) generation from biomass down to attractive cost levels in many regions. Nevertheless, the competitive production of bio-electricity (through methane or biofuels) depends on the integration with the end-use systems (Sections 8.2 and 8.3), performance of alternatives such as wind and solar energy, developing CCS technologies coupled with coal conversion, and nuclear energy (Sections 10.2.2.4, 10.2.2.6, 9.3, and 9.4). The implications of successful deployment of CCS in combination with biomass conversion could result in removal of GHG from the atmosphere and attractive mitigation cost levels but have so far received limited attention (Section 2.6.3.3).

With respect to lignocellulosic biofuels, recent analyses have indicated that the improvement potential is large enough for competition with oil at oil prices of USD_{2005} 60 to 80/barrel (USD_{2005} 0.38 to 0.44/litre). Currently available scenario analyses indicate that if shorter-term R&D and market support is strong, technological progress could allow for their commercialization around 2020 (depending on oil and carbon prices). Some scenarios also indicate that this would mean a major shift in the deployment of biomass for energy, because competitive production would decouple deployment from policy targets (mandates), and demand for biomass would move away from food crops to biomass residues, forest biomass and perennial cropping systems. The implications of such a (rapid) shift are so far poorly studied.

Integrated biomass gasification is a major avenue for the development of a variety of biofuels, with equivalent properties to gasoline, diesel and jet fuel (see Table 2.15.C for composition of hydrocarbon fuels). An option highlighted as promising in the literature is fuel product generation passing syngas through the catalytic reactor only once with the unreacted gas going to the power generation system instead of being recycled through the catalytic reactor. Other hybrid biochemical and thermochemical concepts have also been contemplated (Laser et al., 2009). Biomass pyrolysis routes and hydrothermal concepts are also developing in conjunction with the oil industry and have demonstrated that upgrading of oils to blendstocks of gasoline or diesel or even jet fuel quality products is technically possible (IATA, 2009).

Lignocellulosic ethanol development and demonstration continues in several countries. A key development step is pretreatment to overcome the recalcitrance of the cell wall of woody, herbaceous or agricultural residues to release the simple sugar components of biomass polymers and lignin. A review of the progress in this area suggests that a 40% reduction in cost could be expected by 2025 from process improvements, which would bring down the estimated cost of pilot plant production from USD_{2005} 18 to 22/GJ to USD_{2005} 12 to 15/GJ (Hamelinck et al., 2005a; Foust et al., 2009; NRC, 2009a) and into a competitive range.

Photosynthetic organisms, such as algae, use CO_2, water, and sunlight to biologically produce a variety of carbohydrates and lipids, chemicals, fuels like H_2, other molecules and oxygen with high photosynthetic efficiency and possibly high potentials (Sections 2.6.1, 3.3.5 and 3.7.6). Estimates of potential bioenergy supply from aquatic plants are very uncertain because of the lack of sufficient data for their assessment (Kheshgi et al., 2000; Smeets et al., 2009). Nevertheless these species need to be explored further because their development can utilize brackish waters and heavily saline soils and thus represent a strategy for low LUC impacts (Chisti, 2007; Weyer et al., 2009). The prospects of algae-based fuels and chemicals are at this stage uncertain, with wide ranges for potential production costs reported in the literature.

Data availability is limited with respect to production of biomaterials; cost estimates for chemicals from biomass are rare in the peer-reviewed literature, and future projections and LRs are even rarer. This condition is linked, in part, to the fact that successful bio-based products are entering the market place either as partial components of otherwise fossil-derived products or as fully new synthetic polymers, such as polylactides based on lactic acid derived from sugar fermentation. Analyses indicate that, in addition to producing biomaterials to replace fossil fuels, cascaded use of biomaterials and subsequent use of waste material for energy can offer more effective and larger mitigation impacts per hectare or tonne of biomass used (e.g., Dornburg and Faaij, 2005).

The benefits of biomass gasification and CCS alone or with coal are significant (see Figures 2.10 and 2.11). Similarly, capturing CO_2 from fermentation processes offers a significant option in many regions of the world, and coupling with CCS may become an attractive medium-term mitigation option. However, such concepts are not deployed at present and cost trends are not available in the literature, making investments in biomass (or coal) gasification technologies risky. Also, geologic sequestration reliability and the uncertainty of the regulatory environment pose further barriers. More detailed analysis is desired in this field.

2.8.4.3 Social and environmental impacts

The effects of bioenergy on social and environmental issues—ranging from health and poverty to biodiversity and water quality—may be positive or negative depending upon local conditions, the specific feedstock production system and technology paths chosen, how criteria and the alternative scenarios are defined, and how actual projects are designed and implemented, among other variables (Sections 9.2 through 9.5). Perhaps most important is the overall management and governance of land use when biomass is produced for energy on top of meeting food and other demands from agricultural production (as well as livestock). In cases where increases in land use due to biomass production are balanced out by improvements in agricultural management, undesirable iLUC effects can be avoided, while if unmanaged, conflicts may emerge. The overall performance of bioenergy production systems is therefore interlinked with management of land use and water resources. Trade-offs between those dimensions exist and need to be resolved through appropriate strategies and decision making. Such strategies are currently emerging due to many efforts targeting the deployment of sustainability frameworks and certification systems for bioenergy production (see also Section 2.4.5), setting standards for GHG performance (including LUC effects), addressing environmental issues and taking into consideration a number of social aspects.

Most bioenergy systems can contribute to climate change mitigation if they replace fossil-based energy that was causing high GHG emissions and if the bioenergy production emissions—including those arising due to LUC or temporal imbalance of terrestrial carbon stocks—are kept low (examples given in Sections 2.3 and 2.6). High N_2O emissions from feedstock production and the use of high carbon intensity fossil fuels in the biomass conversion process can strongly impact the GHG savings. Best fertilizer management practices, process integration minimizing losses, surplus heat utilization, and biomass use as a process fuel can reduce GHG emissions. But in cold climates the displacement efficiency (see Section 2.5.3) can become low when biomass is used both as feedstock and as fuel in the conversion process.

Given the lack of studies on how biomass resources may be distributed over various demand sectors, no detailed allocation of the different biomass supplies for various applications is suggested here. Furthermore, the net avoidance costs per tonne of CO_2 for biomass usage depend on various factors, including the biomass resource and supply (logistics) costs, conversion costs (which in turn depend on availability of improved or advanced technologies) and fossil fuel prices, most notably of oil.

A GHG performance evaluation of key biofuel production systems deployed today and possible second-generation biofuels using different calculation methods is available (Sections 2.5.2, 2.5.3 and 9.3.4; Hoefnagels et al., 2010). Recent insights converge by concluding that well-managed bioenergy production and utilization chains can deliver high GHG mitigation percentages (80 to 90%) compared to their fossil counterparts, especially for lignocellulosic biomass used for power generation and heat and, when the technology would be commercially available, for lignocellulosic biofuels. The use of most residues and organic wastes, principally animal residues, for energy result in such good performance. Also, most current biofuel production systems have positive GHG balances, and for some of them this situation persists even when significant iLUC effects are incorporated (see below).

LUC can strongly affect those scores, and when conversion of land with large carbon stocks takes place for the purpose of biofuel production, emission benefits can shift to negative levels in the near term. This is most extreme for palm oil-based biodiesel production, where extreme carbon emissions are obtained if peatlands are drained and converted to oil palm (Wicke et al., 2008). The GHG mitigation effect of biomass use for energy (and materials) therefore strongly depends on location (in particular avoidance of converting carbon-rich lands to carbon-poor cropping systems), feedstock choice and avoiding iLUC (see below). In contrast, using perennial cropping systems can store large amounts of carbon and enhance sequestration on marginal and degraded soils, and biofuel production can replace fossil fuel use. Governance of land use, proper zoning and choice of biomass production systems are therefore key factors to achieve good performance.

The assessment of available iLUC literature (Figures 2.13, 9.10, and 9.11) indicated that initial models were lacking in geographic resolution, leading to higher proportions than necessary of land use assigned to deforestation, as the models did not have other kinds of lands (e.g., pastures in Brazil) for use. While the early paper of Searchinger et al. (2008) claimed an iLUC factor of 0.8 (losing 0.8 ha of forest land for each hectare of land used for bioenergy), later (2010) studies that coupled macro-economic to biophysical models tuned that down to 0.15 to 0.3 (see, e.g., Al-Riffai et al., 2010). Models used to estimate iLUC effects vary in their estimates of land displacement. Partial and general equilibrium models have different assumptions and reflect different time frames, and thus they incorporate more or less adjustment. More detailed evaluations (e.g., Al-Riffai et al., 2010; Lapola et al., 2010; see Section 2.5.3) do estimate significant iLUC impacts but also suggest that any iLUC effect strongly (up to fully) depends on the rate of improvement in agricultural and livestock management and the rate of deployment of bioenergy production. This balance in development is also the basis for the recent European biomass resource potential analysis, for which expected gradual productivity increments in agriculture are the basis for possible land availability (as reported in Fischer et al. (2010) and de Wit and Faaij (2010); see Figure 2.5(a)) minimizing competition with food (or nature) as a starting point. Increased model sophistication to adapt to the complex type of analysis required and improved data on the actual dynamics of land distribution in the major biofuel-producing countries are now producing results that show lower overall LUC impacts (Figure 9.11) and acknowledge that land use management at large is key (Berndes et al., 2010).

Bioenergy projects can result in gains or losses in associated biospheric stocks and in both direct and indirect LUC, the latter being inherently difficult to quantify. Even so, it can be concluded that LUC can affect GHG balances in several ways, with beneficial or detrimental outcomes for bioenergy's contribution to climate change mitigation, depending on conditions and context. When land high in carbon (notably forests and especially peat soil forests) is converted to bioenergy, upfront emissions may cause a time lag of decades to centuries before net emission savings are achieved. But the establishment of bioenergy plantations can also lead to assimilation of CO_2 into soils and aboveground biomass in the short term. Increased utilization of forest biomass can reduce forest carbon stocks. The longer-term net effect on forest carbon stocks can be positive or negative depending on natural conditions (including disturbances such as insect outbreaks and fires) and forest management practices. The use of post-consumer organic waste and by-products from the agricultural and forest industries does not cause LUC if these biomass sources were not utilized for alternative purposes. Bioenergy feedstocks can be produced in combination with food and fibre, avoiding land use displacement and improving the productive use of land. Lignocellulosic feedstocks for bioenergy can decrease the pressure on prime cropping land. Stimulation of increased productivity in all forms of land use reduces the LUC pressure.

Air pollution effects of bioenergy depend on both the bioenergy technology (including pollution control technologies) and the displaced energy technology (e.g., inefficient coal versus modern natural gas combustion) (Figure 9.12). Improved biomass cookstoves for traditional biomass use can provide large and cost-effective mitigation of GHG emissions with substantial co-benefits in terms of health and living conditions, particularly for the 2.7 billion people in the world that rely on traditional biomass for cooking and heating (Sections 2.5.4, 9.3.4, 9.3.4.2 and 9.3.4.3). Efficient technologies for cooking are even cost-effective compared to other major interventions in health, such as those addressing tobacco, undernourishment or tuberculosis (Figures 2.14 and 9.13).

Other key environmental impacts cover water use, biodiversity and other emissions (Sections 2.5.5 and 9.3.4). Just as for GHG impacts, proper management determines emission levels to water, air and soil. Development of standards or criteria (and continuous improvement processes) will push bioenergy production to lower emissions and higher efficiency than today's systems.

Water is a critical issue that needs to be better analyzed at a regional level to understand the full impact of changes in vegetation and land use management. Recent studies (Berndes, 2002; Dornburg et al., 2008; Rost et al., 2009; Wu et al., 2009) indicate that considerable improvements can be made in water use efficiency in conventional agriculture, bioenergy crops and, depending on location and climate, perennial cropping systems, by improving water retention and lowering direct evaporation from soils (Figure 9.14). Nevertheless, without proper management, increased biomass production could come with increased competition for water in critical areas, which is highly undesirable (Fingerman et al., 2010).

Similar remarks can be made with respect to biodiversity, although more scientific uncertainty exists due to ongoing debates about methods of biodiversity impacts assessment. Clearly, development of large-scale monocultures at the expense of natural areas is detrimental for biodiversity (for example, highlighted in UNEP. 2008b). However, as discussed in Section 2.5, bioenergy can also lead to positive effects by integrating different perennial grasses and woody crops into agricultural landscapes, which could also increase soil carbon and productivity, reduce shallow landslides and local 'flash floods', reduce wind and water erosion, and reduce sediment and nutrients transported into river systems. Forest residue harvesting improves forest site conditions for replanting, and thinning generally improves productivity and growth of the remaining stand. Removal of biomass from overly-dense stands can reduce wildfire risk.

The impact assessments for all these areas deserve considerably more research, data collection and proper monitoring, as exemplified by ongoing activities of governments (see footnote 64) and roundtables[78] for pilot studies.

78 See Roundtable on Sustainable Biofuels pilot studies at www2.epfl.ch/energycenter-jahia4/page65660.html.

Social impacts from a large expansion of bioenergy are very complex and difficult to quantify. Crops grown as biofuel feedstock currently use less than 1% of the world's agricultural land, but demand for biofuels has represented one driver of demand growth and therefore contributed to global food price increases. Increased demand for food and feed, increases in oil prices, speculation on international food markets, and incidental poor harvests due to extreme weather events are examples of events that have likely also had an impact on global food prices. Even considering the benefit of increased prices to poor farmers, increased food prices adversely affect the level of poverty, food security, and malnourishment of children. On the other hand, biofuels can also provide opportunities for developing countries to make progress in rural development and agricultural growth, especially when this growth is economically sustainable.

In general, bioenergy options have a much larger positive impact on job creation in rural areas than other energy sources, for example, 50 to 2,200 jobs/PJ (Section 2.5.7.3). Also when the intensification of conventional agriculture frees up land that could be used for bioenergy, the total job impact and added value generated in rural regions increases when bioenergy production increases. Effective pasture/agriculture land use management could increase the rain-fed production potential significantly (see Table 2.3; Wicke et al., 2009). For many developing countries, the potential of bioenergy to generate employment, economic activity in rural areas, and fuel supply security are key drivers. In addition, expenditures on fossil fuel (imports) can be (strongly) reduced. However, whether such benefits end up with rural farmers depends largely on the way production chains are organized and how land use is governed.

The bioenergy options that are developed, the way they are developed, and under what conditions will have a profound influence on whether impacts will largely be positive or negative (Argentina scenarios; van Dam et al., 2009a,b). The development of standards or criteria (and continuous improvement processes) can push bioenergy production to lower or positive impacts and higher efficiency than today's systems. Bioenergy has the opportunity to contribute to climate change mitigation, a secure and diverse energy supply, and economic development in developed and developing countries alike, but the effects of bioenergy on environmental sustainability may be positive or negative depending upon local conditions, how criteria are defined, and how actual projects are designed and implemented, among many other factors.

2.8.5 Conclusions regarding deployment: Key messages about bioenergy

Bioenergy is currently the largest RE source and is likely to remain one of the largest RE sources for the first half of this century. There is considerable growth potential, but it requires active development.

- Assessments in the recent literature show that the technical potential of biomass for energy may be as large as 500 EJ/yr by 2050. However, large uncertainty exists about important factors such as market and policy conditions that affect this potential.

- The expert assessment in this chapter suggests potential deployment levels by 2050 in the range of 100 to 300 EJ/yr. Realizing this potential represents a major challenge but would make a substantial contribution to the world's primary energy demand in 2050—roughly equal to the equivalent heat content of today's worldwide biomass extraction in agriculture and forestry.

- Bioenergy has significant potential to mitigate GHGs if resources are sustainably developed and efficient technologies are applied. Certain current systems and key future options including perennial crops, forest products and biomass residues and wastes, and advanced conversion technologies, can deliver significant GHG mitigation performance—an 80 to 90% reduction compared to the fossil energy baseline. However, land conversion and forest management that lead to a large loss of carbon stocks and iLUC effects can lessen, and in some cases more than neutralize, the net positive GHG mitigation impacts.

- In order to achieve the high potential deployment levels of biomass for energy, increases in competing food and fibre demand must be moderate, land must be properly managed and agricultural and forestry yields must increase substantially. Expansion of bioenergy in the absence of monitoring and good governance of land use carries the risk of significant conflicts with respect to food supplies, water resources and biodiversity, as well as a risk of low GHG benefits. Conversely, implementation that follows effective sustainability frameworks could mitigate such conflicts and allow realization of positive outcomes, for example, in rural development, land amelioration and climate change mitigation, including opportunities to combine adaptation measures.

- The impacts and performance of biomass production and use are region- and site-specific. Therefore, as part of good governance of land use and rural development, bioenergy policies need to consider regional conditions and priorities along with the agricultural (crops and livestock) and forestry sectors. Biomass resource potentials are influenced by and interact with climate change impacts but the specific impacts are still poorly understood; there will be strong regional differences in this respect. Bioenergy and new (perennial) cropping systems also offer opportunities to combine adaptation measures (e.g., soil protection, water retention and modernization of agriculture) with production of biomass resources.

- Several important bioenergy options (i.e., sugarcane ethanol production in Brazil, select waste-to-energy systems, efficient biomass cookstoves, biomass-based CHP) are competitive today and can provide important synergies with longer-term options. Lignocellulosic biofuels replacing gasoline, diesel and jet fuels, advanced bioelectricity options and biorefinery concepts can offer competitive deployment of bioenergy for the 2020 to 2030 timeframe. Combining biomass conversion with CCS raises the possibility of achieving GHG removal from the atmosphere in the long term—a necessity for substantial GHG emission reductions. Advanced biomaterials are promising as well for the economics of bioenergy production and mitigation, though the potential is less well understood as is the potential role of aquatic biomass (algae), which is highly uncertain.

- Rapidly changing policy contexts, recent market-based activities, the increasing support for advanced biorefineries and lignocellulosic biofuel options, and in particular the development of sustainability criteria and frameworks, all have the potential to drive bioenergy systems and their deployment in sustainable directions. Achieving this goal will require sustained investments that reduce costs of key technologies, improved biomass production and supply infrastructure, and implementation strategies that can gain public and political acceptance.

In conclusion and for illustrating the interrelations between scenario variables (see Figure 2.26), key preconditions under which bioenergy production capacity is developed and what the resulting impacts may be, Figure 2.27 presents four different sketches for biomass deployment for energy on a global scale by 2050. The 100 to 300 EJ range that follows from the resource potential review delineates the lower and upper limit for deployment. The assumed storylines roughly follow the IPCC SRES definitions, applied to bioenergy and summarized in Figure 2.26 (Hoogwijk et al., 2005), that were also used to derive the technical potential shown on the stacked bar of Figure 2.25 (Dornburg et al., 2008, 2010).

Biomass and its multiple energy products can be developed alongside food, fodder, fibre and forest products in both sustainable and unsustainable ways. As viewed through the IPCC scenario storylines and sketches, high and low penetration levels can be reached with and without taking into account sustainable development and climate change mitigation pathways. Insights into bioenergy technology developments and integrated systems can be gleaned from these sketches.

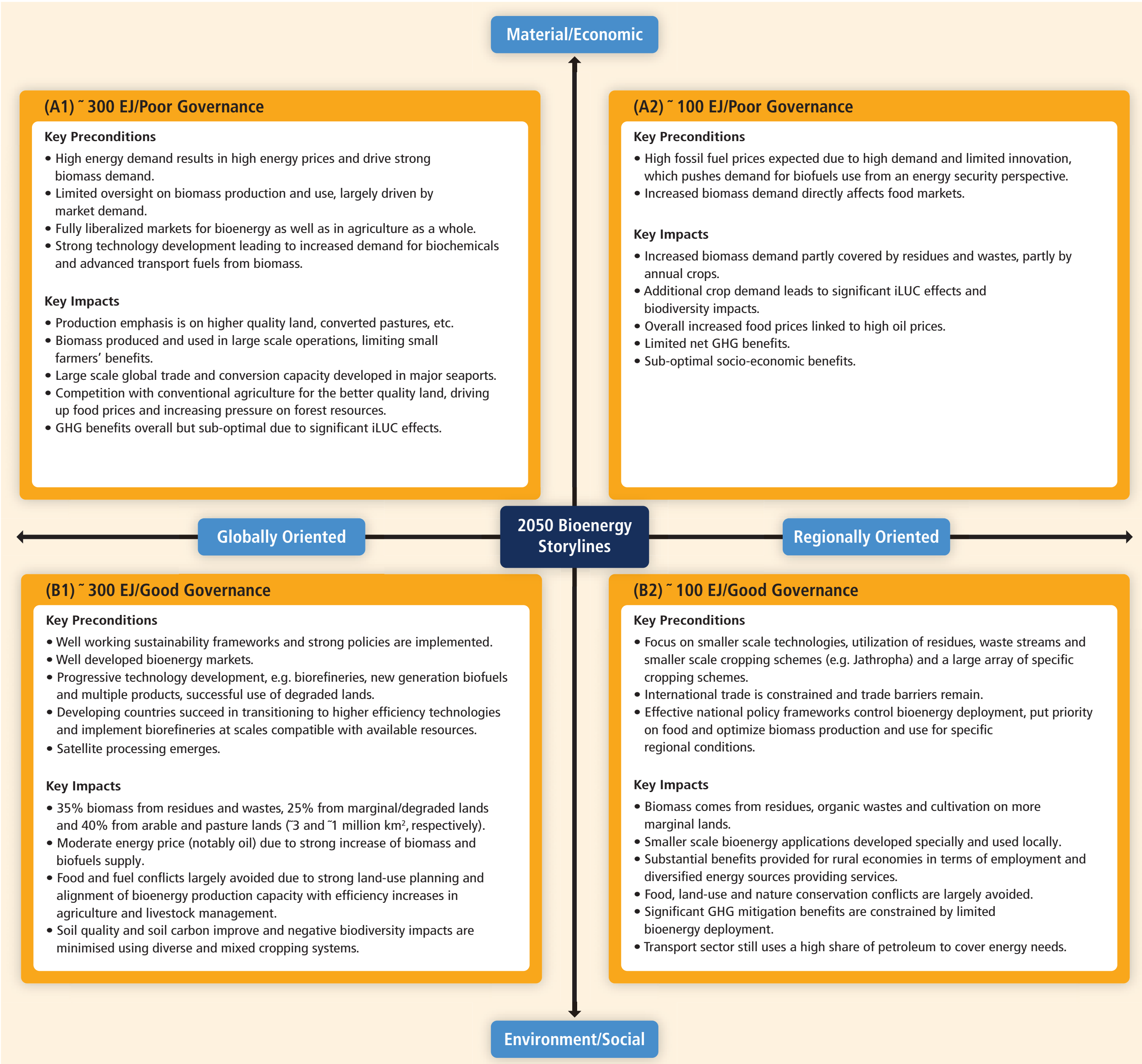


Figure 2.27 | Possible futures for 2050 biomass deployment for energy: Four illustrative contrasting sketches describing key preconditions and impacts following world conditions typical of the IPCC SRES storylines (IPCC, 2000) summarized in Figure 2.26.

References

Abbasi, T., and S.A. Abbasi (2010). Biomass energy and the environmental impacts associated with its production and utilization. *Renewable and Sustainable Energy Reviews*, **14**(3), pp. 919-937.

Adam, J.C. (2009). Improved and more environmentally friendly charcoal production system using a low-cost retort-kiln (Eco-charcoal). *Renewable Energy*, **34**(8), pp. 1923-1925.

Adams, P.W., G.P. Hammond, M.C. McManus, and W.G. Mezzullo (2011). Barriers to and drivers for UK bioenergy development. *Renewable and Sustainable Energy Reviews*, **15**(2), pp. 1217-1227.

Aden, A., M. Ruth, K. Ibsen, J. Jechura, K. Neeves, J. Sheehan, B. Wallace, L. Montague, A. Slayton, and J. Lukas (2002). *Lignocellulosic Biomass to Ethanol Process Design and Economics Utilizing Co-Current Dilute Acid Prehydrolysis and Enzymatic Hydrolysis for Corn Stover.* NREL/TP-510-32438, National Renewable Energy Laboratory, Golden, Colorado, USA, 154 pp.

Ahrens, T.D., D.B. Lobell, J.I. Ortiz-Monasterio, Y. Li, and P.A. Matson (2010). Narrowing the agronomic yield gap with improved nitrogen use efficiency: a modeling approach. *Ecological Applications*, **20**(1), pp. 91-100.

Ainsworth, E.A., and S.P. Long (2005). What have we learned from 15 years of free-air CO_2 enrichment (FACE)? A meta-analytic review of the responses of photosynthesis, canopy properties and plant production to rising CO_2. *New Phytologist*, **165**(2), pp. 351-372.

Al-Riffai, P., B. Dimaranan, and L. Laborde (2010). *Global Trade and Environmental Impact Study of the EU Biofuels Mandate.* Project Report - Specific Contract No SI2.537.787 implementing Framework Contract No TRADE/07/A2, International Food Policy Research Institute, Washington, DC, USA, 123 pp.

Alexandratos, N. (2009). World food and agriculture to 2030/50: highlights and views from mid-2009. In: *Proceedings of the Expert Meeting on How to Feed the World in 2050*, Rome, Italy, 24-26 June 2009. Economic and Social Development Department, Food and Agriculture Organization of the United Nations, Rome, Italy, pp. 78. Available at: www.fao.org/docrep/012/ak542e/ak542e00.htm.

Alfstad, T. (2008). *World Biofuels Study: Scenario Analysis of Global Biofuels Markets*. BNL-80238-2008, Brookhaven National Laboratory, New York, NY, USA, 67 pp.

Allen, J., M. Browne, A. Hunter, J. Boyd, and H. Palmer (1998). Logistics management and costs of biomass fuel supply. *International Journal of Physical Distribution & Logistics Management*, **28**(6), pp. 463-477.

Allen, M.R., D.J. Frame, C. Huntingford, C.D. Jones, J.A. Lowe, M. Meinshausen, and N. Meinshausen (2009). Warming caused by cumulative carbon emissions towards the trillionth tonne. *Nature*, **458**(7242), pp. 1163-1166.

Alper, H., and G. Stephanopoulos (2009). Engineering for biofuels: exploiting innate microbial capacity or importing biosynthetic potential? *Nature Reviews Microbiology*, **7**(10), pp. 715-723.

Anderson-Teixeira, K.J., S.C. Davis, M.D. Masters, and E.H. Delucia (2009). Changes in soil organic carbon under biofuel crops. *Global Change Biology Bioenergy*, **1**(1), pp. 75-96.

APEC (2003). *The New Brunswick Forest Industry: The Potential Economic Impact of Proposals to Increase the Wood Supply*. Atlantic Provinces Economic Council, Halifax, Canada.

Armendáriz, C.A., R.D. Edwards, M. Johnson, M. Zuk, L. Rojas, R.D. Jiménez, H. Riojas-Rodriguez, and O. Masera (2008). Reduction in personal exposures to particulate matter and carbon monoxide as a result of the installation of a Patsari improved cook stove in Michoacan Mexico. *Indoor Air*, **18**(2), pp. 93-105.

Arndt, C., R. Benfica, F. Tarp, and R. Uaiene (2010). Biofuels, poverty, and growth: A computable general equilibrium analysis of Mozambique. *Environment and Development Economics*, **15**(1), pp. 81-105.

Asikainen, A., H. Liiri, S. Peltola, T. Karjalainen, and J. Laitila (2008). *Forest Energy Potential in Europe (EU 27)*. Working Papers of the Finnish Forest Research Institute, No. 69, Finnish Forest Research Institute, Helsinki, Finland, 33 pp.

Asikainen, A., P. Anttila, J. Heinimö, T. Smith, I. Stupak, and W. Ferreira Quirino (2010). Forest and bioenergy production. In: *Forest and Society – Responding to Global Drivers of Change*. G. Mery, P. Katila, G. Galloway, R.I. Alfaro, M. Kanninen, M. Lobovikov, and J. Varjo (eds.). International Union of Forest Research Organizations, Vienna, Austria, pp. 183-200.

Astbury, G. (2008). A review of the properties and hazards of some alternative fuels. *Process Safety and Environmental Protection*, **86**(6), pp. 397-414.

Ausubel, J.H. (2000). The great reversal: nature's chance to restore land and sea. *Technology in Society*, **22**, pp. 289-301.

Azar, C., K. Lindgren, M. Obersteiner, K. Riahi, D. van Vuuren, K. den Elzen, K. Möllersten, and E. Larson (2010). The feasibility of low CO_2 concentration targets and the role of bio-energy with carbon capture and storage (BECCS). *Climatic Change*, **100**(1), pp. 195-202.

Bacovsky, D., M. Dallos, and M. Worgetter (2010a). *Status of 2nd Generation Biofuels Demonstration Facilities in June 2010*. T39-P1b, IEA Bioenergy Task 39, 126 pp. Available at: www.ascension-publishing.com/BIZ/IEATask39-0610.pdf.

Bacovsky, D., W. Mabee, and M. Wörgetter (2010b). How close are second-generation biofuels? *Biofuels, Bioproducts and Biorefining*, **4**(3), pp. 249-252.

Badger, P. (2000). New process for torrefied wood manufacturing. *Bioenergy Update*, **2**(4), pp. 1-4. Available at: www.bioenergyupdate.com/magazine/security/NL0400/gbinl0400.pdf.

Badgley, C., J. Moghtader, E. Quintero, E. Zakem, M.J. Chappell, K. Avilés-Vázquez, A. Samulon, and I. Perfecto (2007). Organic agriculture and the global food supply. *Renewable Agriculture and Food Systems*, **22**(02), pp. 86-86.

Baffes, J., and T. Haniotis (2010). *Placing the 2006/08 Commodity Price Boom into Perspective*. Policy Research Working Paper 5371, The World Bank Group, Washington, DC, USA, 42 pp.

Bai, Z.G., D.L. Dent, L. Olsson, and M.E. Schaepman (2008). Proxy global assessment of land degradation. *Soil Use and Management*, **24**(3), pp. 223-234.

Bailis, R., A. Cowan, V. Berrueta, and O. Masera (2009). Arresting the killer in the kitchen: The promises and pitfalls of commercializing improved cookstoves. *World Development*, **37**(10), pp. 1694-1705.

Bain, R.L. (2007). *World Biofuels Assessment, Worldwide Biomass Potential: Technology Characterizations*. NREL/MP-510-42467, National Renewable Energy Laboratory, Golden, CO, USA, 140 pp.

Bain, R.L. (2011). *Biopower Technologies in Renewable Electricity Alternative Futures*. National Renewable Energy Laboratory, Golden, CO, USA, in press.

Bain, R.L., W.P. Amos, M. Downing, and R.L. Perlack (2003). *Biopower Technical Assessment: State of the Industry and the Technology*. TP-510-33123, National Renewable Energy Laboratory, Golden, CO, USA, 277 pp.

Bairiganjan, S., R. Cheung, E.A. Delio, D. Fuente, S. Lall, and S. Singh (2010). *Power to the People: Investing in Clean Energy for the Base of the Pyramid in India*. Centre for Development Finance, c/o Institute for Financial Management and Research, World Resources Institute, Washington, DC, USA, 74 pp.

Balat, M. (2011). Potential alternatives to edible oils for biodiesel production - A review of current work. *Energy Conversion and Management*, **52**(2), pp. 1479-1492.

Ball, B.C., I. Bingham, R.M. Rees, C.A. Watson, and A. Litterick (2005). The role of crop rotations in determining soil structure and crop growth conditions. *Canadian Journal of Soil Science*, **85**, pp. 557-577.

Balmford, A., R.E. Green, and J.P.W. Scharlemann (2005). Sparing land for nature: exploring the potential impact of changes in agricultural yield on the area needed for crop production. *Global Change Biology*, **11**(10), pp. 1594-1605.

Barker, W.T., C.L. Lura, and J.L. Richardson (2009). Soil organic matter and native plant production on the Missouri Coteau. *North Dakota Farm Research*, **44**(2), pp. 14-21.

Barth, T., and M. Kleinert (2008). Motor fuels from biomass pyrolysis. *Chemical Engineering & Technology*, **31**(5), pp. 773-781.

Bauen, A., G. Berndes, M. Junginger, M. Londo, F. Vuille, R. Ball, T. Bole, C. Chudziak, A. Faaij, and H. Mozaffarian (2009a). *Bioenergy: A Sustainable and Reliable Energy Source: A Review of Status and Prospects*. IEA Bioenergy: ExCo:2009:06, 108 pp.

Bauen, A., F. Vuille, P. Watson, and K. Vad (2009b). *The RSB GHG accounting scheme. Feasibility of a meta-methodology and way forward*. E4tech version 4.1, Roundtable on Sustainable Biofuels., Lausanne, Switzerland, 91 pp. Available at: rsb.epfl.ch/files/content/sites/rsb2/files/Biofuels/Documents%20and%20Resources/09-10-08_E4Tech%20Report%20GHG%20Accounting_V4%201_08October09.pdf.

Baum, C., P. Leinweber, M. Weih, N. Lamersdorf, and I. Dimitriou (2009). Effects of short rotation coppice with willows and poplar on soil ecology. *Landbauforschung vTI Agriculture and Forestry Research*, **59**(3), pp. 183-186.

Baum, S., M. Weih, G. Busch, F. Kroiher, and A. Bolte (2009). The impact of Short Rotation Coppice plantations on phytodiversity. *Landbauforschung vTI Agriculture and Forestry Research*, **59**(3), pp. 163-170.

Beer, T., and T. Grant (2007). Life-cycle analysis of emissions from fuel ethanol and blends in Australian heavy and light vehicles. *Journal of Cleaner Production*, **15**(8-9), pp. 833-837.

Beer, T., T. Grant, R. Brown, J. Edwards, P. Nelson, H. Watson, and D. Williams (2000). *Life Cycle Emissions Analysis of Alternative Fuels for Heavy Vehicles.* Atmospheric Research Report C/0411/1.1/F2, Australian Commonwealth Scientific and Research Organization, Aspendale, Australia, 148 pp.

Beer, T., T. Grant, G. Morgan, J. Lapszewicz, P. Anyon, J. Edwards, P. Nelson, H. Watson, and D. Williams (2001). *Comparison of Transport Fuels*. EV45A/2/F3C, Australian Commonwealth Scientific and Research Organization, Aspendale, Australia, 485 pp.

Beringer, T.I.M., W. Lucht, and S. Schaphoff (2011). Bioenergy production potential of global biomass plantations under environmental and agricultural constraints. *Global Change Biology Bioenergy*, doi:10.1111/j.1757-1707.2010.01088.x.

Berndes, G. (2002). Bioenergy and water--the implications of large-scale bioenergy production for water use and supply. *Global Environmental Change*, **12**(4), pp. 253-271.

Berndes, G. (2008a). Future biomass energy supply: The consumptive water use perspective. *International Journal of Water Resources Development*, **24**(2), pp. 235-245.

Berndes, G. (2008b). *Water Demand for Global Bioenergy Production: Trends, Risks and Opportunities*. Report commissioned by the German Advisory Council on Global Change. Wissenschaftlicher Beirat der Bundesregierung Globale Umweltveränderungen, Berlin, Germany, 46 pp.

Berndes, G., and J. Hansson (2007). Bioenergy expansion in the EU: Cost-effective climate change mitigation, employment creation and reduced dependency on imported fuels. *Energy Policy*, **35**(12), pp. 5965-5979.

Berndes, G., M. Hoogwijk, and R. van den Broek (2003). The contribution of biomass in the future global energy supply: a review of 17 studies. *Biomass and Bioenergy*, **25**(1), pp. 1-28.

Berndes, G., F. Fredrikson, and P. Börjesson (2004). Cadmium accumulation and Salix-based phytoextraction on arable land in Sweden. *Agriculture, Ecosystems & Environment*, **103**(1), pp. 207-223.

Berndes, G., P. Börjesson, M. Ostwald, and M. Palm (2008). Multifunctional biomass production systems – an overview with presentation of specific applications in India and Sweden. *Biofuels, Bioproducts and Biorefining*, **2**(1), pp. 16-25.

Berndes, G., N. Bird, and A. Cowie (2010). *Bioenergy, Land Use Change and Climate Change Mitigation*. IEA Bioenergy: ExCo:2010:03, International Energy Agency, Whakarewarewa, Rotorua, New Zealand, 20 pp. Available at: www.ieabioenergy.com/LibItem.aspx?id=6770.

Berrueta, V.M., R.D. Edwards, and O.R. Masera (2008). Energy performance of wood-burning cookstoves in Michoacan, Mexico. *Renewable Energy*, **33**(5), pp. 859-870.

Bessou, C., F. Ferchaud, B. Gabrielle, and B. Mary (2010). Biofuels, greenhouse gases and climate change. A review. *Agronomy for Sustainable Development*, doi:10.1051/agro/2009039,132 pp.

Bhagwat, S.A., K.J. Willis, H.J.B. Birks, and R.J. Whittaker (2008). Agroforestry: a refuge for tropical biodiversity? *Trends in Ecology & Evolution*, **23**(5), pp. 261-267.

Bhojvaid, P.P. (2007). Recent trends in biodiesel production. In: *Biofuels: Towards a Greener and Secure Energy Future.* P.P. Bhojvaid (ed.), The Energy and Resources Institute (TERI) Press, New Delhi, India, pp. 119-136.

Bickel, P., and R. Friedrich (eds.) (2005). *ExternE - Externalities of Energy: Methodology 2005 Update.* European Commission, Brussels, Belgium, 270 pp.

Biran, A., J. Abbot, and R. Mace (2004). Families and firewood: A comparative analysis of the costs and benefits of children in firewood collection and use in two rural communities in sub-Saharan Africa. *Human Ecology*, **32**(1), pp. 1-25.

Blanco-Canqui, H., and R. Lal (2009). Corn stover removal for expanded uses reduces soil fertility and structural stability. *Soil Science Society of America Journal*, **73**(2), pp. 418-426.

Blanco-Canqui, H., R. Lal, W.M. Post, R.C. Izaurralde, and L.B. Owens (2006). Rapid changes in soil carbon and structural properties due to stover removal from no-till corn plots. *Soil Science*, **171**(6), pp. 468-482.

BNDES/CGEE (2008). *Sugarcane-Based Bioethanol: Energy for Sustainable Development.* Brazilian Development Bank and Center for Strategic Studies and Management Science, Technology and Innovation, Rio de Janeiro, Brazil, 304 pp.

Bohlmann, G.M., and M.A. Cesar (2006). The Brazilian opportunity for biorefineries. *Industrial Biotechnology*, **2**(2), pp. 127-132.

Boman, C., B. Forsberg, and T. Sandström (2006). Shedding new light on wood smoke: a risk factor for respiratory health. *European Respiratory Journal*, **27**(3), pp. 446-447.

Bon, E.P.S., and M.A. Ferrara (2007). Bioethanol production via enzymatic hydrolysis of cellulosic biomass. In: *FAO Symposium on the Role of Agricultural Biotechnologies for Production of Bioenergy in Developing Countries*, 12 October 2007, Food and Agriculture Organization, Rome, Italy, 11 pp. Available at: http://www.fao.org/biotech/docs/bon.pdf.

Börjesson, P. (2000). Economic valuation of the environmental impact of logging residue recovery and nutrient compensation. *Biomass and Bioenergy*, **19**(3), pp. 137-152.

Börjesson, P. (2009). Good or bad bioethanol from a greenhouse gas perspective – What determines this? *Applied Energy*, **86**(5), pp. 589-594.

Börjesson, P., and G. Berndes (2006). The prospects for willow plantations for wastewater treatment in Sweden. *Biomass and Bioenergy*, **30**(5), pp. 428-438.

Borowitzka, M.A., R. Osinga, J. Tramper, J.G. Burgess, and R.H. Wijffels (1999). Commercial production of microalgae: ponds, tanks, and fermenters. *Progress in Industrial Microbiology*, **35**, pp. 313-321.

Bouwman, A.F., L.J.M. Boumans, and N.H. Batjes (2002). Emissions of N_2O and NO from fertilized fields: Summary of available measurement data. *Global Biogeochemical Cycles*, **16**(4), 13 pp.

Bradley, D., F. Diesenreiter, M. Wild, and E. Tromborg (2009). *World Biofuel Maritime Shipping Study.* IEA Bioenergy Task 40, IEA, Paris, France, 38 pp.

Bradley, R.L., A. Olivier, N. Thevathasan, and J. Whalen (2008). Environmental and economic benefits of tree-based intercropping systems. *Policy Options*, February, pp. 46-49. Available at: www.irpp.org/po/archive/feb08/bradley.pdf.

Bravo, R., O. Masera, T. Chalico, D. Pandey, E. Riegelhaupt, and A. Uhlig (2010). *Case-studies from Brazil, India and Mexico.* Food and Agriculture Organization, Rome, Italy, 80 pp.

Bridgwater, A., S. Czernik, J. Diebold, D. Meier, A. Oasmaa, C. Peacocke, J. Piskorz, and D. Radlein (2003). *Fast Pyrolysis of Biomass: A Handbook.* CPL Press, Berks, UK, 180 pp.

Bridgwater, A. Ed. (2007). *Success & Visions for Bioenergy: Thermal processing of biomass for bioenergy, biofuels and bioproducts.* CPL Scientific Publishing Services Ltd., CD-ROM, ISBN 9781872691282.

Bringezu, S., H. Schuetz, M. O Brien, L. Kauppi, R. Howarth, and J. McNeely (2009). *Towards Sustainable Production and Use of Resources: Assessing Biofuels.* United Nations Environment Programme, Paris, France, 102 pp.

Bruce, N., E. Rehfuess, S. Mehta, G. Hutton, and K.R. Smith (2006). Indoor air pollution. In: *Disease Control Priorities in Developing Countries.* 2nd ed. World Bank Group, Washington, DC, USA, pp. 793-815.

Bruinsma, J. (2009). The resource outlook to 2050: by how much do land, water and crop yields need to increase by 2050? In: *Expert Meeting on How to Feed the World in 2050*, 24-26 June 2009, Economic and Social Development Department, Food and Agriculture Organization of the United Nations, Rome, Italy, 33 pp.

Brunner, A.M., S.P. DiFazio, and A.T. Groover (2007). Forest genomics grows up and branches out. *New Phytologist*, **174**(4), pp. 710-713.

Buchholz, T., E. Rametsteiner, T. Volk, and V. Luzadis (2009). Multi Criteria Analysis for bioenergy systems assessments. *Energy Policy*, **37**(2), pp. 484-495.

Bureau, J.-C., H. Guyomard, F. Jacquet, and D. Tréguer (2010). European biofuel policy: How far will public support go? In: *Handbook of Bioenergy Economics and Policy.* M. Khanna, J. Scheffran, and D. Zilberman (eds.), Springer, Heidelberg, Germany, pp. 401-423.

Bush, D.R., and J.E. Leach (2007). Translational genomics for bioenergy production: There's room for more than one model. *The Plant Cell*, **19**(10), pp. 2971-2973.

Calder, I., J. Amezaga, J. Bosch, B. Aylward, and L. Fuller (2004). Forest and water policies: the need to reconcile public and science conceptions. *Geologica acta*, **2**(2), pp. 157-166.

Campbell, J.E., D.B. Lobell, and C.B. Field (2009). Greater transportation energy and GHG offsets from bioelectricity than ethanol. *Science*, **324**(5930), pp. 1055-1057.

CARB (2009). *Proposed Regulation to Implement the Low Carbon Fuel Standard.* California Environmental Protection Agency, Air Resources Board, Stationary Source Division, Sacramento, California, 374 pp.

Carlsson-Kanyama, A., and H. Shanahan (2003). Food and life cycle energy inputs: consequences of diet and ways to increase efficiency. *Ecological Economics*, **44**(2-3), pp. 293-307.

Carolan, J., S. Joshi, and B.E. Dale (2007). Technical and financial feasibility analysis of distributed bioprocessing using regional biomass pre-processing centers. *Journal of Agricultural & Food Industrial Organization*, **5**(2) Article 10, 29 pp. Available at: www.bepress.com/jafio/vol5/iss2/art10.

Carpita, N.C., and M.C. McCann (2008). Maize and sorghum: genetic resources for bioenergy grasses. *Trends in Plant Science*, **13**(8), pp. 415-420.

Carslaw, K.S., O. Boucher, D.V. Spracklen, G.W. Mann, J.G.L. Rae, S. Woodward, and M. Kulmala (2010). A review of natural aerosol interactions and feedbacks within the Earth system. *Atmospheric Chemistry and Physics*, **10**(4), pp. 1701-1737.

Cascone, R. (2008). Biobutanol: a replacement for bioethanol? In: *Chemical Engineering Progress Special Edition Biofuels*, **104**, pp. S4–S9.

Cassman, K.G. (1999). Ecological intensification of cereal production systems: Yield potential, soil quality, and precision agriculture. *Proceedings of the National Academy of Sciences of the United States of America*, **96**(11), pp. 5952-5959.

Cassman, K.G., A. Dobermann, D.T. Walters, and H. Yang (2003). Meeting cereal demand while protecting natural resources and improving environmental quality. *Annual Review of Environment and Resources*, **28**(1), pp. 315-358.

Castiglioni, P., D. Warner, R.J. Bensen, D.C. Anstrom, J. Harrison, M. Stoecker, M. Abad, G. Kumar, S. Salvador, R. D'Ordine, S. Navarro, S. Back, M. Fernandes, J. Targolli, S. Dasgupta, C. Bonin, M.H. Luethy, and J.E. Heard (2008). Bacterial RNA chaperones confer abiotic stress tolerance in plants and improved grain yield in maize under water-limited conditions. *Plant Physiology*, **147**(2), pp. 446-455.

CBOT (2006). *CBOT® Soybean Crush Reference Guide.* Board of Trade of the City of Chicago, Chicago, IL, USA.

Chakravorty, U., M. Hubert, and L. Nostbakken (2009). Fuel versus food. *Annual Review of Resource Economics*, **1**(1), pp. 645-663.

Chapotin, S.M., and J. Wolt (2007). Genetically modified crops for the bioeconomy: meeting public and regulatory expectations. *Transgenic Research*, **16**(6), pp. 675-688.

Chapple, C., M. Ladisch, and R. Meilan (2007). Loosening lignin's grip on biofuel production. *Nature Biotechnology*, **25**(7), pp. 746-748.

Cheng, J.J., and G.R. Timilsina (2010). *Advanced Biofuel Technologies: Status and Barriers.* Policy Research Working Paper 5411, The World Bank, Washington, DC, USA, 47 pp.

Cherubini, F., and A.H. Strømman (2010). Life cycle assessment of bioenergy systems: State of the art and future challenges. *Bioresource Technology*, **102**(2), pp. 437-451.

Cherubini, F., N.D. Bird, A. Cowie, G. Jungmeier, B. Schlamadinger, and S. Woess-Gallasch (2009a). Energy- and greenhouse gas-based LCA of biofuel and bioenergy systems: Key issues, ranges and recommendations. *Resources, Conservation and Recycling*, **53**(8), pp. 434-447.

Cherubini, F., G. Jungmeier, M. Mandl, M. Wellisch, C. Philips, and H. Joergensen (2009b). *Biorefineries: Adding Value to the Sustainable Utilisation of Biomass.* IEA Bioenergy Publication T42:2009:01, IEA Bioenergy Task 42 on Biorefineries, 16 pp.

Chisti, Y. (2007). Biodiesel from microalgae. *Biotechnology Advances*, **25**(3), pp. 294-306.

Chiu, Y.-W., B. Walseth, and S. Suh (2009). Water embodied in bioethanol in the United States. *Environmental Science & Technology*, **43**(8), pp. 2688-2692.

Chum, H.L., and R.P. Overend (2003). Biomass and bioenergy in the United States. In: *Advances in Solar Energy: An Annual Review of Research and Development.* Vol. 15. D.Y. Goswami (ed.), American Solar Energy Society (ASES), Boulder, CO, USA, pp. 83-148.

Cirne, D.G., A. Lehtomäki, L. Björnsson, and L.L. Blackall (2007). Hydrolysis and microbial community analyses in two-stage anaerobic digestion of energy crops. *Journal of Applied Microbiology*, **103**(3), pp. 516-527.

Clayton, R., G. McDougall, M. Perry, D. Doyle, J. Doyle, and D. O'Connor (2010). *A Study of Employment Opportunities from Biofuel Production in APEC Economies.* APEC#210-RE-01.9, APEC Energy Working Group, Asia-Pacific Economic Cooperation (APEC), Singapore, Singapore, 82 pp.

Clifton-Brown, J.C., and I. Lewandowski (2000). Water use efficiency and biomass partitioning of three different Miscanthus genotypes with limited and unlimited water supply. *Annals of Botany*, **86**(1), pp. 191-200.

Clifton-Brown, J., P.F. Stampfl, and M.B. Jones (2004). Miscanthus biomass production for energy in Europe and its potential contribution to decreasing fossil fuel carbon emissions. *Global Change Biology*, **10**(4), pp. 509-518.

Cline, W.R. (2007). *Global Warming and Agriculture: Impact Estimates by Country*. Peterson Institute for International Economics, Washington, DC, USA, 201 pp.

Colla, L.M., C. Oliveira Reinehr, C. Reichert, and J.A.V. Costa (2007). Production of biomass and nutraceutical compounds by Spirulina platensis under different temperature and nitrogen regimes. *Bioresource Technology*, **98**(7), pp. 1489-1493.

Cortright, R.D., R.R. Davda, and J.A. Dumesic (2002). Hydrogen from catalytic reforming of biomass-derived hydrocarbons in liquid water. *Nature*, **418**(6901), pp. 964-967.

Cremers, M.F.G. (2009). *Deliverable 4, Technical Status of Biomass Co-firing.* 50831165-Consulting 09-1654, IEA Bioenergy Task 32, Arnhem, The Netherlands, 43 pp.

Crutzen, P., A. Moiser, K. Smith, and W. Winiwarter (2007). N_2O release from agro-biofuel production negates global warming reduction by replacing fossil fuels. *Atmospheric Chemistry and Physics*, **7**, pp. 11191-11205.

Curtis, B. (2010). *2008-2009 Review U.S. Biofuels Industry: Mind the Gap.* Concentric Energies & Resource Group, Inc., Los Gatos, CA, USA, 52 pp.

Cusick, R.D., B. Bryan, D.S. Parker, M.D. Merrill, M. Mehanna, P.D. Kiely, G. Liu, and B.E. Logan (2011). Performance of a pilot-scale continuous flow microbial electrolysis cell fed winery wastewater. *Applied Microbiology and Biotechnology*, **89**, pp. 2053-2063.

da Costa Sousa, L., S.P.S. Chundawat, V. Balan, and B.E. Dale (2009). 'Cradle-to-grave' assessment of existing lignocellulose pretreatment technologies. *Current Opinion in Biotechnology*, **20**(3), pp. 339-347.

Dale, B.E., M.S. Allen, M. Laser, and L.R. Lynd (2009). Protein feeds coproduction in biomass conversion to fuels and chemicals. *Biofuels, Bioproducts and Biorefining*, **3**(2), pp. 219-230.

Dale, B.E., B.D. Bals, S. Kim, and P. Eranki (2010). Biofuels done right: Land efficient animal feeds enable large environmental and energy benefits. *Environmental Science & Technology*, **44**(22), pp. 8385-8389.

Dale, V.H., R.A. Efroymson, and K.L. Kline (2011). The land use-climate change-energy nexus. *Landscape Ecology*, in press.

Damen, K., and A. Faaij (2006). A greenhouse gas balance of two existing international biomass import chains. *Mitigation and Adaptation Strategies for Global Change*, **11**(5), pp. 1023-1050.

Danielsen, F., H. Beukema, N.D. Burgess, F. Parish, C.A. Brühl, P.F. Donald, D. Murdiyarso, B.E.N. Phalan, L. Reijnders, M. Struebig, and E.B. Fitzherbert (2009). Biofuel plantations on forested lands: Double jeopardy for biodiversity and climate (Plantaciones de biocombustible en terrenos boscosos: Doble peligro para la biodiversidad y el clima). *Conservation Biology*, **23**(2), pp. 348-358.

Dantas, D.N., F.F. Mauad, and A.R. Ometto (2009). Potential for generation of thermal and electrical energy from biomass of sugarcane: A exergetic analysis. In: *11th International Conference on Advanced Materials*, Rio de Janeiro, Brazil, 20-25 September 2009, p. 131.

Darzins, A., P. Pienkos, and L. Edye (2010). *Current Status and Potential for Algal Biofuels Production.* Report T39-02, IEA Bioenergy Task 39, 128 pp.

Daugherty, E. (2001). *Biomass Energy Systems Efficiency Analyzed through a LCA Study.* Masters Thesis, Lund University, Gothenburg, Sweden, 45 pp.

Davda, R.R., J.W. Shabaker, G.W. Huber, R.D. Cortright, and J.A. Dumesic (2005). A review of catalytic issues and process conditions for renewable hydrogen and alkanes by aqueous-phase reforming of oxygenated hydrocarbons over supported metal catalysts. *Applied Catalysis B: Environmental*, **56**(1-2), pp. 171-186.

Davidson, E.A. (2009). The contribution of manure and fertilizer nitrogen to atmospheric nitrous oxide since 1860. *Nature Geoscience*, **2**(9), pp. 659-662.

de Boer, J., M. Helms, and H. Aiking (2006). Protein consumption and sustainability: Diet diversity in EU-15. *Ecological Economics*, **59**(3), pp. 267-274.

de Fraiture, C., and G. Berndes (2009). Biofuels and water. In: *Biofuels: Environmental Consequences and Interactions with Changing Land Use.* R.W. Howarth and S. Bringezu (eds.), Proceedings of the SCOPE - Scientific Committee on Problems of the Environment International Biofuels Project Rapid Assessment, Gummersbach, Germany, 22-25 September 2009, pp. 139-152.

de Fraiture, C., M. Giordano, and Y. Liao (2008). Biofuels and implications for agricultural water uses: blue impacts of green energy. *Water Policy*, **10**(S1), pp. 67-81.

De La Torre Ugarte, D.G., and C.C. Hellwinckel (2010). The problem is the solution: The role of biofuels in the transition to a regenerative agriculture. In: *Plant Biotechnology for Sustainable Production of Energy and Co-products.* P.N. Mascia, J. Scheffran, and J.M. Widholm (eds.), Springer-Verlag, Berlin and Heidelberg, Germany, 475 pp.

De La Torre Ugarte, D.G., L. He, K.L. Jensen, and B.C. English (2010). Expanded ethanol production: Implications for agriculture, water demand, and water quality. *Biomass and Bioenergy*, **34**(11), pp. 1586-1596.

de Wit, M., and A. Faaij (2010). European biomass resource potential and costs. *Biomass and Bioenergy*, **34**(2), pp. 188-202.

de Wit, M., M. Junginger, S. Lensink, M. Londo, and A. Faaij (2010). Competition between biofuels: Modeling technological learning and cost reductions over time. *Biomass and Bioenergy*, **34**(2), pp. 203-217.

DEFRA (2009). *The 2007/08 Agricultural Price Spikes: Causes and Policy Implications.* Department for Environment Food and Rural Affairs (DEFRA), HM Government, London, UK, 123 pp.

Delta-T Corporation (1997). *Proprietary information.* Williamsburg, VA, USA.

DeLucchi, M.A. (2005). *A Multi-Country Analysis of Lifecycle Emissions from Transportation Fuels and Motor Vehicles.* UCD-ITS-RR-05-10, Institute of Transportation Studies, University of California at Davis, Davis, CA, USA, 205 pp.

DeLucchi, M.A. (2010). *A Conceptual Framework for Estimating Bioenergy-Related Land-Use Change and Its Impacts over Time.* Biomass and Bioenergy, 1-24, doi:10.1016/j.biombioe.2010.11.028 (2010).

DeLuchi, M.A. (1993). Greenhouse-gas emissions from the use of new fuels for transportation and electricity. *Transportation Research Part A*, **27A**(3), pp. 187-191.

DeMeo, E.A., and J.F. Galdo (1997). *Renewable Energy Technology Characterizations*. TR-109496, U.S. Department of Energy and Electric Power Research Institute, Washington, DC, USA, 283 pp.

Demirbas, A. (2009). Progress and recent trends in biodiesel fuels. *Energy Conversion and Management*, **50**, pp. 14-34.

den Elzen, M., D. van Vuuren, and J. van Vliet (2010). Postponing emission reductions from 2020 to 2030 increases climate risks and long-term costs. *Climatic Change*, **99**(1), pp. 313-320.

Dias de Moraes, M.A.F. (2007). Indicadores do mercado de trabalho do sistema agroindustrial da cana-de-açúcar do Brasil no período 1992-2005. *Estudos Econ. (São Paulo)*, **37**(4), pp. 875-902.

Diaz-Balteiro, L., and L.C.E. Rodriguez (2006). Optimal rotations on Eucalyptus plantations including carbon sequestration – A comparison of results in Brazil and Spain. *Forest Ecology and Management*, **229**(1-3), pp. 247-258.

DiTomaso, J.M., J.K. Reaser, C.P. Dionigi, O.C. Doering, E. Chilton, J.D. Schardt, and J.N. Barney (2010). Biofuel vs. bioinvasion: seeding policy priorities. *Environmental Science & Technology*, **44**(18), pp. 6906-6910.

Dominguez-Faus, R., S.E. Powers, J.G. Burken, and P.J. Alvarez (2009). The water footprint of biofuels: A drink or drive issue? *Environmental Science & Technology*, **43**(9), pp. 3005-3010.

Dondini, M., A. Hastings, G. Saiz, M.B. Jones, and P. Smith (2009). The potential of Miscanthus to sequester carbon in soils: comparing field measurements in Carlow, Ireland to model predictions. *Global Change Biology Bioenergy*, **1**(6), pp. 413-425.

Donner, S.D., and C.J. Kucharik (2008). Corn-based ethanol production compromises goal of reducing nitrogen export by the Mississippi River. *Proceedings of the National Academy of Sciences*, **105**(11), pp. 4513-4518.

Doornbosch, V., and R. Steenblik (2008). Biofuels: Is the cure worse than the disease? In: *Round Table on Sustainable Development*, 11-12 September 2007, Organisation for Economic Co-operation and Development, Paris, France.

Dornburg, V., and A.P.C. Faaij (2001). Efficiency and economy of wood-fired biomass energy systems in relation to scale regarding heat and power generation using combustion and gasification technologies. *Biomass and Bioenergy*, **21**(2), pp. 91-108.

Dornburg, V., and A.P.C. Faaij (2005). Cost and CO_2-emission reduction of biomass cascading: methodological aspects and case study of SRF poplar. *Climatic Change*, **71**(3), pp. 373-408.

Dornburg, V., and G. Marland (2008). Temporary storage of carbon in the biosphere does have value for climate change mitigation: a response to the paper by Miko Kirschbaum. *Mitigation and Adaptation Strategies for Global Change*, **13**(3), pp. 211-217.

Dornburg, V., J. Vandam, and A. Faaij (2007). Estimating GHG emission mitigation supply curves of large-scale biomass use on a country level. *Biomass and Bioenergy*, **31**(1), pp. 46-65.

Dornburg, V., A. Faaij, P. Verweij, H. Langeveld, G. van de Ven, F. Wester, H. van Keulen, K. van Diepen, M. Meeusen, M. Banse, J. Ros, D. van Vuuren, G.J. van den Born, M. van Oorschot, F. Smout, J. van Vliet, H. Aiking, M. Londo, H. Mozaffarian, K. Smekens, E. Lysen, and S. van Egmond (2008). *Assessment of Global Biomass Potentials and their Links to Food, Water, Biodiversity, Energy Demand and Economy.* WAB 500102 012, The Netherlands Environmental Assessment Agency, Bilthoven, The Netherlands, 108 pp.

Dornburg, V., D. van Vuuren, G. van de Ven, H. Langeveld, M. Meeusen, M. Banse, M. van Oorschot, J. Ros, G.J. van den Born, H. Aiking, M. Londo, H. Mozaffarian, P. Verweij, E. Lysen, and A. Faaij (2010). Bioenergy revisited: Key factors in global potentials of bioenergy. *Energy & Environmental Science*, **3**, pp. 258-267.

Drigo, R., G. Chirici, B. Lasserre, and M. Marchetti (2007). Analisi su base geografica della domanda e dell'offerta di combustibili legnosi in Italia. (Geographical analysis of demand and supply of woody fuel in Italy). *L'italia Forestale e Montana*, **LXII**(5/6), pp. 303-324.

Drigo, R., A. Anschau, N. Flores Marcos, and S. Carballo (2009). *Análisis del balance de energia derivada de biomasa en Argentina – WISDOM Argentina.* Project TCP/ARG/3103 of FAO Dendroenergy, FAO Forestry Department, Rome, Italy, 102 pp.

Dudley, T.L. (2000). Arundo donax. In: *Invasive Plants of California's Wildlands.* C. Bossard and J. Randall (eds.), University of California Press, Berkeley, CA, USA, pp. 53-58.

Dufey, A. (2006). *Biofuels Production, Trade and Sustainable Development: Emerging Issues.* International Institute for Environment and Development, London, UK, 62 pp.

Dupraz, C., and F. Liagre (2008). *Agroforestry: Trees and Crops.* La France Agricole, Paris, France.

Dutta, A., N. Dowe, K.N. Ibsen, D.J. Schell, and A. Aden (2010). An economic comparison of different fermentation configurations to convert corn stover to ethanol using *Z. mobilis* and *Saccharomyces*. *Biotechnology Progress*, **26**(1), pp. 64-72.

Duvick, D.N., and K.G. Cassman (1999). Post-green revolution trends in yield potential of temperate maize in the north-central United States. *Crop Science*, **39**(6), pp. 1622-1630.

Dymond, C.C., B.D. Titus, G. Stinson, and W.A. Kurz (2010). Future quantities and spatial distribution of harvesting residue and dead wood from natural disturbances in Canada. *Forest Ecology and Management*, **260**(2), pp. 181-192.

E4tech (2009). *Review of the Potential for Biofuels in Aviation.* Committee on Climate Change (CCC) of the U.K. Government, London, UK, 117 pp.

E4tech (2010). *Biomass Prices in the Heat and Electricity Sectors in the UK.* Report prepared for the UK Department of Energy and Climate Change. URN 10D/546, E4tech, London, UK, 33 pp.

Easterling, W.E., J. Morton, J.F. Soussana, J. Schmidhuber, F.N. Tubiello, P.K. Aggarwal, P. Batima, K.M. Brander, L. Erda, S.M. Howden, and A. Kirilenko (2007). Food, fibre and forest products. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability: Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson (eds.), Cambridge University Press, pp. 273-313.

Eaton, J., N. McGoff, K. Byrne, P. Leahy, and G. Kiely (2008). Land cover change and soil organic carbon stocks in the Republic of Ireland 1851–2000. *Climatic Change*, **91**(3), pp. 317-334.

Ecobilan (2002). *Energy and Greenhouse Gas Balances of Biofuels' Production Chains in France.* Ecobilan, Neuilly-sur-Seine Cedex, France, 9 pp.

Econ Poyry (2008). *Current Bioenergy Application and Conversion Technologies in the Nordic Countries.* 2008-052, Nordic Energy Research, Copenhagen, Denmark, 37 pp.

Edenhofer, O., B. Knopf, M. Leimbach, and N. Bauer (2010). The economics of low stabilization. *The Energy Journal*, **31**(Special Issue 1), pp. 57-90.

Edgerton, M.D. (2009). Increasing crop productivity to meet global needs for feed, food, and fuel. *Plant Physiology*, **149**(1), pp. 7-13.

Edwards, R., D. Mulligan, and L. Marelli (2010). *Indirect Land Use Change from Increased Biofuel Demand. Comparison of Models and Results for Marginal Biofuels Production from Different Feedstocks.* EUR 24485 EN-2010, European Commission, Joint Research Centre, Institute for Energy, Ispra, Italy, 150 pp.

Edwards, R., J.F. Larivé, V. Mahieu, and P. Rouveirolles (2007). *Well-To-Wheels Analysis of Future Automotive Fuels and Power Trains in the European Context.* Version 2c, Joint Research Center, Brussels, Belgium, 88 pp.

Edwards, R., J.F. Larivé, V. Mahieu, and P. Rouveirolles (2008). *Well-To-Wheels analysis of future automotive fuels and power trains in the European context.* Version 3, Joint Research Center, Brussels, Belgium, 43 pp.

EEA (2006). *How Much Bioenergy can Europe Produce without Harming the Environment?* European Environment Agency (EEA), Copenhagen, Denmark, 72 pp.

EEA (2007). *Estimating the Environmentally Compatible Bio-energy Potential from Agriculture.* European Environment Agency (EEA), Copenhagen, Denmark.

Egsgaard, H.U., P. Hansen, J. Arendt, P. Glarborg, and C. Nielsen (2009). Combustion and gasification technologies. In: *Risø Energy Report 2.* Risø, Roskilde, Denmark, pp. 35-39.

EIA (2009). *2006 Energy Consumption by Manufacturers – Data Table 7.2.* U.S. Energy Information Administration, U.S. Department of Energy, Washington, DC, USA.

EIA (2010a). *Annual Energy Review*, DOE/EIA-0384(2009) updated August 2011, Energy Information Administration, U.S. Department of Energy, Washington, DC, USA.

EIA (2010b). *Updated Capital Costs for Electricity Generation Plants.* U.S. Energy Information Administration, U.S. Department of Energy, Washington, DC, USA.

EISA, 2007. *Energy Independence and Security Act*, United States Congress, Public Law 110-140. U.S. Government Printing Office, Washington, DC, USA.

Eisenbies, M., E. Vance, W. Aust, and J. Seiler (2009). Intensive utilization of harvest residues in southern pine plantations: Quantities available and implications for nutrient budgets and sustainable site productivity. *BioEnergy Research*, **2**(3), pp. 90-98.

Elander, R., B. Dale, M. Holtzapple, M. Ladisch, Y. Lee, C. Mitchinson, J. Saddler, and C. Wyman (2009). Summary of findings from the Biomass Refining Consortium for Applied Fundamentals and Innovation (CAFI): corn stover pretreatment. *Cellulose*, **16**(4), pp. 649-659.

Elferink, E.V., and S. Nonhebel (2007). Variations in land requirements for meat production. *Journal of Cleaner Production*, **15**, pp. 1778-1786.

Elliott, D.C. (2008). Catalytic hydrothermal gasification of biomass. *Biofuels, Bioproducts, Biorefining*, **2**, pp. 254-265.

Elobeid, A., and C. Hart (2007). Ethanol expansion in the food versus fuel debate: How will developing countries fare? *Journal of Agricultural & Food Industrial Organization*, **5**(2), pp. 1-21.

EMBRAPA (2010). *Brazilian Sugarcane Agroecological Zoning (in English), Zoneamento Agroecológico da Cana de Açúcar (in Portuguese).* Empresa Brasileira de Pesquisa Agropecuária (Brazilian Agricultural Research Corporation, EMBRAPA), Brasilia, Brazil, 58 pp.

EPA (2010). *Renewable Fuel Standard Program (RFS2) Regulatory Impact Analysis.* EPA-420-R-10-006, Environmental Protection Agency, Washington, DC, USA, 1120 pp.

EPE (2008). *Plano Decenal De Expansao De Energia 2008 – 2017.* Ministry of Mines and Energy Secretariat of Planning and Energy Development, Brasilia, Brazil, 354 pp.

EPE (2010). *2010 Balanco Energetico Nacional - Ano Base 2009.* CDU 620.9:553.04(81), Ministry of Mines and Energy and Energy Planning Enterprise (EPE), Brasilia, Brazil, 271 pp.

EPRI (2008). *Technical Performance Indicators for Biomass Energy.* Electric Power Research Institute, Palo Alto, CA, USA, 86 pp.

Ericsson, K., and L.J. Nilsson (2006). Assessment of the potential biomass supply in Europe using a resource-focused approach. *Biomass and Bioenergy*, **30**(1), pp. 1-15.

Ericsson, K., H. Rosenqvist, and L.J. Nilsson (2009). Energy crop production costs in the EU. *Biomass and Bioenergy*, **33**(11), pp. 1577-1586.

Erikson, S., and M. Prior (1990). *The Briquetting of Agricultural Wastes for Fuel.* FAO paper No. 11, Food and Agriculture Organization, Rome, Italy.

EurObserv'ER (2010). Biofuels barometer/Baromètre Biocarburant Observ'ER. *Systèmes Solaires le journal des énergies renouvelables*, Paris, France, pp. 72-96.

European Commission (2009). *Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources.* European Commission, Brussels, Belgium.

European Commission (2010). *Report from the commission to the council and the European parliament on sustainability requirements for the use of solid and gaseous biomass sources in electricity, heating and cooling.* SEC(2010) 65, European Commission, Brussels, Belgium, 20 pp.

Evans, L.T. (2003). Agricultural intensification and sustainability. *Outlook on Agriculture*, **32**(2), pp. 83-89.

Evenson, R.E., and D. Gollin (2003). Assessing the impact of the Green Revolution, 1960 to 2000. *Science*, **300**(5620), pp. 758-762.

Ezeji, T., N. Quereshi, and H.P. Blaschek (2007a). Butanol production from agricultural residues: impact of degradation products on Clostridium beijerinckii growth and butanol fermentation. *Biotechnology and Bioengineering*, **97**(6), pp. 1460-1467.

Ezeji, T.C., N. Qureshi, and H.P. Blaschek (2007b). Bioproduction of butanol from biomass: from genes to bioreactors. *Current Opinion in Biotechnology*, **18**(3), pp. 220-227.

Ezzati, M., A. Lopez, S. Vander Hoorn, A. Rodgers, and C.L.J. Murray (2002). Comparative Risk Assessment Collaborative Group. Selected major risk factors and global regional burden of disease. *The Lancet*, **360**(9343), pp. 1347-1360.

Ezzati, M., R. Bailis, D.M. Kammen, T. Holloway, L. Price, L.A. Cifuentes, B. Barnes, A. Chaurey, and K.N. Dhanapala (2004). Energy management and global health. *Annual Review of Environment and Resources*, **29**(1), pp. 383-419.

Faaij, A. (2006). Modern biomass conversion technologies. *Mitigation and Adaptation Strategies for Global Change*, **11**(2), pp. 335-367.

Fagernäs, L., A. Johansson, C. Wilén, K. Sipilä, T. Mäkinen, S. Helynen, E. Daugherty, H. den Uil, J. Vehlow, T. Kåberger, and M. Rogulska (2006). *Bioenergy in Europe: Opportunities and Barriers.* VTT Res. Notes 2532, VTT, Espoo, Finland, 122 pp.

Fallot, A., L. Saint-Andre, G. Le Maire, J.-P. Laclau, Y. Nouvellon, C. Marsden, J.-P. Bouillet, T. Silva, M.-G. Piketty, and O. Hamel (2009). Biomass sustainability, availability and productivity. *Revue de Métallurgie Paris*, **106**(10), pp. 410-418.

FAO (1985). Industrial charcoal making technologies. In: *Industrial Charcoal Making.* FAO Forestry Paper 63, FAO Forestry Department, Food and Agriculture Organization, Rome, Italy. Available at: www.fao.org/docrep/X5555E/x5555e02.htm#1.1%20what%20are%20industrial%20charcoal%20making%20methods.

FAO (2004). *The State of Food and Agriculture 2003-2004 – Agricultural Biotechnology: Meeting the Needs of the Poor?* 0081-4539, Food and Agriculture Organization, Rome, Italy, 196 pp.

FAO (2005). *World Forest Assessment.* Food and Agriculture Organization, Rome, Italy, 166 pp.

FAO (2006). *Energy and Gender in Rural Sustainable Development.* Food and Agriculture Organization, Rome, Italy, 46 pp.

FAO (2008a). *The State of Food and Agriculture 2008 – Biofuels: Prospects, Risks, and Opportunities.* Food and Agriculture Organization, Rome, Italy, 138 pp.

FAO (2008b). The role of agricultural biotechnologies for production of bioenergy in developing countries. In: *Background Document to Conference 15 of the FAO Biotechnology Forum*, 10 November to 14 December 2008, Food and Agriculture Organization, Rome, Italy.

FAO (2010a). *What Woodfuels can do to Mitigate Climate Change.* 0258-6150, Food and Agricultural Organization (FAO), Rome, Italy, 98 pp.

FAO (2010b). *Criteria and Indicators for Sustainable Biofuels.* FAO Forestry Paper 160, Food and Agricultural Organization (FAO), Rome, Italy, 102 pp.

FAOSTAT (2011). *FAOSTAT.* Food and Agriculture Organization, Rome, Italy. Available at: faostat.fao.org/default.aspx.

FAPRI (2009). *FAPRI 2009: U.S. and World Agricultural Outlook.* Food and Agricultural Policy Research Institute, Ames, Iowa, 411 pp.

Fargione, J., J. Hill, D. Tilman, S. Polasky, and P. Hawthorne (2008). Land clearing and the biofuel carbon debt. *Science*, **319**(5867), pp. 1235-1238.

Farley, K.A., E.G. Jobbagy, and R.B. Jackson (2005). Effects of afforestation on water yield: a global synthesis with implications for policy. *Global Change Biology*, **11**(10), pp. 1565-1576.

Farrell, A.E., R.J. Plevin, B.T. Turner, A.D. Jones, M. O'Hare, and D.M. Kammen (2006). Ethanol can contribute to energy and environmental goals. *Science*, **311**(5760), pp. 506-508.

Fearnside, P.M. (2008). The roles and movements of actors in the deforestation of Brazilian Amazonia. *Ecology and Society*, **13**(23), pp. 23-55.

Feng, Z., K.J. Stadt, and V.J. Lieffers (2006). Linking juvenile white spruce density, dispersion, stocking, and mortality to future yield. *Canadian Journal of Forest Research*, **36**, pp. 3173-3182.

Field, C.B., J.E. Campbell, and D.B. Lobell (2008). Biomass energy: the scale of the potential resource. *Trends in Ecology & Evolution*, **23**(2), pp. 65-72.

Fingerman, K.R., M.H. Torn, M.S. O'Hare, and D.M. Kammen (2010). Accounting for the water impacts of ethanol production. *Environmental Research Letters*, **5**(1), 014020 (7pp.).

Firbank, L. (2008). Assessing the ecological impacts of bioenergy projects. *BioEnergy Research*, **1**(1), pp. 12-19.

Fischer, G., and L. Schrattenholzer (2001). Global bioenergy potentials through 2050. *Biomass and Bioenergy*, **20**(3), pp. 151-159.

Fischer, G., H. van Velthuizen, M. Shah, and F. Nachtergaele (2002). *Global Agro-ecological Assessment for Agriculture in the 21st Century: Methodology and Results.* RR-02-02, International Institute for Applied Systems Analysis, Laxenburg, Austria, 156 pp.

Fischer, G., F. Nachtergaele, S. Prieler, F. Teixeira, H. van Velthuizen, L. Verelst, and D. Wiberg (2008). *Global Agro-ecological Zones Assessment for Agriculture (GAEZ 2008).* Version 2, International Institute for Applied Systems Analysis and Food and Agriculture Organization, Laxenburg, Austria and Rome, Italy, 43 pp.

Fischer, G., E. Hizsnyik, S. Prieler, M. Shah, and H. van Velthuizen (2009). *Biofuels and Food Security.* The OPEC Fund for International Development (OFID) and International Institute of Applied Systems Analysis (IIASA), Vienna, Austria, 228 pp.

Fischer, G., S. Prieler, H. van Velthuizen, G. Berndes, A. Faaij, M. Londo, and M. de Wit (2010). Biofuel production potentials in Europe: Sustainable use of cultivated land and pastures, Part II: Land use scenarios. *Biomass and Bioenergy*, **34**(2), pp. 173-187.

Fitzherbert, E.B., M.J. Struebig, A. Morel, F. Danielsen, C.A. Brühl, P.F. Donald, and B. Phalan (2008). How will oil palm expansion affect biodiversity? *Trends in Ecology & Evolution*, **23**(10), pp. 538-545.

Fleming, J.S., S. Habibi, and H.L. MacLean (2006). Investigating the sustainability of lignocellulose-derived fuels for light-duty vehicles. *Transportation Research Part D: Transport and Environment*, **11**(2), pp. 146-159.

Foley, J.A., R. DeFries, G.P. Asner, B. Carol, G. Bonan, S.R. Carpenter, F.S. Chapin, M.T. Coe, G.C. Daily, H.K. Gibbs, J.H. Helkowski, T. Holloway, E.A. Howard, C.J. Kucharik, C. Monfreda, J.A. Patz, I.C. Prentice, N. Ramankutty, and P.K. Snyder (2005). Global consequences of land use. *Science*, **309**(5734), pp. 570-574.

Folha (2005). Bagaço da cana será usado para fabricação de papel. *Folha da Região - Araçatuba.* São Paulo, Brazil.

Folke, C., S. Carpenter, B. Walker, M. Scheffer, T. Elmqvist, L. Gunderson, and C.S. Holling (2004). Regime shifts, resilence, and biodiversity in ecosystem management. *Annual Review of Ecology, Evolution, and Systematics*, **35**(1), pp. 557-581.

Folke, C., F.S. Chapin, and P. Olsson (2009). Transformations in ecosystem stewardship. In: *Principles of Ecosystem Stewardship: Resilience-Based Natural Resource Management in a Changing World.* F.S. Chapin III, G.P. Kofinas, and C. Folke (eds.), Springer Verlag, New York, NY, USA, pp. 103-128.

Forman, J. (2003). The introduction of American plant species into Europe: issues and consequences. In: *Plant Invasions: Ecological Threats and Management Solutions.* L. Child, J. H. Brock, G. Brundu, K. Prach, P. Pysek, P. M. Wade, and M. Williamson (eds.), Backhuys Publishers, Leiden, Netherlands, pp. 17-39.

Foust, T.D., A. Aden, A. Dutta, and S. Phillips (2009). Economic and environmental comparison of a biochemical and a thermochemical lignocellulosic ethanol conversion process. *Cellulose*, **16**, pp. 547-565.

Francis, G., R. Edinger, and K. Becker (2005). A concept for simultaneous wasteland reclamation, fuel production, and socio-economic development in degraded areas in India: Need, potential and perspectives of Jatropha plantations. *Natural Resources Forum*, **29**(1), pp. 12-24.

Fritsche, U., K. Hennenberg, and K. Hünecke (2010). *The "iLUC factor" as a Means to Hedge Risks of GHG Emissions from Indirect Land Use Change.* Öko Institute, Darmstadt, Germany, 64 pp.

Fulton, L., T. Howes, and J. Hardy (2004). *Biofuels for Transport - An International Perspective.* Organization for Economic Cooperation and Development and International Energy Agency, Paris, France, 210 pp.

GAIN (2009a). *Biofuel's Impact on Food Crops (China).* CH9059, Global Agriculture Information Network, United States Department of Agriculture, Washington, DC, USA, 14 pp.

GAIN (2009b). *Biofuel's Impact on Food Crops (Indonesia).* ID9017, Global Agriculture Information Network, United States Department of Agriculture, Washington, DC, 7 pp.

GAIN (2009c). *Biofuel's Impact on Food Crops (Thailand).* TH9047, Global Agriculture Information Network, United States Department of Agriculture, Washington, DC, USA, 11 pp.

GAIN (2010a). *Biofuel's Impact on Food Crops (Argentina).* Global Agriculture Information Network, United States Department of Agriculture, Washington, DC, USA, 15 pp.

GAIN (2010b). *Biofuel's Impact on Food Crops (Brazil).* BR10006, Global Agriculture Information Network, United States Department of Agriculture, Washington, DC, USA, 52 pp.

GAIN (2010c). *Biofuel's Impact on Food Crops (Canada).* CA0023, Global Agriculture Information Network, United States Department of Agriculture, Washington, DC, USA, 34 pp.

GAIN (2010d). *Biofuel's Impact on Food Crops (India).* IN1058, Global Agriculture Information Network, United States Department of Agriculture, Washington, DC, USA, 11 pp.

GAIN (2010e). *Biofuel's Impact on Food Crops (Korea).* KS1001, Global Agriculture Information Network, United States Department of Agriculture, Washington, DC, USA, 6 pp.

GAIN (2010f). *Biofuel's Impact on Food Crops (Malaysia).* MY0008, Global Agriculture Information Network, United States Department of Agriculture, Washington, DC, USA, 9 pp.

GAIN (2010g). *Biofuel's Impact on Food Crops (Peru).* Global Agriculture Information Network, United States Department of Agriculture, Washington, DC, USA, 7 pp.

GAIN (2010h). *Biofuel's Impact on Food Crops (Philippines).* Global Agriculture Information Network, United States Department of Agriculture, Washington, DC, USA, 21 pp.

GAIN (2010i). *Biofuel's Impact on Food Crops (Thailand).* TH0098, Global Agriculture Information Network, United States Department of Agriculture, Washington, DC, USA, 15 pp.

GAIN (2010j). *Biofuel's Impact on Food Crops (Turkey).* Global Agriculture Information Network, United States Department of Agriculture, Washington, DC, USA, 6 pp.

Galdos, M.V., C.C. Cerri, R. Lal, M. Bernoux, B. Feigl, and C.E.P. Cerri (2010). Net greenhouse gas fluxes in Brazilian ethanol production systems. *Global Change Biology Bioenergy*, **2**(1), pp. 37-44.

Gallagher, E. (2008). *The Gallagher Review of the Indirect Effects of Biofuels Production.* Renewable Fuels Agency, London, UK, 92 pp.

Gallagher, P., M. Dikeman, J. Fritz, E. Wailes, W. Gauther, and H. Shapouri (2003). *Biomass from Crop Residues: Cost and Supply Estimates.* Agricultural Economic Report No. 819, Economic Research Service, United States Department of Agriculture, Washington, DC, USA, 30 pp.

Gan, J. (2007). Supply of biomass, bioenergy, and carbon mitigation: Method and application. *Energy Policy*, **35**(12), pp. 6003-6009.

Gan, J., and C. Smith (2010). Integrating biomass and carbon values with soil productivity loss in determining forest residue removals. *Biofuels*, **1**(4), pp. 539-546.

García-Frapolli, E., A. Schilmann, V.M. Berrueta, H. Riojas-Rodríguez, R.D. Edwards, M. Johnson, A. Guevara-Sanginés, C. Armendariz, and O. Masera (2010). Beyond fuelwood savings: Valuing the economic benefits of introducing improved biomass cookstoves in the Purépecha region of Mexico. *Ecological Economics*, **69**(12), pp. 2598-2605.

Garg, V.K. (1998). Interaction of tree crops with a sodic soil environment: potential for rehabilitation of degraded environments. *Land Degradation & Development*, **9**(1), pp. 81-93.

Garrison, T. (2008). *Essentials of Oceanography.* 5th ed., Brooks/Cole Cengage Learning, Belmont, CA, USA, 464 pp.

GBEP (2008). *A Review of the Current State of Bioenergy Development in G8+5 Countries.* Global Bioenergy Partnership (GBEP), Food and Agriculture Organization of the United Nations, Rome, Italy, 278 pp.

Gerasimov, Y., and T. Karjalainen (2009). *Estimation of supply and delivery cost of energy wood from Northwest Russia.* Working Papers of the Finnish Forest Research Institute Number 123, Finnish Forest Research Institute, Vantaa, Finland, 21 pp.

Gerbens-Leenes, P., and S. Nonhebel (2002). Consumption patterns and their effects on land required for food. *Ecological Economics*, **42**(1-2), pp. 185-199.

Gerbens-Leenes, W., A.Y. Hoekstra, and T.H. van der Meer (2009). The water footprint of bioenergy. *Proceedings of the National Academy of Sciences*, **106**(25), pp. 10219-10223.

Gerber, N. (2008). *Bioenergy and Rural Development in Developing Countries: A Review of Existing Studies.* Discussion Papers On Development Policy No. 122, Center for Development Research (ZEF), Bonn, Germany, 58 pp.

Gerten, D., W. Lucht, S. Schaphoff, W. Cramer, T. Hickler, and W. Wagner (2005). Hydrologic resilience of the terrestrial biosphere. *Geophysical Research Letters*, **32**(21), L21408.

Gibbs, H.K., M. Johnston, J.A. Foley, T. Holloway, C. Monfreda, N. Ramankutty, and D. Zaks (2008). Carbon payback times for crop-based biofuel expansion in the tropics: the effects of changing yield and technology. *Environmental Research Letters*, **3**(3), 034001 (10 pp.).

Gielen, D., J. Newman, and M.K. Patel (2008). Reducing industrial energy use and CO_2 emissions: The role of materials science. In: *MRS Bulletin Harnessing Materials for Energy*, **33**, pp. 471-477.

Gisladottir, G., and M. Stocking (2005). Land degradation control and its global environmental benefits. *Land Degradation & Development*, **16**(2), pp. 99-112.

Glass, R. (2006). Disease control priorities in developing countries. *The New England Journal of Medicine*, **355**(10), pp. 1074-1075.

Godfray, H.C.J., C. Toulmin, J.R. Beddington, I.R. Crute, L. Haddad, D. Lawrence, J.F. Muir, J. Pretty, S. Robinson, and S.M. Thomas (2010). Food security: The challenge of feeding 9 billion people. *Science*, **327**(5967), pp. 812-818.

Goldemberg, J., S.T. Coelho, P.M. Nastari, and L. O (2004). Ethanol learning curve - the Brazilian experience. *Biomass and Bioenergy*, **26**, pp. 301-304.

Gorissen, L., V. Buytaert, D. Cuypers, T. Dauwe, and L. Pelkmans (2010). Why the debate about land use change should not only focus on biofuels. *Environmental Science & Technology*, **44**(11), pp. 4046-4049.

Grann, H. (1997). The industrial symbiosis at Kalundborg, Denmark. In: *The Industrial Green Game. Implications for Environmental Design and Management.* D.J. Richards (ed.), National Academy Press, Washington, DC, USA, pp. 117-123.

Grassi, G., A. Nardi, and S. Vivarelli (2006). Low cost production of bioethanol from sweet sorghum. In: *Proceedings of the 14th European Biomass Conference*, Paris, France, 17-21 October 2005, pp. 91-95.

Green, R.E., S.J. Cornell, J.P.W. Scharlemann, and A. Balmford (2005). Farming and the fate of wild nature. *Science*, **307**(5709), pp. 550-555.

Gronowska, M., S. Joshi, and H.L. MacLean (2009). A review of U.S. and Canadian biomass supply studies. *BioResources*, **4**(1), pp. 341-369.

Grove, S. and J. Hanula (eds) (2006). *Insect Biodiversity and Dead Wood: Proceedings of the 22nd International Congress of Entomology.* Report SRS–93, United States Department of Agriculture, Asheville, NC, USA, 109 pp.

Guille, T. (2007). *Evaluation of the Potential Uses of Agricultural Residues for Energy Purposes.* Master's Thesis, Montpellier SupAgro, Paris, France.

Gunderson, P. (2008). Biofuels and North American agriculture - Implications for the health and safety of North American producers. *Journal of Agromedicine*, **13**(4), pp. 219-224.

Gurbuz, E.I., E.L. Kunkes, and J.A. Dumesic (2010). Dual-bed catalyst system for C–C coupling of biomass-derived oxygenated hydrocarbons to fuel-grade compounds. *Green Chemistry*, **12**(2), pp. 223-227.

Gustavsson, L., J. Holmberg, V. Dornburg, R. Sathre, T. Eggers, K. Mahapatra, and G. Marland (2007). Using biomass for climate change mitigation and oil use reduction. *Energy Policy*, **35**(11), pp. 5671-5691.

Haas, M.J., A.J. McAloon, W.C. Yee, and T.A. Foglia (2006). A process model to estimate biodiesel production costs. *Bioresource Technology*, **97**(4), pp. 671-678.

Haberl, H., K.H. Erb, F. Krausmann, V. Gaube, A. Bondeau, C. Plutzar, S. Gingrich, W. Lucht, and M. Fischer-Kowalski (2007). Quantifying and mapping the human appropriation of net primary production in earth's terrestrial ecosystems. *Proceedings of the National Academy of Sciences*, **104**(31), pp. 12942-12947.

Haberl, H., T. Beringer, S.C. Bhattacharya, K.-H. Erb, and M. Hoogwijk (2010). The global technical potential of bio-energy in 2050 considering sustainability constraints. *Current Opinion in Environmental Sustainability*, **2**(5-6), pp. 394-403.

Hakala, K., M. Kontturi, and K. Pahkala (2009). Field biomass as global energy source. *Agricultural and Food Science*, **18**, pp. 347-365.

Hamelinck, C.N. (2004). *Outlook for Advanced Biofuels.* Master's Thesis, University of Utrecht, Utrecht, The Netherlands, 232 pp.

Hamelinck, C.N., and A.P.C. Faaij (2002). Future prospects for production of methanol and hydrogen from biomass. *Journal of Power Sources*, **111**(1), pp. 1-22.

Hamelinck, C.N., and A.P.C. Faaij (2006). Outlook for advanced biofuels. *Energy Policy*, **34**(17), pp. 3268-3283.

Hamelinck, C.N., A.P.C. Faaij, H. den Uil, and H. Boerrigter (2004). Production of FT transportation fuels from biomass; technical options, process analysis and optimisation, and development potential. *Energy*, **29**(11), pp. 1743-1771.

Hamelinck, C.N., G.v. Hooijdonk, and A.P.C. Faaij (2005a). Ethanol from lignocellulosic biomass: techno-economic performance in short-, middle- and long-term. *Biomass and Bioenergy*, **28**(4), pp. 384-410.

Hamelinck, C.N., R.A.A. Suurs, and A.P.C. Faaij (2005b). International bioenergy transport costs and energy balance. *Biomass and Bioenergy*, **29**(2), pp. 114-134.

Hartley, M.J. (2002). Rationale and methods for conserving biodiversity in plantation forests. *Forest Ecology and Management*, **155**(1-3), pp. 81-95.

Headey, D., and S. Fan (2008). Anatomy of a crisis: the causes and consequences of surging food prices. *Agricultural Economics*, **39**, pp. 375-391.

Heggenstaller, A.H., R.P. Anex, M. Liebman, D.N. Sundberg, and L.R. Gibson (2008). Productivity and nutrient dynamics in bioenergy double-cropping systems. *Agronomy Journal*, **100**(6), pp. 1740-1748.

Heinimö, J., and M. Junginger (2009). Production and trading of biomass for energy – An overview of the global status. *Biomass and Bioenergy*, **33**(9), pp. 1310-1320.

Helynen, S., M. Flyktman, T. Mäkinen, K. Sipilä, and P. Vesterinen (2002). *The possibilities of bioenergy in reducing greenhouse gases.* VTT Tiedotteita 2145, VTT Technical Research Centre of Finland, Espoo, Finland, 110 pp.

Hemakanthi, D.A., and D.N. Heller (2010). Multiclass, multiresidue method for the detection of antibiotic residues in distillers grains by liquid chromatography and ion trap tandem mass spectrometry. *Journal of Chromatography A*, **1217**(18), pp. 3076-3084.

Herrero, M., J. van de Steeg, J. Lynam, P.P. Rao, S. Macmillan, B. Gerard, J. McDermott, C. Sere, M. Rosegrant, P.K. Thornton, A.M. Notenbaert, S. Wood, S. Msangi, H.A. Freeman, D. Bossio, J. Dixon, and M. Peters (2010). Smart investments in sustainable food production: Revisiting mixed crop-livestock systems. *Science*, **327**(5967), pp. 822-825.

Hertel, T.W., A.A. Golub, A.D. Jones, M. O'Hare, R.J. Plevin, and D.M. Kammen (2010a). Effects of US maize ethanol on global land use and greenhouse gas emissions: Estimating market mediated responses. *BioScience*, **60**(3), pp. 223-231.

Hertel, T.W., W.E. Tyner, and D.K. Birur (2010b). Global impacts of biofuels. *Energy Journal*, **31**(1), pp. 35-100.

Hettinga, W.G., H.M. Junginger, M. Hoogwijk, A. McAloon, and T. Hickler (2007). Technological learning in U.S. ethanol production. In: *15th European Biomass Conference and Exhibition*, Berlin, Germany, 7-11 May 2007.

Hettinga, W.G., H.M. Junginger, S.C. Dekker, M. Hoogwijk, A.J. McAloon, and K.B. Hicks (2009). Understanding the reductions in US corn ethanol production costs: An experience curve approach. *Energy Policy*, **37**(1), pp. 190-203.

Hiederer, R., F. Ramos, C. Capitani, R. Koeble, V. Blujdea, O. Gomez, D. Mulligan, and L. Marelli (2010). *Biofuels: A New Methodology to Estimate GHG Emissions from Global Land Use Change, A methodology involving spatial allocation of agricultural land demand and estimation of CO_2 and N_2O emissions.* EUR 24483 EN - 2010, Joint Research Center, European Commission, Ispa, Italy, 168 pp.

Hill, J. (2007). Environmental costs and benefits of transportation biofuel production from food- and lignocellulose-based energy crops. A review. *Agronomy for Sustainable Development*, **27**(1), pp. 1-12.

Hill, J., E. Nelson, D. Tilman, S. Polasky, and D. Tiffany (2006). Environmental, economic, and energetic costs and benefits of biodiesel and ethanol biofuels. *Proceedings of the National Academy of Sciences*, **103**(30), pp. 11206-11210.

Hill, J., S. Polasky, E. Nelson, D. Tilman, H. Huo, L. Ludwig, J. Neumann, H. Zheng, and D. Bonta (2009). Climate change and health costs of air emissions from biofuels and gasoline. *Proceedings of the National Academy of Sciences*, **106**(6), pp. 2077-2082.

Hillier, J., C. Whittaker, G. Dailey, M. Aylott, E. Casella, G.M. Richter, A. Riche, R. Murphy, G. Taylor, and P. Smith (2009). Greenhouse gas emissions from four bioenergy crops in England and Wales: Integrating spatial estimates of yield and soil carbon balance in life cycle analyses. *Global Change Biology Bioenergy*, **1**(4), pp. 267-281.

Hilman, H.J., E. Gidwani, P. Morris, S. Sagar, and S. Chowdhary (2007). *Using Microfinance to Expand Access to Energy Services: The Emerging Experiences in Asia of Self-Employed Women's Association Bank (SEWA), Sarvodaya Economic Enterprise Development Services (SEEDS), Nirdhan Utthan Bank Limited (NUBL), and AMRET.* The SEEP Network, Washington, DC, USA, 124 pp.

Himmel, M.E., Q. Xu, Y. Luo, S.-Y. Ding, R. Lamed, and E.A. Bayer (2010). Microbial enzyme systems for biomass conversion: emerging paradigms. *Biofuels*, **1**(2), pp. 323-341.

Hoefnagels, R., E. Smeets, and A. Faaij (2010). Greenhouse gas footprints of different biofuel production systems. *Renewable and Sustainable Energy Reviews*, **14**(7), pp. 1661-1694.

Hoekstra, A.Y., P.W. Gerbens-Leenes, and T.H. Van der Meer (2010). The water footprint of bio-energy. In: *Climate Change and Water: International Perspectives on Mitigation and Adaptation.* C. Howe, J.B. Smith, and J. Henderson (eds.), American Water Works Association, IWA Publishing, London, UK, pp. 81-95.

Hollebone, B.P., and Z. Yang (2009). Biofuels in the environment: A review of behaviours, fates, effects and possible remediation techniques. In: *Proceedings of the 32nd Arctic and Marine Oil Spill Program (AMOP) Technical Seminar on Environmental Contamination and Response*, Emergencies Science Division, Environment Canada, Ottawa, Canada, pp. 127-139.

Holmgren, J., R. Marinangeli, P. Nair, D. Elliott, and R. Bain (2008). Consider upgrading pyrolysis oils into renewable fuels. *Hydrocarbon Processing*, **87**(9), pp. 95-113.

Hoogwijk, M. (2004). *On the Global and Regional Potential of Renewable Energy Sources*. PhD Thesis, Utrecht University, Utrecht, The Netherlands, 257 pp.

Hoogwijk, M., A. Faaij, R. van den Broek, G. Berndes, D. Gielen, and W. Turkenburg (2003). Exploration of the ranges of the global potential of biomass for energy. *Biomass and Bioenergy*, **25**(2), pp. 119-133.

Hoogwijk, M., A. Faaij, B. Eickhout, B. de Vries, and W. Turkenburg (2005). Potential of biomass energy out to 2100, for four IPCC SRES land-use scenarios. *Biomass and Bioenergy*, **29**(4), pp. 225-257.

Hoogwijk, M., A. Faaij, B. de Vries, and W. Turkenburg (2009). Exploration of regional and global cost-supply curves of biomass energy from short-rotation crops at abandoned cropland and rest land under four IPCC SRES land-use scenarios. *Biomass and Bioenergy*, **33**(1), pp. 26-43.

Hooijer, A., M. Silvius, H. Wösten, and S. Page (2006). *PEAT- CO_2, Assessment of CO_2 Emissions from Drained Peatlands in SE Asia.* Delft Hydraulics report Q3943, WL Delft Hydraulics, Delft, The Netherlands, 41 pp.

Howard, D., and S. Ziller (2008). Alien alert – plants for biofuel may be invasive. *Bioenergy Business*, July/August, pp. 14-16.

Howarth, R.W., S. Bringezu, L.A. Martinelli, R. Santoro, D. Messem, and O.E. Sala (2009). Introduction: biofuels and the environment in the 21st century. In: *Biofuels: Environmental Consequences and Interactions with Changing Land Use.* R.W. Howarth and S. Bringezu (eds.), Proceedings of the SCOPE - Scientific Committee on Problems of the Environment International Biofuels Project Rapid Assessment, Gummersbach, Germany, 22-25 September 2009, pp. 15-36.

Hsu, D.D., D. Inman, G.A. Heath, E.J. Wolfrum, M.K. Mann, and A. Aden (2010). Life cycle environmental impacts of selected U.S. ethanol production and use pathways in 2022. *Environmental Science & Technology*, **44**, pp. 5289-5297.

Hu, Q., M. Sommerfeld, E. Jarvis, M. Ghirardi, M. Posewitz, M. Seibert, and A. Darzins (2008). Microalgal triacylglycerols as feedstocks for biofuel production: perspectives and advances. *The Plant Journal*, **54**, pp. 621-639.

Huber, G.W., R.D. Cortright, and J.A. Dumesic (2004). Renewable alkanes by aqueous-phase reforming of biomass-derived oxygenates. *Angewandte Chemie*, **116**(12), pp. 1575-1577.

Huber, G.W., J.N. Chheda, C.J. Barrett, and J.A. Dumesic (2005). Production of liquid alkanes by aqueous-phase processing of biomass-derived carbohydrates. *Science*, **308**(5727), pp. 1446-1450.

Huber, G.W., S. Iborra, and A. Corma (2006). Synthesis of transportation fuels from biomass: chemistry, catalysts, and engineering. *Chemical Reviews*, **106**(9), pp. 4044-4098.

Huertas, D.A., G. Berndes, M. Holmen, and G. Sparovek (2010). Sustainability certification of bioethanol. How is it perceived by Brazilian stakeholders? *Biomass and Bioenergy*, **4**(4), pp. 369-384.

Huo, H., M. Wang, C. Bloyd, and V. Putsche (2009). Life-cycle assessment of energy use and greenhouse gas emissions of soybean-derived biodiesel and renewable fuels. *Environmental Science & Technology*, **43**(3), pp. 750-756.

IAASTD (2009). *Agriculture at a Crossroads.* International Assessment of Agricultural Knowledge, Science and Technology for Development, Washington, DC, USA, 606 pp.

IATA (2009). *Report on Alternative Fuels.* International Air Transport Association, Montreal, Canada, 92 pp.

Ibsen, K., R. Wallace, S. Jones, and T. Werpy (2005). *Evaluating Progressive Technology Scenarios in the Development of the Advanced Dry Mill Biorefinery.* FY05-630, National Renewable Energy Laboratory, Golden, CO, USA, 35 pp.

IEA (2000). *Experience Curves for Energy Technology Policy.* International Energy Agency, Paris, France, 133 pp.

IEA (2006). *World Energy Outlook 2006.* International Energy Agency, Paris, France, 601 pp.

IEA (2007a). *World Energy Outlook 2007.* International Energy Agency, Paris, France, 600 pp.

IEA (2007b). *Biomass for Power Generation and CHP.* Energy Technology Essentials ETE03, International Energy Agency, Paris, France, 4pp.

IEA (2008a). *Energy Technology Perspectives 2008. Scenarios and Strategies to 2050.* International Energy Agency, Paris, France, 646 pp.

IEA (2008b). *World Energy Outlook 2008.* International Energy Agency, Paris, France, 578 pp.

IEA (2009). *World Energy Outlook 2009.* International Energy Agency, Paris, France, 696 pp.

IEA (2010a). *World Energy Statistics 2010.* International Energy Agency, Paris, France.[1]

IEA (2010b). *World Energy Outlook 2010.* International Energy Agency, Paris, France, 736 pp.

IEA (2010c). *Renewables Information 2010 with 2009 Data.* International Energy Agency, Paris, France, 428 pp (ISBN 978-92-64-08416-2).

IEA (2011). *Technology Roadmap: Biofuels for Transport.* International Energy Agency, Renewable Energy Division, Paris, France, 52 pp.

IEA Bioenergy (2007). *Potential Contribution of Bioenergy to the World's Future Energy Demand.* IEA Bioenergy: ExCo: 2007:02, 12 pp.

1 Combination of four IEA publications: IEA energy balances and statistics databases for most of the OECD countries for the years 1960 to 2008, with supply estimates for 2009, and energy statistics and balances for more than 100 non-OECD countries for the years 1971 to 2008.

IEA Bioenergy (2009). *Bioenergy: A Sustainable and Reliable Energy Source. Main Report.* IEA Bioenergy: ExCo:2009:06, 108 pp.

IEA Bioenergy (2010). *Algae – The Future for Bioenergy?* Summary and conclusions from the IEA Bioenergy ExCo64 Workshop. IEA Bioenergy: ExCo: 2010:02, 16 pp.

IEA Renewable Energy Division (2010). *Sustainable Production of Second-Generation Biofuels: Potential and Perspectives in Major Economies and Developing Countries.* International Energy Agency, Paris, France, 217 pp.

IFPRI (2008). *High Food Prices: The What, Who, and How of Proposed Policy Actions.* International Food Policy Research Institute, Washington, DC, USA, 12 pp.

Ileleji, K.E., S. Sokhansanj, and J.S. Cundiff (2010). Farm-gate to plant-gate delivery of lignocellulosic feedstocks from plant biomass for biofuel production. In: *Biofuels from Agricultural Wastes and Byproducts.* H.P. Blaschek, T. Ezeji, and J. Scheffran (eds.), Wiley-Blackwell, Oxford, UK, pp. 117-159.

Imhoff, M.L., L. Bounoua, T. Ricketts, C. Loucks, R. Harriss, and W.T. Lawrence (2004). Global patterns in human consumption of net primary production. *Nature*, **429**(6994), pp. 870-873.

IPCC (1996). *Climate Change 1995: Impacts, Adaptation, and Mitigation: Scientific-Technical Analyses.* R.T. Watson, M.C. Zinyowera, and R.H. Moss (eds.), Cambridge University Press, 878 pp.

IPCC (2000a). *Special Report on Emissions Scenarios.* N. Nakicenovic and R. Swart (eds.), Cambridge University Press, 570 pp.

IPCC (2000b). *Land Use, Land Use Change and Forestry.* R.T. Watson, I.R. Noble, B. Bolin, N.H. Ravindranath, D.J. Verardo and D.J. Dokken (eds.), Cambridge University Press, 375 pp.

IPCC (2005). *Special Report on Carbon Dioxide Capture and Storage.* B. Metz, O. Davidson, H. de Coninck, M. Loos, and L. Meyer (eds.), Cambridge University Press, 431 pp.

IPCC (2007a). *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson (eds.),Cambridge University Press, 979 pp.

IPCC (2007b). *Climate Change 2007: Synthesis Report. Contributions of Working Groups I, II and II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Core Writing Team, R.K. Pachauri, and A. Reisinger (eds.), Cambridge University Press, 104 pp.

IPCC (2007c). *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller (eds.), Cambridge University Press, 996 pp.

IPCC (2007d). *Climate Change 2007: Mitigation of Climate Change. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, and L.A. Meyer (eds.), Cambridge University Press, 851 pp.

IUCN (2009). *Guidelines on Biofuels and Invasive Species.* IUCN, Gland, Switzerland, 20 pp. (ISBN: 978-2-8317-1222-2).

Ivanic, M., and W. Martin (2008). Implications of higher global food prices for poverty in low-income countries. *Agricultural Economics*, **39**, pp. 405-416.

Jackson, R.B., B.C. Murray, E.G. Jobbagy, R. Avissar, S.B. Roy, D.J. Barrett, C.W. Cook, K.A. Farley, D.C. le Maitre, and B.A. McCarl (2005). Trading water for carbon with biological carbon sequestration. *Science*, **310**(5756), pp. 1944-1947.

Jacobsen, N.B. (2006). Industrial symbiosis in Kalundborg, Denmark: A quantitative assessment of economic and environmental aspects. *Journal of Industrial Ecology*, **10**(1-2), pp. 239-255.

Jaggard, K.W., A. Qi, and E.S. Ober (2010). Possible changes to arable crop yields by 2050. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **365**(1554), pp. 2835-2851.

Jauhiainen, J., S. Limin, H. Silvennoinen, and H. Vasander (2008). Carbon dioxide and methane fluxes in drained tropical peat before and after hydrological restoration. *Ecology*, **89**(12), pp. 3503-3514.

Jechura, J. (2005). *Dry Mill Cost-By-Area: ASPEN Case Summary.* National Renewable Energy Laboratory, Golden, CO, USA, 2 pp.

Jeffries, T.W. (2006). Engineering yeasts for xylose metabolism. *Current Opinion in Biotechnology*, **17**(3), pp. 320-326.

Jeffries, T.W., I.V. Grigoriev, J. Grimwood, J.M. Laplaza, A. Aerts, A. Salamov, J. Schmutz, E. Lindquist, P. Dehal, H. Shapiro, Y.-S. Jin, V. Passoth, and P.M. Richardson (2007). Genome sequence of the lignocellulose-bioconverting and xylose-fermenting yeast Pichia stipitis. *Nature Biotechnology*, **25**(3), pp. 319-326.

Jensen, E.S. (1996). Grain yield, symbiotic N_2 fixation and interspecific competition for inorganic N in pea-barley intercrops. *Plant and Soil*, **182**(1), pp. 25-38.

Jetter, J.J., and P. Kariher (2009). Solid-fuel household cook stoves: Characterization of performance and emissions. *Biomass and Bioenergy*, **33**(2), pp. 294-305.

Johansson, D., and C. Azar (2007). A scenario based analysis of land competition between food and bioenergy production in the US. *Climatic Change*, **82**(3), pp. 267-291.

Johnson, J.M.F., D. Reicosky, B. Sharratt, M. Lindstrom, W. Voorhees, and L. Carpenter-Boggs (2004). Characterization of soil amended with the by-product of corn stover fermentation. *Soil Science Society of America Journal*, **68**(1), pp. 139-147.

Johnson, M., R. Edwards, A. Ghilardi, V. Berrueta, D. Gillen, C.A. Frenk, and O. Masera (2009). Quantification of carbon savings from improved biomass cookstove projects. *Environmental Science & Technology*, **43**(7), pp. 2456-2462.

Johnson, T.M., C. Alatorre, Z. Romo, and F. Liu (2009). *Low-Carbon Development for Mexico.* The International Bank for Reconstruction and Development, The World Bank, Washington, DC, USA.

Johnston, M., and T. Holloway (2007). A global comparison of national biodiesel production potentials. *Environmental Science & Technology*, **41**(23), pp. 7967-7973.

Johnston, M., J.A. Foley, T. Holloway, C. Kucharik, and C. Monfreda (2009). Resetting global expectations from agricultural biofuels. *Environmental Research Letters*, **4**(1), 014004.

Jongschaap, R.E.E., W.J. Corré, P.S. Bindraban, and W.A. Brandenburg (2007). *Claims and Facts on Jatropha curcas L. Global Jatropha curcas Evaluation, Breeding And Propagation Programme.* Report 158, Plant Research International BV, Wageningen, The Netherlands and Stichting Het Groene Woudt, Laren, The Netherlands, 66 pp.

Junginger, M. (2007). *Lessons from (European) Bioenergy Policies; Results of a Literature Review for IEA Bioenergy Task 40.* Utrecht University, Utrecht, Netherlands, 14 pp. Available at: www.bioenergytrade.org/downloads/jungingerlessonsfromeuropeanbioenergypolicies.pdf.

Junginger, M., A. Faaij, R. van den Broek, A. Koopmans, and W. Hulscher (2001). Fuel supply strategies for large-scale bio-energy projects in developing countries. Electricity generation from agricultural and forest residues in Northeastern Thailand. *Biomass and Bioenergy*, **21**(4), pp. 259-275.

Junginger, M., A. Faaij, R. Björheden, and W.C. Turkenburg (2005). Technological learning and cost reductions in wood fuel supply chains in Sweden. *Biomass and Bioenergy*, **29**(6), pp. 399-418.

Junginger, M., E. de Visser, K. Hjort-Gregersen, J. Koornneef, R. Raven, A. Faaij, and W. Turkenburg (2006). Technological learning in bioenergy systems. *Energy Policy*, **34**(18), pp. 4024-4041.

Junginger, M., T. Bolkesjø, D. Bradley, P. Dolzan, A. Faaij, J. Heinimö, B. Hektor, Ø. Leistad, E. Ling, M. Perry, E. Piacente, F. Rosillo-Calle, Y. Ryckmans, P.-P. Schouwenberg, B. Solberg, E. Trømborg, A.d.S. Walter, and M.d. Wit (2008). Developments in international bioenergy trade. *Biomass and Bioenergy*, **32**(8), pp. 717-729.

Junginger, M., A. Faaij, J. van Dam, S. Zarrilli, A. Mohammed, and D. Marchal (2010). *Opportunities and Barriers for International Bioenergy Trade and Strategies to Overcome Them.* IEA Bioenergy Task 40, 17 pp. Available at: www.bioenergytrade.org/downloads/t40opportunitiesandbarriersforbioenergytradefi.pdf.

Jungk, N., and G. Reinhardt (2000). *Landwirtschaftliche Referenzsysteme in Ökologischen Bilanzierungen: eine Basis Analyse.* Institute für Energie- und Umweltforschung, Heidelberg, Germany.

Kaliyan, N., R.V. Morey, and D.G. Tiffany (2010). Reducing life cycle greenhouse gas emissions of corn ethanol by integrating biomass to produce heat and power at ethanol plants. *Biomass and Bioenergy*, **35**(3), pp. 1103-1113.

Kalnes, T.N., K.P. Koers, T. Marker, and D.R. Shonnard (2009). A technoeconomic and environmental life cycle comparison of green diesel to biodiesel and syndiesel. *Environmental Progress & Sustainable Energy*, **28**(1), pp. 111-120.

Kamm, B., P.R. Gruber, and M. Kamm (eds.) (2006). *Biorefineries - Industrial Processes and Products: Status Quo and Future Directions.* Wiley-VCH, Weinheim, UK, 949 pp.

Kang, S., M. Khanna, J. Scheffran, D. Zilberman, H. Önal, Y. Ouyang, and Ü.D. Tursun (2010). Optimizing the biofuels infrastructure: Transportation networks and biorefinery locations in Illinois. In: *Handbook of Bioenergy Economics and Policy.* M. Khanna, J. Scheffran, and D. Zilberman (eds.), Springer New York, New York, NY, USA, pp. 151-173.

Karekezi , S., and L. Majoro (2002). Improving modern energy services for Africa's urban poor. *Energy Policy*, **30**(11-12), pp. 1015-1028.

Karekezi, S., and P. Turyareeba (1995). Woodstove dissemination in Eastern Africa - a review. *Energy for Sustainable Development*, **1**(6), pp. 12-19.

Karlen, D.L. (2010). Corn stover feedstock trials to support predictive modeling. *Global Change Biology Bioenergy*, **2**(5), pp. 235-247.

Karp, A., and I. Shield (2008). Bioenergy from plants and the sustainable yield challenge. *New Phytologist*, **179**(1), pp. 15-32.

Kartha, S., P. Hazel, and R.K. Pachauri (2006). Environmental effects of bioenergy. In: *Bioenergy and Agriculture: Promises and Challenges.* P.B.R. Hazell and R.K. Pachauri (eds.), International Food Policy Research Institute, Washington, D.C., USA, 2 pp.

Kazi, F.K., J.A. Fortman, R.P. Anex, D.D. Hsu, A. Aden, A. Dutta, and G. Kothandaraman (2010). Techno-economic comparison of process technologies for biochemical ethanol production from corn stover. *Fuel*, **89**(Supplement 1), pp. S20-S28.

Keasling, J.D., and H. Chou (2008). Metabolic engineering delivers next-generation biofuels. *Nature Biotechnology*, **26**(3), pp. 298-299.

Keeney, D., and T.W. Hertel (2008). *Yield Response to Prices: Implications for Policy Modeling.* Working paper 08/13, Department of Agricultural Economics, Purdue University, West Lafayette, IN, USA, 37 pp.

Keeney, D., and T.W. Hertel (2009). The indirect land use impacts of United States biofuel policies: The importance of acreage, yield, and bilateral trade responses. *American Journal of Agricultural Economics*, **91**, pp. 895-909.

Keeney, D., and M. Muller (2006). *Water Use by Ethanol Plants: Potential Challenges.* Institute for Agriculture and Trade Policy, Minneapolis, MN, USA, 7 pp.

Keeney, R., and T. Hertel (2005). *GTAP-AGR : A Framework for Assessing the Implications of Multilateral Changes in Agricultural Policies.* GTAP Technical Paper No.24, Center for Global Trade Analysis, Department of Agricultural Economics, Purdue University, West Lafayette, IN, USA, 61 pp.

Kendall, A., B. Chang, and B. Sharpe (2009). Accounting for time-dependent effects in biofuel life cycle greenhouse gas emissions calculations. *Environmental Science & Technology*, **43**(18), pp. 7142-7147.

Keys, E., and W. McConnell (2005). Global change and the intensification of agriculture in the tropics. *Global Environmental Change*, **15**(4), pp. 320-337.

Kheshgi, H.S., R.C. Prince, and G. Marland (2000). The potential of biomass fuels in the context of global climate change: Focus on transportation fuels. *Annual Review of Energy and the Environment*, **25**(1), pp. 199-244.

Kim, H., S. Kim, and B.E. Dale (2009). Biofuels, land use change, and greenhouse gas emissions: Some unexplored variables. *Environmental Science & Technology*, **43**(3), pp. 961-967.

Kim, S., and B. Dale (2002). Allocation procedure in ethanol production system from corn grain i. system expansion. *The International Journal of Life Cycle Assessment*, **7**(4), pp. 237-243.

Kim, S., and B.E. Dale (2004). Global potential bioethanol production from wasted crops and crop residues. *Biomass and Bioenergy*, **26**(4), pp. 361-375.

Kinchin, C. and R.L. Bain (2009). *Hydrogen Production from Biomass via Indirect Gasification: The Impact of NREL Process Development Unit Gasifier Correlations.* NREL Report No. TP-510-44868. National Renewable Energy Laboratory, Golden, CO, USA, 27 pp.

King, C.W., and M.E. Webber (2008). Water intensity of transportation. *Environmental Science & Technology*, **42**(21), pp. 7866-7872.

King, D., O.R. Inderwildi, and A. Williams (2010). *The Future of Industrial Biorefineries.* 210610, World Economic Forum White Paper, Cologn/Geneva, Switzerland, 40 pp.

Kirkels, A., and G. Verbong (2011). Biomass gasification: Still promising? A 30-year global overview. *Renewable and Sustainable Energy Reviews*, **15**(1), pp. 471-481.

Kirkinen, J., A. Sahay, and I. Savolainen (2009). Greenhouse impact of fossil, forest residues and Jatropha diesel: a static and dynamic assessment. *Progress in Industrial Ecology, An International Journal*, **6**, pp. 185-206.

Kirschbaum, M.U.F. (2003). To sink or burn? A discussion of the potential contributions of forests to greenhouse gas balances through storing carbon or providing biofuels. *Biomass and Bioenergy*, **24**(4-5), pp. 297-310.

Kirschbaum, M.U.F. (2006). Temporary carbon sequestration cannot prevent climate change. *Mitigation and Adaptation Strategies for Global Change*, **11**(5), pp. 1151-1164.

Kishore, V.V.N., P.M. Bhandari, and P. Gupta (2004). Biomass energy technologies for rural infrastructure and village power – opportunities and challenges in the context of global climate change concerns. *Energy Policy*, **32**(6), pp. 801-810.

Kituyi, E. (2004). Towards sustainable production and use of charcoal in Kenya: exploring the potential in life cycle management approach. *Journal of Cleaner Production*, **12**(8-10), pp. 1047-1057.

Kline, K.L., and V.H. Dale (2008). Biofuels: Effects on land and fire. *Science*, **321**(5886), pp. 199-201.

Kline, K.L., G. Oladosu, A. Wolfe, R.D. Perlack, and M. McMahon (2007). *Biofuel Feedstock Assessment for Selected Countries.* ORNL/TM-2007/224, Oak Ridge National Laboratory, Oak Ridge, TN, USA, 243 pp.

Knothe, G. (2010). Biodiesel and renewable diesel: a comparison. *Progress in Energy and Combustion Science*, **36**(3), pp. 364-373.

Knowler, D.J. (2004). The economics of soil productivity: local, national and global perspectives. *Land Degradation & Development*, **15**(6), pp. 543-561.

Koh, L.P., and J. Ghazoul (2008). Biofuels, biodiversity, and people: Understanding the conflicts and finding opportunities. *Biological Conservation*, **141**(10), pp. 2450-2460.

Köhlin, G., and M. Ostwald (2001). Impact of plantations on forest use and forest status in Orissa, India. *AMBIO*, **30**(1), pp. 37-42.

Koizumi, T., and K. Ohga (2008). Biofuels policies in Asian countries: Impact of the expanded biofuels programs on world agricultural markets. *Journal of Agricultural & Food Industrial Organization*, **5**(2), Article 8, 22 pp.

Koning, N. (2008). Long-term global availability of food: continued abundance or new scarcity? *NJAS - Wageningen Journal of Life Sciences*, **55**(3), pp. 229-292.

Körner, C., J.A. Morgan, and R.J. Norby (2007). CO_2 fertilization: When, where and how much? In: *Terrestrial ecosystems in a changing world.* Springer, Berlin, Germany, pp. 9-22.

Koukouzas, N., A. Katsiadakis, E. Karlopoulos, and E. Kakaras (2008). Co-gasification of solid waste and lignite - A case study for Western Macedonia. *Waste Management*, **28**(7), pp. 1263-1275.

Krausmann, F., K.-H. Erb, S. Gingrich, C. Lauk, and H. Haberl (2008). Global patterns of socioeconomic biomass flows in the year 2000: A comprehensive assessment of supply, consumption and constraints. *Ecological Economics*, **65**(3), pp. 471-487.

Kreutz, T.G., E.D. Larson, G. Liu, and R.H. Williams (2008). Fischer-Tropsch fuels from coal and biomass. In: *Proceedings of the 25th International Pittsburgh Coal Conference.* Princeton Environmental Institute, Pittsburgh, PA, 29 September – 2 October 2008.

Krewitt, W., K. Nienhaus, C. Kleßmann, C. Capone, E. Stricker, W. Graus, M. Hoogwijk, N. Supersberger, U. von Winterfeld, and S. Samadi (2009). *Role and Potential of Renewable Energy and Energy Efficiency for Global Energy Supply.* ISSN 1862-4359, Federal Environment Agency, Dessau-Roßlau, Germany, 336 pp.

Krey, V., and L. Clarke (2011). Role of renewable energy in climate change mitigation: A synthesis of recent scenarios. *Climate Policy*, in press.

Krich, K., D. Augenstein, J.P. Batmale, J. Benemann, B. Rutledge, and D. Salour (2005). *Biomethane from Dairy: A Sourcebook for the Production and Use of Renewable Natural Gas in California.* Report prepared for Western United Dairymen with funding from USDA Rural Development, Washington, DC, USA, 282 pp. Available at: www.suscon.org/cowpower/biomethaneSourcebook/Full_Report.pdf.

Kumar, B.M. (2006). Agroforestry: the new old paradigm for Asian food security. *Journal of Tropical Agriculture*, **44**(1-2), pp. 1-14.

Kumar, L.N.V., and S. Maithel (2007). Alternative feedstock for Bio-ethanol production in India. In: *Biofuels: Towards a Greener and Secure Energy Future.* P.P. Bhojvaid (ed.), The Energy Resources Institute Press (TERI Press), New Delhi, India, pp. 89-104.

Kurz, W.A., G. Stinson, and G. Rampley (2008a). Could increased boreal forest ecosystem productivity offset carbon losses from increased disturbances? *Philosophical Transactions of the Royal Society B: Biological Sciences*, **363**(1501), pp. 2259-2268.

Kurz, W.A., C.C. Dymond, G. Stinson, G.J. Rampley, E.T. Neilson, A.L. Carroll, T. Ebata, and L. Safranyik (2008b). Mountain pine beetle and forest carbon feedback to climate change. *Nature*, **452**(7190), pp. 987-990.

Kuuva, K., and L. Ruska (2009). *Final Report of Feed-in Tariff Task Force.* 59/2009, Ministry of Employment and the Economy of Finland, Helsinki, Finland, 101 pp.

Laird, D.A. (2008). The charcoal vision: A win-win-win scenario for simultaneously producing bioenergy, permanently sequestering carbon, while improving soil and water quality. *Agronomy Journal*, **100**(1), pp. 178-181.

Laird, D.A., R.C. Brown, J.E. Amonette, and J. Lehmann (2009). Review of the pyrolysis platform for coproducing bio-oil and biochar. *Biofuels, Bioproducts and Biorefining*, **3**(5), pp. 547-562.

Lal, R. (2003). Offsetting global CO_2 emissions by restoration of degraded soils and intensification of world agriculture and forestry. *Land Degradation & Development*, **14**(3), pp. 309-322.

Lal, R. (2004). Soil carbon sequestration impacts on global climate change and food security. *Science*, **304**(5677), pp. 1623-1627.

Lal, R. (2005). World crop residues production and implications of its use as a biofuel. *Environment International*, **31**(4), pp. 575-584.

Lal, R. (2008). Crop residues as soil amendments and feedstock for bioethanol production. *Waste Management*, **28**(4), pp. 747-758.

Lal, R., and D. Pimentel (2007). Bio-fuels from crop residues. *Soil & Tillage Research*, **93**(2), pp. 237-238.

Lamers , P., C. Hamelinck, M. Junginger, and A. Faaij (2011). International Bioenergy, Trade - A Review of Past Developments in the Liquid Biofuels Market. *Renewable and Sustainable Energy Reviews*, **15**(6), pp. 2655-2676.

Lapola, D.M., R. Schaldach, J. Alcamo, A. Bondeau, J. Koch, C. Koelking, and J.A. Priess (2010). Indirect land-use changes can overcome carbon savings from biofuels in Brazil. *Proceedings of the National Academy of Sciences*, **107**(8), pp. 3388-3393.

Larson, E. (2006). A review of life-cycle analysis studies on liquid biofuel systems for the transport sector. *Energy for Sustainable Development*, **10**(2), pp. 109-126.

Larson, E.D., G. Fiorese, G. Liu, R.H. Williams, T.G. Kreutz, and S. Consonni (2009). Co-production of synfuels and electricity from coal + biomass with zero net carbon emissions: An Illinois case study. *Energy Procedia*, **1**(1), pp. 4371-4378.

Larson, E.D., G. Fiorese, G. Liu, R.H. Williams, T.G. Kreutz, and S. Consonni (2010). Co-production of decarbonized synfuels and electricity from coal + biomass with CO_2 capture and storage: an Illinois case study. *Energy & Environmental Science*, **3**(1), pp. 28-42.

Laser, M., E. Larson, B. Dale, M. Wang, N. Greene, and L.R. Lynd (2009). Comparative analysis of efficiency, environmental impact, and process economics for mature biomass refining scenarios. *Biofuels, Bioproducts and Biorefining*, **3**(2), pp. 247-270.

Lattimore, B., C.T. Smith, B.D. Titus, I. Stupak, and G. Egnell (2009). Environmental factors in woodfuel production: Opportunities, risks, and criteria and indicators for sustainable practices. *Biomass and Bioenergy*, **33**(10), pp. 1321-1342.

Laurance, W.F. (2007). Switch to corn promotes Amazon deforestation. *Science*, **318**(5857), pp. 1721-1724.

Lawrence, C.J., and V. Walbot (2007). Translational genomics for bioenergy production from fuelstock grasses: Maize as the model species. *Plant Cell*, **19**(7), pp. 2091-2094.

Lee, D.R., C.B. Barrett, and J.G. McPeak (2006). Policy, technology, and management strategies for achieving sustainable agricultural intensification. *Agricultural Economics*, **34**(2), pp. 123-127.

Lee, J. (1997). Biological conversion of lignocellulosic biomass to ethanol. *Journal of Biotechnology*, **56**(1), pp. 1-24.

Lee, S.K., H. Chou, T.S. Ham, T.S. Lee, and J.D. Keasling (2008). Metabolic engineering of microorganisms for biofuels production: from bugs to synthetic biology to fuels. *Current Opinion in Biotechnology*, **19**(6), pp. 556-563.

Leemans, R., A. van Amstel, C. Battjes, E. Kreileman, and S. Toet, (1996). The land cover and carbon cycle consequences of large-scale utilizations of biomass as an energy source. *Global Environmental Change*, **6**(4), pp. 335-357.

Legros, G., I. Havet, N. Bruce, and S. Bonjour (2009). *The Energy Access Situation in Developing Countries: A Review Focusing on the Least Developed Countries and Sub-Saharan Africa.* United Nations Development Programme and the World Health Organization, New York, NY, USA, 142 pp.

Lehtomäki, A., S. Huttunen, and J.A. Rintala (2007). Laboratory investigations on co-digestion of energy crops and crop residues with cow manure for methane production: Effect of crop to manure ratio. *Resources, Conservation and Recycling*, **51**(3), pp. 591-609.

Leng, R., C. Wang, C. Zhang, D. Dai, and G. Pu (2008). Life cycle inventory and energy analysis of cassava-based fuel ethanol in China. *Journal of Cleaner Production*, **16**(3), pp. 374-384.

Levasseur, A., P. Lesage, M. Margni, L. Deschênes, and R. Samson (2010). Considering time in LCA: Dynamic LCA and its application to global warming impact assessments. *Environmental Science & Technology*, **44**(8), pp. 3169-3174.

Lewis, S.L., G. Lopez-Gonzalez, B. Sonke, K. Affum-Baffoe, T.R. Baker, L.O. Ojo, O.L. Phillips, J.M. Reitsma, L. White, J.A. Comiskey, M.-N.D. K, C.E.N. Ewango, T.R. Feldpausch, A.C. Hamilton, M. Gloor, T. Hart, A. Hladik, J. Lloyd, J.C. Lovett, J.-R. Makana, Y. Malhi, F.M. Mbago, H.J. Ndangalasi, J. Peacock, K.S.H. Peh, D. Sheil, T. Sunderland, M.D. Swaine, J. Taplin, D. Taylor, S.C. Thomas, R. Votere, and H. Woll (2009). Increasing carbon storage in intact African tropical forests. *Nature*, **457**(7232), pp. 1003-1006.

Li, W., R. Fu, and R.E. Dickinson (2006). Rainfall and its seasonality over the Amazon in the 21st century as assessed by the coupled models for the IPCC AR4. *Journal of Geophysical Research*, **111**(D2), D02111.

Liebig, M., M. Schmer, K. Vogel, and R. Mitchell (2008). Soil carbon storage by switchgrass grown for bioenergy. *BioEnergy Research*, **1**(3), pp. 215-222.

Lindenmayer, D.B., and H.A. Nix (1993). Ecological principles for the design of wildlife corridors. *Conservation Biology*, **7**(3), pp. 627-631.

Lindner, M., M. Maroschek, S. Netherer, A. Kremer, A. Barbati, J. Garcia-Gonzalo, R. Seidl, S. Delzon, P. Corona, M. Kolström, M.J. Lexer, and M. Marchetti (2010). Climate change impacts, adaptive capacity, and vulnerability of European forest ecosystems. *Forest Ecology and Management*, **259**(4), pp. 698-709.

Lioubimtseva, E., and J.M. Adams (2004). Possible implications of increased carbon dioxide levels and climate change for desert ecosystems. *Environmental Management*, **33**(Supplement 1), pp. S388-S404.

Liska, A.J., and R.K. Perrin (2010). Securing foreign oil: A case for including military operations in the climate change impact of fuels. *Environment: Science and Policy for Sustainable Development*, **52**(4), pp. 9-12.

Lobell, D.B., and M.B. Burke (2008). Why are agricultural impacts of climate change so uncertain? The importance of temperature relative to precipitation. *Environmental Research Letters*, **3**(3), 034007.

Lobell, D.B., M.B. Burke, C. Tebaldi, M.D. Mastrandrea, W.P. Falcon, and R.L. Naylor (2008). Prioritizing climate change adaptation needs for food security in 2030. *Science*, **319**(5863), pp. 607-610.

Londo, M., A. Faaij, M. Junginger, G. Berndes, S. Lensink, A. Wakker, G. Fischer, S. Prieler, H. van Velthuizen, and M. de Wit (2010). The REFUEL EU road map for biofuels in transport: Application of the project's tools to some short-term policy issues. *Biomass and Bioenergy*, **34**(2), pp. 244-250.

López, R., and G.I. Galinato (2007). Should governments stop subsidies to private goods? Evidence from rural Latin America. *Journal of Public Economics*, **91**(5-6), pp. 1071-1094.

Lotze-Campen, H., A. Popp, T. Beringer, C. Müller, A. Bondeau, S. Rost, and W. Lucht (2009). Scenarios of global bioenergy production: The trade-offs between agricultural expansion, intensification and trade. *Ecological Modelling*, **221**(18), pp. 2188-2196.

Loustau, D., A. Bosc, A. Colin, J. Ogee, H. Davi, C. Francois, E. Dufrene, M. Deque, E. Cloppet, D. Arrouays, C. Le Bas, N. Saby, G. Pignard, N. Hamza, A. Granier, N. Breda, P. Ciais, N. Viovy, and F. Delage (2005). Modeling climate change effects on the potential production of French plains forests at the sub-regional level. *Tree Physiology*, **25**(7), pp. 813-823.

Low, T., and C. Booth (2007). *The Weedy Truth about Biofuels.* Invasive Species Council, Melbourne, Fairfield, Australia, 46 pp.

Luyssaert, S., E.D. Schulze, A. Börner, A. Knohl, D. Hessenmöller, B.E. Law, P. Ciais, and J. Grace (2008). Old-growth forests as global carbon sinks. *Nature*, **455**(7210), pp. 213-215.

Lywood, W. (2008). *Indirect Effects of Biofuels.* Renewable Fuels Agency, East Sussex, UK.

Lywood, W., J. Pinkney, and S.A.M. Cockerill (2009a). Impact of protein concentrate coproducts on net land requirement for European biofuel production. *Global Change Biology Bioenergy*, **1**(5), pp. 346-359.

Lywood, W., J. Pinkney, and S.A.M. Cockerill (2009b). The relative contributions of changes in yield and land area to increasing crop output. *Global Change Biology Bioenergy*, **1**(5), pp. 360-369.

Macedo, I.C., and J.E.A. Seabra (2008). Mitigation of GHG emissions using sugarcane bioethanol. In: *Sugarcane Ethanol: Contributions to Climate Change Mitigation and the Environment.* P. Zuubier and J. van de Vooren (eds.), Wageningen Academic Publishers, Wageningen, The Netherlands, pp. 95-112.

Macedo, I.C., J.E.A. Seabra, and J.E.A.R. Silva (2008). Green house gases emissions in the production and use of ethanol from sugarcane in Brazil: The 2005/2006 averages and a prediction for 2020. *Biomass and Bioenergy*, **32**(7), pp. 582-595.

Madsen, A.M. (2006). Exposure to airborne microbial components in autumn and spring during work at Danish biofuel plants. *Annals of Occupational Hygiene*, **50**(8), pp. 821-831.

Madsen, A.M., L. Martensson, T. Schneider, and L. Larsson (2004). Microbial dustiness and particle release of different biofuels. *Annals of Occupational Hygiene*, **48**(4), pp. 327-338.

Maes, W., W. Achten, and B. Muys (2009). Use of inadequate data and methodological errors lead to a dramatic overestimation of the water footprint of *Jatropha curcas*. *Nature Precedings*, hdl:10101/npre.2009.3410.1, 3 pp.

Malézieux, E., Y. Crozat, C. Dupraz, M. Laurans, D. Makowski, H. Ozier-Lafontaine, B. Rapidel, S. de Tourdonnet, and M. Valantin-Morison (2009). Mixing plant species in cropping systems: concepts, tools and models. A review. *Agronomy for Sustainable Development*, **29**(1), pp. 43-62.

Malmer, A., D. Murdiyarso, L.A.S. Bruijnzeel, and U. Lstedt (2010). Carbon sequestration in tropical forests and water: a critical look at the basis for commonly used generalizations. *Global Change Biology*, **16**(2), pp. 599-604.

Markewitz, D. (2006). Fossil fuel carbon emissions from silviculture: Impacts on net carbon sequestration in forests. *Forest Ecology and Management*, **236**(2-3), pp. 153-161.

Marlair, G., P. Rotureau, S. Breulet, and S. Brohez (2009). Booming development of biofuels for transport: Is fire safety of concern? *Fire and Materials*, **33**(1), pp. 1-19.

Marland, G., and B. Schlamadinger (1997). Forests for carbon sequestration or fossil fuel substitution? A sensitivity analysis. *Biomass and Bioenergy*, **13**(6), pp. 389-397.

Marland, G., M. Obersteiner, and B. Schlamadinger (2007). The carbon benefits of fuels and forests. *Science*, **318**(5853), pp. 1066.

Martens, W., and R. Böhm (2009). Overview of the ability of different treatment methods for liquid and solid manure to inactivate pathogens. *Bioresource Technology*, **100**(22), pp. 5374-5378.

Martinelli, L.A., and S. Filoso (2007). Polluting effects of Brazil's sugar-ethanol industry. *Nature*, **445**(7126), pp. 364-364.

Masera, O.R., and J. Navia (1997). Fuel switching or multiple cooking fuels: Understanding interfuel substitution patterns in rural Mexican households. *Biomass and Bioenergy*, **12**(5), pp. 347-361.

Masera, O.R., B.D. Saatkamp, and D.M. Kammen (2000). From linear fuel switching to multiple cooking strategies: A critique and alternative to the energy ladder model. *World Development*, **28**(12), pp. 2083-2103.

Masera, O.R., R. Diaz, and V. Berrueta (2005). From cookstoves to cooking systems: the integrated program on sustainable household energy use in Mexico. *Energy for Sustainable Development*, **9**(1), pp. 25-36.

Masera, O., A. Ghilardi, R. Drigo, and M. Angel Trossero (2006). WISDOM: A GIS-based supply demand mapping tool for woodfuel management. *Biomass and Bioenergy*, **30**(7), pp. 618-637.

Matsuoka, S., J. Ferro, and P. Arruda (2009). The Brazilian experience of sugarcane ethanol industry. *In Vitro Cellular & Developmental Biology - Plant*, **45**(3), pp. 372-381.

Matthews, H.D., and K. Caldeira (2008). Stabilizing climate requires near-zero emissions. *Geophysical Research Letters*, **35**(4), L04705.

Matthews, H.D., N.P. Gillett, P.A. Stott, and K. Zickfeld (2009). The proportionality of global warming to cumulative carbon emissions. *Nature*, **459**(7248), pp. 829-832.

Maués, J.A. (2007). Maximizacao da geracao eletrica a partir do bagaco e palha em usinas de acucar e alcool. *Revista Engenharia*, **583**, pp. 88-98.

Mayfield, C.A., C.D. Foster, C.T. Smith, J. Gan, and S. Fox (2007). Opportunities, barriers, and strategies for forest bioenergy and bio-based product development in the Southern United States. *Biomass & Bioenergy*, **31**, pp. 631-637.

McAloon, A., F. Taylor, W. Lee, K. Ibsen, and R. Wooley (2000). *Determining the Cost of Producing Ethanol from Corn Starch and Lignocellulosic Feedstocks.* NREL/TP-580-28893, National Renewable Energy Laboratory, Golden, CO, USA, 43 pp.

McCoy, M. (2006). Glycerin surplus. *Chemical & Engineering News*, **83**(4), pp. 21-22.

McDonald, A., and L. Schrattenholzer (2001). Learning rates for energy technologies. *Energy Policy*, **29**(4), pp. 255-261.

McGowin, C. (2008). *Renewable Energy Technical Assessment Guide.* TAG-RE:2007, Electric Power Research Institute, Palo Alto, CA, USA.

McKeough, P., and E. Kurkela (2008). *Process Evaluations and Design Studies in the UCG Project 2004-2007.* VTT Research Notes 2434, VTT Technical Research Centre of Finland, Espoo, Finland, 49 pp.

McKeough, P., Y. Solantausta, H. Kyllönen, A. Faaij, C. Hamelinck, M. Wagener, D. Beckman and B. Kjellström (2005). *Technoeconomic Analysis of Biotrade Chains: Upgraded Biofuels from Russia and Canada to the Netherlands.* VTT Research Notes 2312, VTT Technical Research Centre of Finland, Espoo, Finland, 65 pp.

McLeod, J.E., J.E. Nunez, and S.S. Rivera (2008). A discussion about how to model biofuel plants for the risk optimization. In: *Proceedings of the World Congress on Engineering 2008, Vol. II*, London, UK, 2-4 July 2008, pp. 1214-1219.

McWhorter, C. (1971). Introduction and spread of johnsongrass in the United States. *Weed Science*, **19**(5), pp. 496-500.

Melillo, J.M., J.M. Reilly, D.W. Kicklighter, A.C. Gurgel, T.W. Cronin, S. Paltsev, B.S. Felzer, X. Wang, A.P. Sokolov, and C.A. Schlosser (2009). Indirect emissions from biofuels: How important? *Science*, **326**(5958), pp. 1397-1399.

Menichetti, E., and M. Otto (2009). Energy balance and greenhouse gas emissions of biofuels from a product life-cycle perspective. In: *Biofuels: Environmental Consequences and Interactions with Changing Land Use.* R.W. Howarth and S. Bringezu (eds.), Proceedings of the SCOPE - Scientific Committee on Problems of the Environment International Biofuels Project Rapid Assessment, Gummersbach, Germany, 22-25 September 2009, pp. 81-109.

Metzger, J.O., and A. Hüttermann (2009). Sustainable global energy supply based on lignocellulosic biomass from afforestation of degraded areas. *Naturwissenschaften*, **96**(2), pp. 279-288.

Milbrandt, A., and R.P. Overend (2008). *Future of Liquid Biofuels for APEC Economies.* NREL/TP-6A2-43709, report prepared for Asia-Pacific Economic Cooperation by the National Renewable Energy Laboratory, Golden, CO, USA, 103 pp. Available at: www.biofuels.apec.org/pdfs/ewg_2008_liquid_biofuels.pdf.

Millennium Ecosystem Assessment (2005). *Ecosystems and Human Well-being.* Island Press, Washington, DC, USA, 36 pp.

Mishra, V., X. Dai, K. Smith, and L. Mike (2004). Maternal exposure to biomass smoke and reduced birth weight in Zimbabwe. *Annals of Epidemiology*, **14**(10), pp. 740-747.

Mitchell, D. (2008). *A Note on Rising Food Prices.* Policy Research Working Paper 4682, The World Bank Group, Washington, DC, USA, 22 pp.

Molden, D. (ed.) (2007). *Water for Food, Water for Life: A Comprehensive Assessment of Water Management in Agriculture.* Earthscan, London, UK.

Molina Grima, E., E.H. Belarbi, F.G. Acien Fernandez, A. Robles Medina, and Y. Chisti (2003). Recovery of microalgal biomass and metabolites: process options and economics. *Biotechnology Advances*, **20**(7-8), pp. 491-515.

Möllersten, K., J. Yan, and J. R. Moreira (2003). Potential market niches for biomass energy with CO_2 capture and storage – Opportunities for energy supply with negative CO_2 emissions. *Biomass and Bioenergy*, **25**(3), pp. 273-285.

Molofsky, J., S.L. Morrison, and C.J. Goodnight (1999). Genetic and environmental controls on the establishment of the invasive grass, Phalaris arundinacea. *Biological Invasions*, **1**(2), pp. 181-188.

Moral, R., C. Paredes, M.A. Bustamante, F. Marhuenda-Egea, and M.P. Bernal (2009). Utilisation of manure composts by high-value crops: Safety and environmental challenges. *Bioresource Technology*, **100**(22), pp. 5454-5460.

Moreira, J.R. (2006). *Bioenergy and Agriculture, Promises and Challenges: Brazil's Experience with Bioenergy.* International Food Policy Research Institute, Washington, DC, USA, 2 pp.

Mosier, A., C. Kroeze, C. Nevison, O. Oenema, S. Seitzinger, and O. van Cleemput (1998). Closing the global N_2O budget: nitrous oxide emissions through the agricultural nitrogen cycle. *Nutrient Cycling in Agroecosystems*, **52**(2-3), pp. 1385-1314.

Mosier, N., C. Wyman, B. Dale, R. Elander, Y.Y. Lee, M. Holtzapple, and M. Ladisch (2005). Features of promising technologies for pretreatment of lignocellulosic biomass. *Bioresource Technology*, **96**(6), pp. 673-686.

Mozaffarian, H., R.W.R. Zwart, H. Boerrigeter, and E.P. Deurwaarder (2004). Biomass and waste-related SNG production technologies; technical, economic and ecological feasibility. In: *2nd World Conference and Technology Exhibition on Biomass for Energy, Industry and Climate Protection*, Rome, Italy, 10-14 May 2004. Available at: www.biosng.com/fileadmin/biosng/user/documents/reports/rx04024.pdf.

Mukunda, H.S., S. Dasappa, P.J. Paul, N.K.S. Rajan, M. Yagnaraman, D.R. Kumar, and M. Deogaonkar (2010). Gasifier stoves - science, technology and field outreach. *Current Science (Bangalore)*, **98**(5), pp. 627-638.

Müller, C. (2007). *Anaerobic Digestion of Biodegradable Solid Waste in Low- and Middle-Income Countries - Overview Over Existing Technologies and Relevant Case Studies.* Eawag Aquatic Research, Dübendorf, Switzerland, 63 pp.

Myles, R. (2001). Implementation of Household Biogas Plant by NGOs in India-Practical Experience in Implementation Household Biogas Technology, Lessons Learned, Key Issues and Future Approach for Sustainable Village Development. In: *VODO International Conference on Globalisation and Sustainable Development*, Antwerp, Brussels, 19-21 Nov 2001, 19 pp. Available at: www.inseda.org/Additional%20material/Lessons%20learnt%20NGOs%20Biogas%20programme.pdf.

Nabuurs, G.-J., A. Pussinen, T. Karjalainen, M. Erhard, and K. Kramer (2002). Stemwood volume increment changes in European forests due to climate change—a simulation study with the EFISCEN model. *Global Change Biology*, **8**(4), pp. 304-316.

Nabuurs, G.J., O. Masera, K. Andrasko, P. Benitez-Ponce, R. Boer, M. Dutschke, E. Elsiddig, J. Ford-Robertson, P. Frumhoff, T. Karjalainen, O. Krankina, W.A. Kurz, M. Matsumoto, W. Oyhantcabal, N.H. Ravindranath, M.Z. Sanz Sanchez, and X. Zhang (2007). Forestry. In: *Climate Change 2007: Mitigation of Climate Change. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, and L.A. Meyer (eds.), Cambridge University Press, pp. 541-584.

Nagatomi, Y., Y. Hiromi, Y. Kenji, I. Hiroshi, and Y. Koichi (2008). A system analysis of energy utilization and competing technology using oil palm residue in Malaysia. *Journal of Japan Society of Energy and Resources*, **29**(5), pp. 1-7.

Narayanan, D., Y. Zhang, and M.S. Mannan (2007). Engineering for Sustainable Development (ESD) in bio-diesel production. *Process Safety and Environmental Protection*, **85**(5), pp. 349-359.

Näslund-Eriksson, L., and L. Gustavsson (2008). Biofuels from stumps and small roundwood – Costs and CO_2 benefits. *Biomass and Bioenergy*, **32**(10), pp. 897-902.

Nassar, A., L. Harfurch, M.M.R. Moreira, L.C. Bachion, L.B. Antoniazzi, and G. Sparovek (2009). *Impacts on Land Use and GHG Emissions from a Shock on Brazilian Sugarcane Ethanol Exports to the United States using the Brazilian Land Use Model (BLUM).* EPA HQ OAR 2005 0161, Institute for International Negotiations, Geneva, Switzerland, 32 pp.

Nassar, A., L.B. Antoniazzi, M.R. Moreira, L. Chiodi, and L. Harfurch (2010). *An Allocation Methodology to Assess GHG Emissions Associated with Land Use Change.* Institute for International Negotiations, Geneva, Switzerland, 31 pp.

NRC (2008). *Water Implications of Biofuels Production in the United States.* National Research Council, The National Academies Press, Washington, DC, USA, 88 pp.

NRC (2009a). *Liquid Transportation Fuels from Coal and Biomass Technological Status, Costs, and Environmental Impacts.* National Research Council, National Academies Press, Washington, DC, USA, 50 pp.

NRC (2009b). *America's Energy Future: Electricity from Renewable Resources: Status, Prospects, and Impediments.* National Research Council, The National Academies Press, Washington, DC, 367 pp.

NRC (2010). *Impact of Genetically Engineered Crops on Farm Sustainability in the United States, 2010.* Committee on the Impact of Biotechnology on Farm-Level Economics and Sustainability; National Research Council, Washington, DC, USA, 35 pp.

Nehlsen, J., M. Mukherjee, and R.V. Porcelli (2007). Apply an integrated approach to catalytic process design. *Chemical Engineering Progress*, **103**(2), pp. 31-41.

Nelson, D.E., P.P. Repetti, T.R. Adams, R.A. Creelman, J. Wu, D.C. Warner, D.C. Anstrom, R.J. Bensen, P.P. Castiglioni, M.G. Donnarummo, B.S. Hinchey, R.W. Kumimoto, D.R. Maszle, R.D. Canales, K.A. Krolikowski, S.B. Dotson, N. Gutterson, O.J. Ratcliffe, and J.E. Heard (2007). Plant nuclear factor Y (NF-Y) B subunits confer drought tolerance and lead to improved corn yields on water-limited acres. *Proceedings of the National Academy of Sciences*, **104**(42), pp. 16450-16455.

NETL (2008). *Development of Baseline Data and Analysis of Life Cycle Greenhouse Gas Emissions of Petroleum-Based Fuels.* DOE/NETL-2009/1362, National Energy Technology Laboratory, Pittsburgh, PA, USA.

NETL (2009a). *An Evaluation of the Extraction, Transport and Refining of Imported Crude Oils and the Impact on Life Cycle Greenhouse Gas Emissions.* DOE/NETL-2009/1362, National Energy Technology Laboratory, Pittsburgh, PA, USA.

NETL (2009b). *Affordable, Low Carbon Diesel Fuel from Domestic Coal and Biomass.* DOE/NETL-2009/1349, National Energy Technology Laboratory, Pittsburgh, PA, USA.

Neumann, K., P.H. Verburg, E. Stehfest, and C. Müller (2010). The yield gap of global grain production: A spatial analysis. *Agricultural Systems*, **103**(5), pp. 316-326.

Nguyen, T.L.T., and S.H. Gheewala (2008). Life cycle assessment of fuel ethanol from Cassava in Thailand. *International Journal of Life Cycle Assessment*, **13**(2), pp. 147-154.

Nishi, T., M. Konishi, and S. Hasebe (2005). An autonomous decentralized supply chain planning system for multi-stage production processes. *Journal of Intelligent Manufacturing*, **16**(3), pp. 259-275.

Nohrstedt, H.O. (2001). Response of coniferous forest ecosystems on mineral soils to nutrient additions: A review of Swedish experiences. *Scandinavian Journal of Forest Research*, **16**(6), pp. 555-573.

Nusser, M., B. Hüsing, and S. Wydra (2007). *Potenzialanalyse der Industriellen, Weißen Biotechnologie, Karlsruhe.* Fraunhofer-Institut für System- und Innovationsforschung, Karlsruhe, Germany, 426 pp.

O'Hare, M., R.J. Plevin, J.I. Martin, A.D. Jones, A. Kendall, and E. Hopson (2009). Proper accounting for time increases crop-based biofuels' greenhouse gas deficit versus petroleum. *Environmental Research Letters*, **4**(2), 024001 (7 pp.).

OANDA (2011). *Historical Exchange Rates.* Oanda Corporation, New York, NY, USA. Available at: www.oanda.com/currency/historical-rates/.

Obernberger, I., and G. Thek (2004). *Techno-economic evaluation of selected decentralised CHP applications based on biomass combustion in IEA partner countries.* BIOS Bioenergiesysteme GmbH, Graz, Austria, 87 pp.

Obernberger, I., G. Thek, and D. Reiter (2008). *Economic evaluation of decentralised CHP applications based on biomass combustion and biomass gasification.* BIOS Bioenergiesysteme GmbH, Graz, Austria, 19 pp.

Obersteiner, M., K. Mollersten, J. Moreira, S. Nilsson, P. Read, K. Riahi, B. Schlamadinger, Y. Yamagata, J. Yan, J.P. Ypserle, C. Azar, and P. Kauppi (2001). Managing climate risk. *Science*, **294**(5543), pp. 786-787.

OECD-FAO (2008). *Agricultural Outlook 2008-2017.* Organisation for Economic Cooperation and Development and Food and Agriculture Organization, Paris, France, 73 pp.

Okada, M., C. Lanzatella, M.C. Saha, J. Bouton, R. Wu, and C.M. Tobias (2010). Complete switchgrass genetic maps reveal subgenome collinearity, preferential pairing and multilocus interactions. *Genetics*, **185**(3), pp. 745-760.

Oliveira, F.C.R. (2009). *Ocupação, emprego e remuneração na cana-de-açúcar e em outras atividades agropecuárias no Brasil, de 1992 a 2007.* Master's Thesis, Universidade de São Paulo, São Paulo, Brazil, 168 pp.

Oliver, R.J., J.W. Finch, and G. Taylor (2009). Second generation bioenergy crops and climate change: a review of the effects of elevated atmospheric CO_2 and drought on water use and the implications for yield. *Global Change Biology Bioenergy*, **1**(2), pp. 97-114.

Oliverio, J.L. (2006). Technological evolution of the Brazilian sugar and alcohol sector: Dedini's contribution. *International Sugar Journal*, **108**(1287), pp. 120-129.

Oliverio, J.L., and J.E. Ribeiro (2006). Cogeneration in Brazilian sugar and bioethanol mills: Past, present and challenges. *International Sugar Journal*, **108**(191), pp. 391-401.

Openshaw, K. (2000). A review of Jatropha curcas: an oil plant of unfulfilled promise. *Biomass and Bioenergy*, **19**(1), pp. 1-15.

Pacca, S., and J.R. Moreira (2009). Historical carbon budget of the Brazilian ethanol program. *Energy Policy*, **37**(11), pp. 4863-4873.

Patel, M.K., M. Crank, V. Dornburg, B. Hermann, L. Roes, B. Hüsing, L. van Overbeek, F. Terragni, and E. Recchia (2006). *Medium and Long-Term Opportunities and Risks of the Biotechnological Production of Bulk Chemicals from Renewable Resources.* Copernicus Institute for Sustainable Development and Innovation, Utrecht, The Netherlands, 420 pp.

Paustian, K., J.M. Antle, J. Sheehan, and A.P. Eldor (2006). *Agriculture's Role in Greenhouse Gas Mitigation.* Pew Center on Global Climate Change, Arlington, VA, USA.

Peksa-Blanchard, M., P. Dolzan, A. Grassi, J. Heinimö, M. Junginger, T. Ranta, and A. Walter (2007). *Global Wood Pellets Markets and Industry: Policy Drivers, Market Status and Raw Material Potential.* IEA Bioenergy Task 40 Publication, 120 pp. Available at: www.canbio.ca/documents/publications/ieatask40pelletandrawmaterialstudynov2007final.pdf.

Perlack, R.D., L.L. Wright, A.F. Turhollow, R.L. Graham, B.J. Stokes, and D.C. Erbach (2005). *Biomass as Feedstock for a Bioenergy and Bioproducts Industry: The Technical Feasibility of a Billion-Ton Annual Supply.* ORNL/TM-2005/66, Oak Ridge National Laboratory, Oak Ridge, TN, USA, 78 pp.

Perry, J.A. (2009). Catastrophic incident prevention and proactive risk management in the new biofuels industry. *Environmental Progress & Sustainable Energy*, **28**(1), pp. 72-82.

Persson, U.M., and C. Azar (2010). Preserving the world's tropical forests – A price on carbon may not do. *Environmental Science & Technology*, **44**(1), pp. 210-215.

Petersson, A. and A. Wellinger (2009). *Biogas Upgrading Technologies – Developments and Innovations.* IEA Bioenergy Task 37 publication, Malmo, Sweden, 20 pp. Available at: www.biogasmax.com/media/iea_2biogas_upgrading_tech__025919000_1434_30032010.pdf.

Phillips, S., A. Aden, J. Jechura, D. Dayton, and T. Eggeman (2007). *Thermochemical Ethanol via Indirect Gasification and Mixed Alcohol Synthesis of Lignocellulosic Biomass.* NREL/TP-510-41168, National Renewable Energy Laboratory, Golden, CO, USA, 132 pp.

Pimentel, D., S. McNair, J. Janecka, J. Wightman, C. Simmonds, C. O'Connell, E. Wong, L. Russel, J. Zern, T. Aquino, and T. Tsomondo (2001). Economic and environmental threats of alien plant, animal, and microbe invasions. *Agriculture, Ecosystems & Environment*, **84**(1), pp. 1-20.

Pimentel, D., P. Hepperly, J. Hanson, D. Douds, and R. Seidel (2005). Environmental, energetic, and economic comparisons of organic and conventional farming systems. *BioScience*, **55**(7), pp. 573-582.

Pingali, P.L., and P.W. Heisey (1999). *Cereal Crop Productivity in Developing Counties: Past Trends and Future Prospects.* Working Paper 99-03, International Maize and Wheat Improvement Center, Texcoco, Mexico, 34 pp.

Plevin, R.J. (2009). Modeling corn ethanol and climate. *Journal of Industrial Ecology*, **13**(4), pp. 495-507.

Plevin, R.J., O.H. Michael, A.D. Jones, M.S. Torn, and H.K. Gibbs (2010). Greenhouse gas emissions from biofuels indirect land use change are uncertain but may be much greater than previously estimated. *Environmental Science & Technology*, **44**(21), pp. 8015-8021.

Practical Action Consulting (2009). *Small Scale Bioenergy can Benefit Poor: Brief Description and Preliminary Lessons on Livelihood Impacts from Case Studies in Asia, Latin America and Africa.* Food and Agriculture Organization and Policy Innovation Systems for Clean Energy Security, Rome, Italy, 142 pp.

Purdon, M., S. Bailey-Stamler, and R. Samson (2009). Better bioenergy: Rather than picking bioenergy "winners," effective policy should let a lifecycle analysis decide. *Alternatives Journal*, **35**(2), pp. 23-29.

Rabaey, K., and W. Verstraete (2005). Microbial fuel cells: novel biotechnology for energy generation. *Trends in Biotechnology*, **23**(6), pp. 291-298.

Ragauskas, A.J., C.K. Williams, B.H. Davison, G. Britovsek, J. Cairney, C.A. Eckert, W.J. Frederick, Jr., J.P. Hallett, D.J. Leak, C.L. Liotta, J.R. Mielenz, R. Murphy, R. Templer, and T. Tschaplinski (2006). The path forward for biofuels and biomaterials. *Science*, **311**(5760), pp. 484-489.

Raghu, S., R.C. Anderson, C.C. Daehler, A.S. Davis, R.N. Wiedenmann, D. Simberloff, and R.N. Mack (2006). Adding biofuels to the invasive species fire? *Science*, **313**(5794), pp. 1742.

Rajagopal, D., G. Hochman, and D. Zilberman (2011). Indirect fuel use change (IFUC) and the lifecycle environmental impact of biofuel policies. *Energy Policy*, **39**(1), pp. 228-233.

Ramanathan, V., and G. Carmichael (2008). Global and regional climate changes due to black carbon. *Nature Geoscience*, **1**(4), pp. 221-227.

Randall, J.M. (1996). Plant Invaders: How Non-native Species Invade & Degrade Natural Areas Invasive Plants. In: *Weeds of the Global Garden.* J. Marinelli and J.M. Randall (eds.), Brooklyn Botanic Garden, Brooklyn, NY, pp. 7-12.

Ranius, T., and L. Fahrig (2006). Targets for maintenance of dead wood for biodiversity conservation based on extinction thresholds. *Scandinavian Journal of Forest Research*, **21**(3), pp. 201-208.

Rauch, R. (2010). *Indirect Gasification. In: IEA Bioenergy Joint Tasks 32 &33 Workshop, State-of-the-Art Technologies for Small Biomass Co-generation*, International Energy Agency, Copenhagen, Denmark, 7 Oct 2010. Available at: www.ieabcc.nl/meetings/task32_Copenhagen/09%20TU%20Vienna.pdf.

Ravindranath, N.H., P. Balachandra, S. Dasappa, and K. Usha Rao (2006). Bioenergy technologies for carbon abatement. *Biomass and Bioenergy*, **30**(10), pp. 826-837.

Regalbuto, J.R. (2009). Cellulosic biofuels – got gasoline? *Science*, **325**(5942), pp. 822-824.

Reijnders, L. (2008). Ethanol production from crop residues and soil organic carbon. *Resources, Conservation and Recycling*, **52**(4), pp. 653-658.

Reinhardt, G. (1991). *Biofuels: Energy and GHG balances: Methodology and Case Study Rape Seed Biodiesel.* Institut für Energie- und Umweltforschung Heidelberg, Heidelberg, Germany.

Reinhardt, G., S. Gartner, A. Patyk, and N. Rettenmaier (2006). *Ökobilanzen zu BTL: Eine ökologische Einschätzung.* 2207104, ifeu Institut für Energie- und Umweltforschung Heidelberg gGmbH, Heidelberg, Germany, 108 pp.

REN21 (2007). *Global Status Report.* Renewable Energy Policy Network for the 21st Century Secretariat, Paris, France, 54 pp.

REN21 (2009). *Renewables Global Status Report: 2009 Update.* Renewable Energy Policy Network for the 21st Century Secretariat, Paris, France, 42 pp.

Rendleman, C.M., and H. Shapouri (2007). *New Technologies in Ethanol Production.* Report Number 842, United States Department of Agriculture, Washington, DC, USA.

RFA (2010). *U.S. Cellulosic.* Renewable Fuels Association, Washington, DC, USA. Available at: www.ethanolrfa.org/pages/cellulosic-ethanol

RFA (2011). *Biorefinery Plant Locations.* Renewable Fuels Association, Washington, DC, USA. Available at: www.ethanolrfa.org/bio-refinery-locations/.

Rentizelas, A.A., A.J. Tolis, and I.P. Tatsiopoulos (2009). Logistics issues of biomass: The storage problem and the multi-biomass supply chain. *Renewable and Sustainable Energy Reviews*, **13**(4), pp. 887-894.

Reynolds, M.P., and N.E. Borlaug (2006). Applying innovations and new technologies for international collaborative wheat improvement. *The Journal of Agricultural Science*, **144**(02), pp. 95-95.

Rhodes, J.S., and D.W. Keith (2008). Biomass with capture: negative emissions within social and environmental constraints: an editorial comment. *Climatic Change*, **87**(3-4), pp. 321-328.

Righelato, R., and D.V. Spracklen (2007). Carbon mitigation by biofuels or by saving and restoring forests? *Science*, **317**(5840), pp. 902.

Ringer, M., V. Putsche, and J. Scahill (2006). *Large-Scale Pyrolysis Oil Production: A Technology Assessment and Economic Analysis.* TP-510-37779, National Renewable Energy Laboratory, Golden, CO, USA, 93 pp.

Riviére, C., and G. Marlair (2009). BIOSAFUEL®, a pre-diagnosis tool of risks pertaining to biofuels chains. *Journal of Loss Prevention in the Process Industries*, **22**(2), pp. 228-236.

Riviére, C., and G. Marlair (2010). The use of multiple correspondence analysis and hierarchical clustering to identify incident typologies pertaining to the biofuel industry. *Biofuels, Bioproducts and Biorefining*, **4**(1), pp. 53-65.

Robertson, G.P., V.H. Dale, O.C. Doering, S.P. Hamburg, J.M. Melillo, M.M. Wander, W.J. Parton, P.R. Adler, J.N. Barney, R.M. Cruse, C.S. Duke, P.M. Fearnside, R.F. Follett, H.K. Gibbs, J. Goldemberg, D.J. Mladenoff, D. Ojima, M.W. Palmer, A. Sharpley, L. Wallace, K.C. Weathers, J.A. Wiens, and W.W. Wilhelm (2008). Sustainable biofuels redux. *Science*, **322**(5898), pp. 49-50.

Rockström, J., M. Lannerstad, and M. Falkenmark (2007). Assessing the water challenge of a new green revolution in developing countries. *Proceedings of the National Academy of Sciences*, **104**(15), pp. 6253-6260.

Rockström, J., L. Karlberg, S.P. Wani, J. Barron, N. Hatibu, T. Oweis, A. Bruggeman, J. Farahani, and Z. Qiang (2010). Managing water in rainfed agriculture – The need for a paradigm shift. *Agricultural Water Management*, **97**(4), pp. 543-550.

Romieu, I., H. Riojas-Rodriguez, A.T. Marron-Mares, A. Schilmann, R. Perez-Padilla, and O. Masera (2009). Improved biomass stove intervention in rural Mexico: Impact on the respiratory health of women. *American Journal of Respiratory and Critical Care Medicine*, **180**(7), pp. 649-656.

Rosegrant, M.W., T. Zhu, S. Msangi, and T. Sulser (2008). Biofuels: Long-run implications for food security and the environment. *Review of Agricultural Economics*, **30**(3), pp. 495-505.

Rosillo-Calle, F., S.V. Bajay, and H. Rothman (eds.) (2000). *Industrial Uses of Biomass Energy: The Example of Brazil.* Taylor & Francis, London, UK.

Ross, A.B., K. Anastasakis, M. Kubacki, and J.M. Jones (2009). Investigation of the pyrolysis behaviour of brown algae before and after pre-treatment using PY-GC/MS and TGA. *Journal of Analytical and Applied Pyrolysis*, **85**(1-2), pp. 3-10.

Rost, S., D. Gerten, H. Hoff, W. Lucht, M. Falkenmark, and J. Rockstrom (2009). Global potential to increase crop production through water management in rainfed agriculture. *Environmental Research Letters*, **4**(4), 044002 (9 pp.).

Rowe, R., J. Whitaker, J. Chapman, D. Howard, and G. Talor (2008). *Life-Cycle Assessment in Bioenergy Sector: Developing a Systematic Review Working Paper.* UKERC/WP/FSE/2008/002, UK Energy Research Centre, London, UK, 20 pp.

Royal Society (2008). *Sustainable Biofuels: Prospects and Challenges.* Policy document 01/08,The Royal Society, London, UK, 90 pp.

Rude, M.A., and A. Schirmer (2009). New microbial fuels: a biotech perspective. *Current Opinion in Microbiology*, **12**(3), pp. 274-281.

(S&T)^2 Consultants (2009). *An Examination of the Potential for Improving Carbon/Energy Balance of Bioethanol.* T39-TR1, (S&T)^2 Consultants Inc., Delta, Canada, 72 pp.

Saarinen, V.-M. (2006). The effects of slash and stump removal on productivity and quality of forest regeneration operations – preliminary results. *Biomass and Bioenergy*, **30**(4), pp. 349-356.

Saarsalmi, A., and E. Mälkönen (2001). Forest fertilization research in Finland: A literature review. *Scandinavian Journal of Forest Research*, **16**(6), pp. 514-535.

Sala, O.E., A. Kinzig, R. Leemans, D.M. Lodge, H.A. Mooney, M. Oesterheld, N.L. Poff, M.T. Sykes, B.H. Walker, M. Walker, D.H. Wall, F.S. Chapin, J.J. Armesto, E. Berlow, J. Bloomfield, R. Dirzo, E. Huber-Sanwald, L.F. Huenneke, and R.B. Jackson (2000). Global biodiversity scenarios for the year 2100. *Science*, **287**(5459), pp. 1770-1774.

Sánchez, Ó.J., and C.A. Cardona (2008). Trends in biotechnological production of fuel ethanol from different feedstocks. *Bioresource Technology*, **99**(13), pp. 5270-5295.

Sannigrahi, P., A.J. Ragauskas, and G.A. Tuskan (2010). Poplar as a feedstock for biofuels: A review of compositional characteristics. *Biofuels, Bioproducts and Biorefining*, **4**(2), pp. 209-226.

Sawin, J.L. (2004). *National Policy Instruments: Policy Lessons for the Advancement and Diffusion of Renewable Energy Technologies around the World.* World Watch Institute, Washington, DC, USA.

SCBD (2006). *Global Biodiversity Outlook 2.* Secretariat of the Convention on Biological Diversity, Montreal, Canada, 92 pp. (ISBN-92-9225-040-X).

Schei, M.A., J.O. Hessen, K.R. Smith, N. Bruce, J. McCracken, and V. Lopez (2004). Childhood asthma and indoor woodsmoke from cooking in Guatemala. *Journal of Exposure Analysis and Environmental Epidemiology*, **14**, pp. S110-S117.

Schlamadinger, B., F. Bohlin, L. Gustavsson, G. Jungmeier, G. Marlandii, K. Pingoudt, and I. Savolaine (1997). Towards a standard methodology for greenhouse gas balances of bioenergy systems in comparison with fossil energy systems. *Biomass and Bioenergy*, **13**(6), pp. 359-375.

Schlamadinger, B., M. Grubb, C. Azar, A. Bauen, and G. Berndes (2001). Carbon sinks and the CDM: could a bioenergy linkage offer a constructive compromise? *Climate Policy*, **1**, pp. 411-417.

Schlamadinger, B., B. Bosquet, C. Streck, I. Noble, M. Dutschke, and N. Bird (2005). Can the EU emission trading scheme support CDM forestry. *Climate Policy*, **5**, pp. 199-208.

Schmidhuber, J. (2008). Impact of an increased biomass use on agricultural markets, prices and food security: A longer-term perspective. In: *Energy Security in Europe: Proceedings from the Conference 'Energy Security in Europe'*, Lund, Sweden, 24-25 September 2007, Lund University, Lund, Sweden, pp. 133-170. Available at: www.cfe.lu.se/upload/LUPDF/CentrumforEuropaforskning/Confpap2.pdf.

Schneider, U.E., B. A. McCarl, and E. Schmid (2007). Agricultural sector analysis on greenhouse gas mitigation in US agriculture and forestry. *Agricultural Systems*, **94** (2), pp. 128-140

Schouten, J.C., E.V. Rebrov, and M.H.J.M. de Croon (2002). Miniaturization of heterogeneous catalytic reactors: prospects for new developments in catalysis and process engineering. *CHIMIA International Journal for Chemistry*, **56**(11), pp. 627-635.

Schulz, U., O. Brauner, and H. Gruss (2009). Animal diversity on short-rotation coppices – a review. *Landbauforschung vTI Agriculture and Forestry Research 3*, **59**(3), pp. 171-182.

Schwaiger, H.P., and D.N. Bird (2010). Integration of albedo effects caused by land use change into the climate balance: Should we still account in greenhouse gas units? *Forest Ecology and Management*, **260**(3), pp. 278-286.

Schwilch, G., F. Bachmann, and H. Liniger (2009). Appraising and selecting conservation measures to mitigate desertification and land degradation based on stakeholder participation and global best practices. *Land Degradation & Development*, **20**(3), pp. 308-326.

Scolforo, J.R. (2008). *Mundo Eucalipto – Os Fatos E Mitos De Sua Cultura.* Editora Mar de Ideias, Rio de Janeiro, Brazil, 72 pp.

Seabra, J.E.A., L. Tao, H.L. Chum, and I.C. Macedo (2010). A techno-economic evaluation of the effects of centralized cellulosic ethanol and co-products refinery options with sugarcane mill clustering. *Biomass and Bioenergy*, **34**(8), pp. 1065-1078.

Searchinger, T., R. Heimlich, R.A. Houghton, F. Dong, A. Elobeid, J. Fabiosa, S. Tokgoz, D. Hayes, and T.H. Yu (2008). Use of U.S. croplands for biofuels increases greenhouse gases through emissions from land-use change. *Science*, **319**, pp. 1238-1240.

Seidenberger, T., D. Thran, R. Offermann, U. Seyfert, M. Buchhorn, and J. Zeddies (2008). *Global Biomass Potentials.* Report prepared for Greenpeace International by the German Biomass Research Center, Leipzig, Germany, 137 pp.

Semere, T., and F. Slater (2007). Ground flora, small mammal and bird species diversity in miscanthus (*Miscanthus×giganteus*) and reed canary-grass (*Phalaris arundinacea*) fields. *Biomass and Bioenergy*, **31**(1), pp. 20-29.

Sepp, S. (2008). *Analysis of Charcoal Value Chains – General Considerations.* GTZ Household Energy Programme, Eschborn, Germany, 11 pp.

Shah, S. (2007). Modular mini-plants: A new paradigm. *Chemical Engineering Progress*, **103**(3), pp. 36-41.

Shapouri, H., and M. Salassi (2006). *The Economic Feasibility of Ethanol Production in the United States.* United States Department of Agriculture, Washington, DC, USA, 69 pp.

Sharma, M.M. (2002). Strategies of conducting reactions on a small scale. Selectivity engineering and process intensification. *Pure and Applied Chemistry*, **74**(12), pp. 2265-2269.

Sheehan, J., T. Dunahay, J. Benemann, G. Roessler, and C. Weissman (1998a). *A Look Back at the U.S. Department of Energy's Aquatic Species Program: Biodiesel from Algae.* NREL/TP-580-24190, National Renewable Energy Laboratory, Golden, CO, USA, 295 pp.

Sheehan, J., V. Camobreco, J. Duffield, M. Graboski, and H. Shapouri (1998b). *Life Cycle Inventory of Biodiesel and Petroleum Diesel for Use in an Urban Bus.* NREL/SR-580-24089, National Renewable Energy Laboratory, Golden, CO, USA, 314 pp.

Sheehan, J., A. Aden, K. Paustian, K. Killian, J. Brenner, M. Walsh, and R. Nelson (2003). Energy and environmental aspects of using corn stover for fuel ethanol. *Journal of Industrial Ecology*, **7**(3-4), pp. 117-146.

Shen, L., J. Haufe, and M.K. Patel (2009). *Product Overview and Market Projection of Emerging Bio-based Plastics: PRO-BIP 2009.* Copernicus Institute for Sustainable Development and Innovation for the European Polysaccharide Network of Excellence (EPNOE) and European Bioplastics, Utrecht University, Utrecht, The Netherlands, 78 pp.

Sikkema, R., M. Junginger, W. Pichler, S. Hayes, and A.P.C. Faaij (2010). The international logistics of wood pellets for heating and power production in Europe: Costs, energy-input and greenhouse gas balances of pellet consumption in Italy, Sweden and the Netherlands. *Biofuels, Bioproducts and Biorefining*, **4**(2), pp. 132-153.

Sikkema, R., M. Steiner, M. Junginger, W. Hiegl, M.T. Hansen, and A. Faaij (2011). The European wood pellet markets: current status and prospects for 2020. *Biofuels, Bioproducts and Biorefining*, doi:10.1002/bbb.277.

Simpson, T.W., A.N. Sharpley, R.W. Howarth, H.W. Paerl, and K.R. Mankin (2008). The new gold rush: Fueling ethanol production while protecting water quality. *Journal of Environmental Quality*, **37**(2), pp. 318-324.

Simpson, T.W., L.A. Martinelli, A.N. Sharpley, R.W. Howarth, and S. Bringezu (2009). Impact of ethanol production on nutrient cycles and water quality: the United States and Brazil as case studies. In: *Biofuels: Environmental Consequences and Interactions with Changing Land Use.* R.W. Howarth and S. Bringezu (eds.), Proceedings of the SCOPE - Scientific Committee on Problems of the Environment International Biofuels Project Rapid Assessment, Gummersbach, Germany, 22-25 September 2009,, pp. 153-167.

Sims, R. (ed.) (2007). *Renewables for Heating and Cooling. An Untapped Potential.* Joint report for the Renewable Energy Technology Deployment Implementing Agreement and the Renewable Energy Working Party published by the International Energy Agency, Paris, France, 210 pp.

Sims, R., M. Taylor, J. Saddler, W. Mabee, and J. Riese (2008). *From 1st-to 2nd Generation Biofuel Technologies. An overview of current industry and R&D activities.* IEA Bioenergy, Paris, France, 124 pp.

Sims, R.E.H., W. Mabee, J.N. Saddler, and M. Taylor (2010). An overview of second generation biofuel technologies. *Bioresource Technology*, **101**(6), pp. 1570-1580.

Skjoldborg, B. (2010). Optimization of I/S Skive District Heating Plant. In: IEA Joint Task 32 & 33 Workshop, *State-of-the-Art Technologies for Small Biomass Co-generation*, International Energy Agency, Copenhagen, Denmark, 7 Oct 2010. Available at: www.ieabcc.nl/meetings/task32_Copenhagen/11%20Skive.pdf.

Smeets, E.M.W., and A.P.C. Faaij (2007). Bioenergy potentials from forestry in 2050. *Climatic Change*, **81**(3-4), pp. 353-390.

Smeets, E.M.W., A. Faaij, I. Lewandowski, and W. Turkenburg (2007). A bottom-up assessment and review of global bio-energy potentials to 2050. *Progress in Energy and Combustion Science*, **33**(1), pp. 56-106.

Smeets, E.M.W., L.F. Bouwman, E. Stehfest, D.P. van Vuuren, and A. Posthuma (2009). Contribution of N_2O to the greenhouse gas balance of first-generation biofuels. *Global Change Biology*, **15**(1), pp. 1-23.

Smil, V. (2002). Worldwide transformation of diets, burdens of meat production and opportunities for novel food proteins. *Enzyme and Microbial Technology*, **30**(3), pp. 305-311.

Smith, K.R., and E. Haigler (2008). Co-benefits of climate mitigation and health protection in energy systems: Scoping methods. *Annual Review of Public Health*, **29**(1), pp. 11-25.

Smith, K.R., R. Uma, V.V.N. Kishore, J. Zhang, V. Joshi, and M.A.K. Khalil (2000). Greenhouse implications of household stoves: An analysis for India. *Annual Review of Energy and the Environment*, **25**(1), pp. 741-763.

Soimakallio, S., R. Antikainen, and R. Thun (2009a). *Assessing the Sustainability of Liquid Biofuels from Evolving Technologies.* VTT Research Notes 2482, VTT Technical Research Centre of Finland, Espoo, Finland, 268 pp.

Soimakallio, S., T. Mäkinen, T. Ekholm, K. Pahkala, H. Mikkola, and T. Paappanen (2009b). Greenhouse gas balances of transportation biofuels, electricity and heat generation in Finland – Dealing with the uncertainties. *Energy Policy*, **37**(1), pp. 80-90.

Solomon, S., G.K. Plattner, R. Knutti, and P. Friedlingstein (2009). Irreversible climate change due to carbon dioxide emissions. *Proceedings of the National Academy of Sciences*, **106**(6), pp. 1704-1709.

Sparovek, G., G. Berndes, A. Egeskog, F.L.M. de Freitas, S. Gustafsson, and J. Hansson (2007). Sugarcane ethanol production in Brazil: an expansion model sensitive to socioeconomic and environmental concerns. *Biofuels, Bioproducts and Biorefining*, **1**(4), pp. 270-282.

Spatari, S., and H.L. MacLean (2010). Characterizing model uncertainties in the life cycle of lignocellulose-based ethanol fuels. *Environmental Science & Technology*, **44**(22), pp. 8773-8780.

Spranger, T., J.P. Hettelingh, J. Slootweg, and M. Posch (2008). Modelling and mapping long-term risks due to reactive nitrogen effects: An overview of LRTAP convention activities. *Environmental Pollution*, **154**(3), pp. 482-487.

Steenblik, R. (2007). *Subsidies: The Distorted Economics of Biofuels.* Discussion Paper No. 2007-3, International Transport Forum, Organisation for Economic Co-operation and Development, Geneva, Switzerland, 66 pp.

Stehfest, E., and L. Bouwman (2006). N_2O and NO emission from agricultural fields and soils under natural vegetation: summarizing available measurement data and modeling of global annual emissions. *Nutrient Cycling in Agroecosystems*, **74**(3), pp. 207-228.

Stehfest, E., L. Bouwman, D.P. Vuuren, M.G.J. Elzen, B. Eickhout, and P. Kabat (2009). Climate benefits of changing diet. *Climatic Change*, **95**(1-2), pp. 83-102.

Still, D., M. Pinnell, D. Ogle, and B. van Appel (2003). Insulative ceramics for improved cooking stoves. *Boiling Point*, **49**, pp. 7-10.

Stoft, S. (2010). *Renewable Fuel and the Global Rebound Effect.* Research Paper No. 10-06, Global Energy policy Center, Berkeley, CA, USA, 19 pp.

Strengers, B., R. Leemans, B. Eickhout, B. Vries, and L. Bouwman (2004). The land-use projections and resulting emissions in the IPCC SRES scenarios as simulated by the IMAGE 2.2 model. *GeoJournal*, **61**(4), pp. 381-393.

Sulser, T.B., C. Ringler, T. Zhu, S. Msangi, E. Bryan, and M.W. Rosegrant (2010). Green and blue water accounting in the Ganges and Nile basins: Implications for food and agricultural policy. *Journal of Hydrology*, **384**(3-4), pp. 276-291.

Sumner, S.A., and P.M. Layde (2009). Expansion of renewable energy industries and implications for occupational health. *Journal of the American Medical Association*, **302**(7), pp. 787-789.

Sustainable Transport Solutions (2006). *Biogas as a Road Transport Fuel: An Assessment of the Potential Role of Biogas as a Renewable Transport Fuel.* National Society for Clean Air and Environmental Protection, London, UK, 66 pp.

Swanson, R.M., A. Platon, J.A. Satrio, and R.C. Brown (2010). Techno-economic analysis of biomass-to-liquids production based on gasification. *Fuel*, **89**(Supplement 1), pp. S11-S19.

Tabeau, A., B. Eickhout, and H. van Meijl (2006). Endogenous agricultural land supply: estimation and implementation in the GTAP model. In: *Ninth Annual Conference on Global Economic Analysis*, Addis Ababa, Ethiopia, 15-17 June 2006. Available at: https://www.gtap.agecon.purdue.edu/resources/res_display.asp?RecordID=2007.

Tao, L., and A. Aden (2009). The economics of current and future biofuels. *In Vitro Cellular & Developmental Biology - Plant*, **45**(3), pp. 199-217.

Thorn, J., J. Brisman, and K. Toren (2001). Adult-onset asthma is associated with self-reported mold or environmental tobacco smoke exposures in the home. *Allergy*, **56**(4), pp. 287-292.

Thornley, P., J. Rogers, and Y. Huang (2008). Quantification of employment from biomass power plants. *Renewable Energy*, **33**(8), pp. 1922-1927.

Thornley, P., P. Upham, Y. Huang, S. Rezvani, J. Brammer, and J. Rogers (2009). Integrated assessment of bioelectricity technology options. *Energy Policy*, **37**(3), pp. 890-903.

Tilman, D., K.G. Cassman, P.A. Matson, R. Naylor, and S. Polasky (2002). Agricultural sustainability and intensive production practices. *Nature*, **418**(6898), pp. 671-677.

Tilman, D., J. Hill, and C. Lehman (2006a). Carbon-negative biofuels from low-input high-diversity grassland biomass. *Science*, **314**(5805), pp. 1598-1600.

Tilman, D., P.B. Reich, and J.M.H. Knops (2006b). Biodiversity and ecosystem stability in a decade-long grassland experiment. *Nature*, **441**(7093), pp. 629-632.

Titus, B.D., D.G. Maynard, C.C. Dymond, G. Stinson, and W.A. Kurz (2009). Wood energy: Protect local ecosystems. *Science*, **324**(5933), pp. 1389-1390.

Tobias, C.M., G. Sarath, P. Twigg, E. Lindquist, J. Pangilinan, B.W. Penning, K. Barry, M.C. McCann, N.C. Carpita, and G.R. Lazo (2008). Comparative genomics in switchgrass using 61,585 high-quality expressed sequence tags. *The Plant Genome*, **1**(2), pp. 111-124.

Tonkovich, A.Y., S. Perry, Y. Wang, D. Qiu, T. LaPlante, and W.A. Rogers (2004). Microchannel process technology for compact methane steam reforming. *Chemical Engineering Science*, **59**(22-23), pp. 4819-4824.

Towle, D.W., and J.S. Pearse (1973). Production of the giant kelp, Macrocystis, estimated by in situ incorporation of ^{14}C in polyethylene bags. *American Society of Limnology and Oceanography*, **18**(1), pp. 155-159.

Turhollow, A. (1994). The economics of energy crop production. *Biomass and Bioenergy*, **6**(3), pp. 229-241.

Tyner, W.E., and F. Taheripour (2008). Policy options for integrated energy and agricultural markets. *Applied Economic Perspectives and Policy*, **30**(3), pp. 387-396.

Tyner, W., F. Taheripour, Q. Zhuang, D. Birur, and U. Baldos (2010). *Land Use Changes and Consequent CO_2 Emissions due to U.S. Corn Ethanol Production: A Comprehensive Analysis.* GTAP Resource 3288, Department of Agricultural Economics, Purdue University, West Lafayette, IN, USA, 90 pp.

UN-Water (2007). *Coping with Water Scarcity: Challenge of the Twenty-First Century.* Prepared for World Water Day 2007, United Nations, New York, NY, USA, 29 pp.

UNECE/FAO TIMBER Database (2011). Market Presentations at http: timber.unece.org/. United Nations Economic Commission for Europe and Food and Agricultural Organization.

UNEP (2008a). *UNEP Year Book 2008: an Overview of Our Changing Environment.* United Nations Environment Programme, Nairobi, Kenya.

UNEP (2008b). *The Potential Impacts of Biofuels on Biodiversity, Notes by the Executive Secretary.* UNEP/CBD/COP/9/26, United Nations Environment Programme, Bonn, Germany, 16 pp.

UNEP/SEFI/Bloomberg (2010). *Global Trends in Sustainable Energy Investment 2010.* DTI/1186/PA, Sustainable Energy Finance Initiative, United Nations Environment Programme and Bloomberg New Energy Finance, Geneva, Switzerland, 61 pp.

UK DfT (2003). *International Resource Costs of Biodiesel and Bioethanol.* AEAT/ENV/ED50273/R1, United Kingdom Department for Transport, Oxfordshire, UK, 51 pp.

University of Illinois (2011). *farmdoc: Historical Corn Prices.* University of Illinois, Urbana, Illinois, USA. Available at: www.farmdoc.illinois.edu/manage/pricehistory/price_history.htm.

US DOE (2009). *National Algal Biofuels Technology Roadmap.* U.S. Department of Energy Biomass Program, Washington, DC, USA, 214 pp.

US DOE (2011). *Biomass as Feedstock for a Bioenergy and Bioproducts Industry: An Update to the Billion-Ton Annual Supply.* R.D. Perlack and B.J. Stokes (Leads), ORNL/TM-2010/xx. U.S. Department of Energy, Oak Ridge National Laboratory, Oak Ridge, TN, USA, in press.

USDA (2006). *Oil Crops Yearbook/OCS-2006/Mar21.* Economic Research Service, US Department of Agriculture (USDA), Washington, DC, USA.

USDA (2007). *Wheat Data: Yearbook Tables.* Economic Research Service, US Department of Agriculture (USDA), Washington, DC, USA.

Uslu, A., A.P.C. Faaij, and P.C.A. Bergman (2008). Pre-treatment technologies, and their effect on international bioenergy supply chain logistics. Techno-economic evaluation of torrefaction, fast pyrolysis and pelletisation. *Energy*, **33**(8), pp. 1206-1223.

van Dam, J., M. Junginger, A. Faaij, I. Jürgens, G. Best, and U. Fritsche (2008). Overview of recent developments in sustainable biomass certification. *Biomass and Bioenergy*, **32**(8), pp. 749-780.

van Dam, J., A.P.C. Faaij, J. Hilbert, H. Petruzzi, and W.C. Turkenburg (2009a). Large-scale bioenergy production from soybeans and switchgrass in Argentina: Part A: Potential and economic feasibility for national and international markets. *Renewable and Sustainable Energy Reviews*, **13**(8), pp. 1710-1733.

van Dam, J., A.P.C. Faaij, J. Hilbert, H. Petruzzi, and W.C. Turkenburg (2009b). Large-scale bioenergy production from soybeans and switchgrass in Argentina: Part B. Environmental and socio-economic impacts on a regional level. *Renewable and Sustainable Energy Reviews*, **13**(8), pp. 1679-1709.

van Dam, J., A.P.C. Faaij, I. Lewandowski, and B. Van Zeebroeck (2009c). Options of biofuel trade from Central and Eastern to Western European countries. *Biomass and Bioenergy*, **33**(4), pp. 728-744.

van Dam, J., M. Junginger, and A.P.C. Faaij (2010). From the global efforts on certification of bioenergy towards an integrated approach based on sustainable land use planning. *Renewable and Sustainable Energy Reviews*, **14**(9), pp. 2445-2472.

van den Wall Bake, J.D. (2006). *Cane as Key in Brazilian Ethanol Industry.* Master's Thesis, Copernicus Institute, Utrecht University, Utrecht, The Netherlands, 83 pp.

van den Wall Bake, J.D., M. Junginger, A. Faaij, T. Poot, and A. Walter (2009). Explaining the experience curve: Cost reductions of Brazilian ethanol from sugarcane. *Biomass and Bioenergy*, **33**(4), pp. 644-658.

van der Horst, D., and J. Evans (2010). Carbon claims and energy landscapes: Exploring the political ecology of biomass. *Landscape Research*, **35**(2), pp. 173-193.

van Iersel, S., L. Gamba, A. Rossi, S. Alberici, B. Dehue, J. van de Staaij, and A. Flammini (2009). *Algae-Based Biofuels: A Review of Challenges and Opportunities for Developing Countries.* Food and Agriculture Organization, Rome, Italy, 59 pp.

van Loo, S., and J. Koppejan (eds.) (2002). *Handbook of Biomass Combustion and Cofiring.* 1st ed. Twente University Press, Enschede, The Netherlands, 442 pp.

van Minnen, J.G., B.J. Strengers, B. Eickhout, R.J. Swart, and R. Leemans (2008). Quantifying the effectiveness of climate change mitigation through forest plantations and carbon sequestration with an integrated land-use model. *Carbon Balance and Management*, **3**(3), 20 pp.

van Vliet, O.P.R., A.P.C. Faaij, and W.C. Turkenburg (2009). Fischer-Tropsch diesel production in a well-to-wheel perspective: A carbon, energy flow and cost analysis. *Energy Conversion and Management*, **50**(4), pp. 855-876.

van Vuuren, D., M. den Elzen, P. Lucas, B. Eickhout, B. Strengers, B. van Ruijven, S. Wonink, and R. van Houdt (2007). Stabilizing greenhouse gas concentrations at low levels: an assessment of reduction strategies and costs. *Climatic Change*, **81**(2), pp. 119-159.

van Vuuren, D.P., J. van Vliet, and E. Stehfest (2009). Future bio-energy potential under various natural constraints. *Energy Policy*, **37**(11), pp. 4220-4230.

van Vuuren, D.P., E. Bellevrat, A. Kitous, and M. Isaac (2010). Bio-energy use and low stabilization scenarios. *The Energy Journal*, **31**(Special Issue), pp. 192-222.

van Zyl, W., L. Lynd, R. den Haan, and J. McBride (2007). Consolidated bioprocessing for bioethanol production using Saccharomyces cerevisiae. *Advanced Biochemical Engineering Biotechnology*, **108**, pp. 205-235.

Vandermeer, J., and I. Perfecto (2006). Response to comments on "A Keystone Mutualism Drives Pattern in a Power Function". *Science*, **313**(5794), pp. 1739.

Venkataraman, C., A.D. Sagar, G. Habib, N. Lam, and K.R. Smith (2010). The Indian National Initiative for Advanced Biomass Cookstoves: The benefits of clean combustion. *Energy for Sustainable Development*, **14**(2), pp. 63-72.

Venter, O., E. Meijaard, H. Possingham, R. Dennis, D. Sheil, S. Wich, L. Hovani, and K. Wilson (2009). Carbon payments as a safeguard for threatened tropical mammals. *Conservation Letters*, **2**(3), pp. 123-129.

Verhaeven, E., L. Pelkmans, L. Govaerts, R. Lamers, and F. Theunissen (2005). Results of demonstration and evaluation projects of biodiesel from rapeseed and used frying oil on light and heavy duty vehicles. In: *2005 SAE Brasil Fuels & Lubricants Meeting.* SAE International, Rio De Janeiro, Brasil, May 2005, 7 pp., doi:10.4271/2005-01-2201.

Vinnerås, B., C. Schönning, and A. Nordin (2006). Identification of the microbiological community in biogas systems and evaluation of microbial risks from gas usage. *Science of the Total Environment*, **367**(2-3), pp. 606-615.

von Blottnitz, H., and M.A. Curran (2007). A review of assessments conducted on bio-ethanol as a transportation fuel from a net energy, greenhouse gas, and environmental life cycle perspective. *Journal of Cleaner Production*, **15**(7), pp. 607-619.

von Geibler, J., C. Liedtke, H. Wallbaum, and S. Schaller (2006). Accounting for the social dimension of sustainability: experiences from the biotechnology industry. *Business Strategy and the Environment*, **15**(5), pp. 334-346.

von Schirnding, Y., N. Bruce, K. Smith, G. Ballard-Treemer, M. Ezzati, and K. Lvovsky (2001). *Addressing the Impact of Household Energy and Indoor Air Pollution on the Health of the Poor - Implications for Policy Action and Intervention Measures.* WHO/HDE/HID/02.9, Commission on Macroeconomics and Health, World Health Organization, Geneva, Switzerland, 52 pp.

von Weyman, N. (2007). *Bioetanolia maatalouden selluloosavirroista (Bioethanol from agricultural lignocellulosic residues).* VTT Tiedotteita 2412, VTT Technical Research Centre of Finland, Espoo, Finland, 48 pp.

Walmsley, J.D., and D.L. Godbold (2010). Stump harvesting for bioenergy - A review of the environmental impacts. *Forestry*, **83**(1), pp. 17-38.

Walsh, M.E. (2008). *U.S. Cellulosic Biomass Feedstock Supplies and Distribution.* Ag Econ Search - Research in Agricultural and Applied Economics, University of Minnesota, St. Paul, Minnesota, 47 pp. Available at: ageconsearch.umn.edu/bitstream/7625/2/U.S.%20Biomass%20Supplies.pdf.

Walter, A., F. Rosillo-Calle, P. Dolzan, E. Piacente, and K. Borges da Cunha (2008). Perspectives on fuel ethanol consumption and trade. *Biomass and Bioenergy*, **32**(8), pp. 730-748.

Wang, M., C. Saricks, and D. Santini (1999). *Effects of fuel ethanol use on fuel-cycle energy and greenhouse gas emissions.* ANL/ESD-38, Argonne Energy Systems Division, Argonne National Laboratory, Argonne, IL, USA, 39 pp.

Wang, M., M. Wu, and H. Huo (2007). Life-cycle energy and greenhouse gas emission impacts of different corn ethanol plant types. *Environmental Research Letters*, **2**(2), 024001.

Wang, M., H. Huo, and S. Arora (2010). Methods of dealing with co-products of biofuels in life-cycle 3 analysis and consequent results within the U.S. context. *Energy Policy*, in press, doi:10.1016/j.enpol.2010.03.052.

Wang, M.Q., J. Han, Z. Haq, W.E. Tyner, M. Wu, and A. Elgowainy (2011). Energy and greenhouse gas emission effects of corn and cellulosic ethanol with technology improvements and land use changes. *Biomass and Bioenergy*, **35**(5), pp. 1885-1896.

Warwick, S.I., H.J. Beckie, and L.M. Hall (2009). Gene flow, invasiveness, and ecological impact of genetically modified crops. *Annals of the New York Academy of Sciences*, **1168**(1), pp. 72-99.

WBGU (2009). *World in Transition – Future Bioenergy and Sustainable Land Use.* German Advisory Council on Global Change (WBGU), Berlin, Germany, 393 pp. (ISBN 978-1-84407-841-7).

Weyer, K., D. Bush, A. Darzins, and B. Willson (2009). Theoretical maximum algal oil production. *BioEnergy Research*, **3**(2), pp. 204-213.

Wicke, B., V. Dornburg, M. Junginger, and A. Faaij (2008). Different palm oil production systems for energy purposes and their greenhouse gas implications. *Biomass and Bioenergy*, **32**(12), pp. 1322-1337.

Wicke, B., E. Smeets, A. Tabeau, J. Hilbert, and A. Faaij (2009). Macroeconomic impacts of bioenergy production on surplus agricultural land – A case study of Argentina. *Renewable and Sustainable Energy Reviews*, **13**(9), pp. 2463-2473.

Wilhelm, W.W., J.M.F. Johnson, J.L. Hatfield, W.B. Voorhees, and D.R. Linden (2004). Crop and soil productivity response to corn residue removal: A literature review. *Agronomy Journal*, **96**(1), pp. 1-17.

Wilhelm, W.W., J.M.E. Johnson, D.L. Karlen, and D.T. Lightle (2007). Corn stover to sustain soil organic carbon further constrains biomass supply. *Agronomy Journal*, **99**, pp. 1665-1667.

Wilkie, A.C., and J.M. Evans (2010). Aquatic plants: an opportunity feedstock in the age of bioenergy. *Biofuels*, **1**(2), pp. 311-321.

Wilkie, A.C., K.J. Riedesel, and J.M. Owens (2000). Stillage characterization and anaerobic treatment of ethanol stillage from conventional and cellulosic feedstocks. *Biomass and Bioenergy*, **19**(2), pp. 63-102.

Wilkinson, P., K.R. Smith, M. Davies, H. Adair, B.G. Armstrong, M. Barrett, N. Bruce, A. Haines, I. Hamilton, T. Oreszczyn, I. Ridley, C. Tonne, and Z. Chalabi (2009). Public health benefits of strategies to reduce greenhouse-gas emissions: household energy. *The Lancet*, **374**(9705), pp. 1917-1929.

Williams, R.H., E.D. Larson, G. Liu, and T.G. Kreutz (2009). Fischer-Tropsch fuels from coal and biomass: Strategic advantages of once-through ("polygeneration") configurations. *Energy Procedia*, **1**(1), pp. 4379-4386.

Wirsenius, S. (2003). Efficiencies and biomass appropriation of food commodities on global and regional levels. *Agricultural Systems*, **77**(3), pp. 219-255.

Wirsenius, S., C. Azar, and G. Berndes (2010). How much land is needed for global food production under scenarios of dietary changes and livestock productivity increases in 2030? *Agricultural Systems*, **103**(9), pp. 621-638.

Wise, M., K. Calvin, A. Thomson, L. Clarke, B. Bond-Lamberty, R. Sands, S.J. Smith, A. Janetos, and J. Edmonds (2009). Implications of limiting CO_2 concentrations for land use and energy. *Science*, **324**(5931), pp. 1183-1186.

Wiskerke, W.T., V. Dornburg, C.D.K. Rubanza, R.E. Malimbwi, and A.P.C. Faaij (2010). Cost/benefit analysis of biomass energy supply options for rural smallholders in the semi-arid eastern part of Shinyanga Region in Tanzania. *Renewable and Sustainable Energy Reviews*, **14**(1), pp. 148-165.

Wolf, J., P.S. Bindraban, J.C. Luijten, and L.M. Vleeshouwers (2003). Exploratory study on the land area required for global food supply and the potential global production of bioenergy. *Agricultural Systems*, **76**, pp. 841-861.

Wooley, R., M. Ruth, D. Glassner, and J. Sheehan (1999). Process design and costing of bioethanol technology: A tool for determining the status and direction of research and development. *Biotechnology Progress*, **15**(5), pp. 794-803.

Woolf, D., J.E. Amonette, F.A. Street-Perrott, J. Lehmann, and S. Joseph (2010). Sustainable biochar to mitigate global climate change. *Nature Communications*, **1**(56), pp. 1-9.

World Bank (2009). *The World Bank - Global Economic Prospects - Commodities at the Crossroad.* The World Bank, The International Bank for Reconstruction and Development, Washington, DC, USA, 196 pp. (see page 73).

World Bank (2010). *Improved Cookstoves and Better Health in Bangladesh: Lessons from Household Energy and Sanitation Programs.* The World Bank, The International Bank for Reconstruction and Development, Washington, DC, USA, 136 pp.

Wright, B. (2009). *International Gain Reserves and Other Instruments to Address Volatility in Grain Market.* Policy Research Working Paper 5028, World Bank Group, Washington, DC, USA, 61 pp.

Wright, D.H. (1990). Human impacts on energy flow through natural ecosystems, and implications for species endangerment. *AMBIO: A Journal of the Human Environment*, **19**(4), pp. 189-194.

Wu, M., Y. Wu, and M. Wang (2005). *Mobility Chains Analysis of Technologies for Passenger Cars and Light Duty Vehicles Fueled with Biofuels: Application of the Greet Model to Project the Role of Biomass in America's Energy Future (RBAEF) project.* ANL/ESD/07-11, Argonne National Laboratory, Argonne, IL, USA, 84 pp.

Wu, M., M. Wang, J. Liu, and H. Huo (2008). Assessment of potential life-cycle energy and greenhouse gas emission effects from using corn-based butanol as a transportation fuel. *Biotechnology Progress*, **24**(6), pp. 1204-1214.

Wu, M., M. Mintz, M. Wang, and S. Arora (2009). Water consumption in the production of ethanol and petroleum gasoline. *Environmental Management*, **44**(5), pp. 981-997.

WWI (2006). *Biofuels for Transportation – Global Potential and Implications for Sustainable Agriculture and Energy in the 21st Century.* World Watch Institute, Washington, DC, USA, 417 pp.

Wydra, S. (2009). *Production and Employment Impacts of New Technologies – Analysis for Biotechnology.* Discussion Paper 08-2009, Forschungszentrum Innovation und Dienstleistung, Universität Hohenheim, Stuttgart, Germany, 31 pp.

Wyman, C.E., B.E. Dale, R.T. Elander, M. Holtzapple, M.R. Ladisch, and Y.Y. Lee (2005). Coordinated development of leading biomass pretreatment technologies. *Bioresource Technology*, **96**(18), pp. 1959-1966.

Yamashita, K., and L. Barreto (2004). *Biomass Gasification for the Co-production of Fischer-Tropsch Liquids and Electricity.* Interim Report IR-04-047, International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria, 50 pp.

Yanowitz, J., and R.L. McCormick (2009). Effect of biodiesel blends on North American heavy-duty diesel engine emissions. *European Journal of Lipid Science and Technology*, **111**(8), pp. 763-772.

Yazdani, S.S., and R. Gonzalez (2007). Anaerobic fermentation of glycerol: a path to economic viability for the biofuels industry. *Current Opinion in Biotechnology*, **18**(3), pp. 213-219.

Yeh, S., S.M. Jordaan, A.R. Brandt, M.R. Turetsky, S. Spatari, and D.W. Keith (2010). Land use greenhouse gas emissions from conventional oil production and oil sands. *Environmental Science & Technology*, **44**(22), pp. 8766-8772.

Yokoyama, S., and Y. Matsumura (eds.) (2008). *The Asian Biomass Handbook: A Guide for Biomass Production and Utilization.* The Japan Institute of Energy, Tokyo, Japan, 326 pp.

Zabowski, D., D. Chambreau, N. Rotramel, and W.G. Thies (2008). Long-term effects of stump removal to control root rot on forest soil bulk density, soil carbon and nitrogen content. *Forest Ecology and Management*, **255**(3-4), pp. 720-727.

Zemke-White, L., and M. Ohno (1999). World seaweed utilisation: An end-of-century summary. *Journal of Applied Phycology*, **11**(4), pp. 369-376.

Zezza, A., B. Davis, C. Azzarri, K. Covarrubias, L. Tasciotti, and G. Anriquez (2008). *The Impact of Rising Food Prices on the Poor.* ESA Working Paper No. 08-07, Agricultural Development Economics Division, Food and Agriculture Organization, Rome, Italy, 37 pp.

Zhang, X., R.C. Izaurralde, D. Manowitz, T.O. West, W.M. Post, A.M. Thomson, V.P. Bandaru, J. Nichols, and J.R. Williams (2010). An integrative modeling framework to evaluate the productivity and sustainability of biofuel crop production systems. *Global Change Biology Bioenergy*, **2**(5), pp. 258-277.

Zomer, R.J., A. Trabucco, O. van Straaten, and D.A. Bossio (2006). *Carbon, Land and Water: A Global Analysis of the Hydrologic Dimensions of Climate Change Mitigation through Afforestation/Reforestation.* IWMI Research Report 101, International Water Management Institute, Colombo, Sri Lanka, 48 pp.

Table of Contents

Executive Summary

Bioenergy has a significant greenhouse gas (GHG) mitigation potential, provided that the resources are developed sustainably and that efficient bioenergy systems are used. Certain current systems and key future options including perennial cropping systems, use of biomass residues and wastes and advanced conversion systems are able to deliver 80 to 90% emission reductions compared to the fossil energy baseline. However, land use conversion and forest management that lead to a loss of carbon stocks (direct) in addition to indirect land use change (d+iLUC) effects can lessen, and in some cases more than neutralize, the net positive GHG mitigation impacts. Impacts of climate change through temperature increases, rainfall pattern changes and increased frequency of extreme events will influence and interact with biomass resource potential. This interaction is still poorly understood, but it is likely to exhibit strong regional differences. Climate change impacts on biomass feedstock production exist but if global temperature rise is limited to less than 2°C compared with the pre-industrial record, it may pose few constraints. Combining adaptation measures with biomass resource production can offer more sustainable opportunities for bioenergy and perennial cropping systems.

Biomass is a primary source of food, fodder and fibre and as a renewable energy (RE) source provided about 10.2% (50.3 EJ) of global total primary energy supply (TPES) in 2008. Traditional use of wood, straws, charcoal, dung and other manures for cooking, space heating and lighting by generally poorer populations in developing countries accounts for about 30.7 EJ, and another 20 to 40% occurs in unaccounted informal sectors including charcoal production and distribution. TPES from biomass for electricity, heat, combined heat and power (CHP), and transport fuels was 11.3 EJ in 2008 compared to 9.6 EJ in 2005 and the share of modern bioenergy was 22% compared to 20.6%.

From the expert review of available scientific literature, potential deployment levels of biomass for energy by 2050 could be in the range of 100 to 300 EJ. However, there are large uncertainties in this potential such as market and policy conditions, and it strongly depends on the rate of improvement in the production of food and fodder as well as wood and pulp products.

The upper bound of the technical potential of biomass for energy may be as large as 500 EJ/yr by 2050. Reaching a substantial fraction of the technical potential will require sophisticated land and water management, large worldwide plant productivity increases, land optimization and other measures. Realizing this potential will be a major challenge, but it could make a substantial contribution to the world's primary energy supply in 2050. For comparison, the equivalent heat content of the total biomass harvested worldwide for food, fodder and fibre is about 219 EJ/yr today.

A scenario review conducted in Chapter 10 indicates that the contribution of bioenergy in GHG stabilization scenarios of different stringency can be expected to be significantly higher than today. By 2050, in the median case bioenergy contributes 120 to 155 EJ/yr to global primary energy supply, or 150 to 190 EJ/yr for the 75th percentile case, and even up to 265 to 300 EJ/yr in the highest deployment scenarios. This deployment range is roughly in line with the IPCC Special Report on Emission Scenarios (SRES) regionally oriented A2 and B2 and globally oriented A1 and B1 conditions and storylines. Success in implementing sustainability and policy frameworks that ensure good governance of land use and improvements in forestry, agricultural and livestock management could lead to both high (B1) and low (B2) potentials. However, biomass supplies may remain limited to approximately 100 EJ/yr in 2050 if such policy frameworks and enforcing mechanisms are not introduced and if there is strong competition for biomaterials from other (innovative future) sectors. In that environment, further biomass expansion could lead to significant regional conflicts for food supplies, water resources and biodiversity, and could even result in additional GHG emissions, especially due to iLUC and loss of carbon stocks. In another deployment scenario, biomass resources may be constrained to use of residues and organic waste, energy crops cultivated on marginal/degraded and poorly utilized lands, and to supplies in endowed world regions where bioenergy is a cheaper energy option compared to market alternatives (e.g., sugarcane ethanol production in Brazil).

Bioenergy has complex societal and environmental interactions, including climate change feedback, biomass production and land use. The impact of bioenergy on social and environmental issues (e.g., health, poverty, biodiversity) may be positive or negative depending on local conditions and the design and implementation of specific projects. The policy context for bioenergy, and particularly biofuels, has changed rapidly and dramatically in recent years. The food versus fuel debate and growing concerns about other conflicts are driving a strong push for the development and implementation of sustainability criteria and frameworks. Many conflicts can be reduced if not avoided by encouraging synergisms in the management of natural resource, agricultural and livestock sectors as part of good governance of land use that increases rural development and contributes to poverty alleviation and a secure energy supply.

Costs vary by world regions, feedstock types, feedstock supply costs for conversion processes, the scale of bioenergy production and production time during the year. Examples of estimated commercial bioenergy levelized cost ranges are roughly USD_{2005} 2 to 48/GJ for liquid and gaseous biofuels; roughly US $cents_{2005}$ 3.5 to 25/kWh (USD_{2005} 10 to 50/GJ) for electricity or CHP systems larger than about 2 MW (with feedstock costs of USD_{2005} $3/GJ_{feed}$ and a heat value of USD_{2005} 5/GJ for steam or USD_{2005} 12/GJ for hot water); and roughly USD_{2005} 2 to 77/GJ for domestic or district heating systems with feedstock costs in the range of USD_{2005} 0 to 20/GJ (solid waste to wood pellets). These calculations refer to 2005 to 2008 data and are expressed in USD_{2005} at a 7% discount rate.

Recent analyses of lignocellulosic biofuels indicate potential improvements that enable them to compete at oil prices of USD_{2005} 60 to 70/barrel (USD_{2005} 0.38 to 0.44/litre) assuming no revenue from carbon dioxide (CO_2) mitigation. Scenario analyses indicate that strong short-term research and development (R&D) and market support could allow for commercialization around 2020 depending on oil and carbon pricing. In addition to ethanol and biodiesel, a range of hydrocarbons and chemicals/materials similar to those currently derived from oil could provide biofuels for not only vehicles but also for the aviation and maritime sectors. Biomass is the only renewable resource that can currently provide high energy density liquid fuels. A wider variety of bio-based products can also be produced at biorefineries to enhance the economics of the overall conversion process. Short-term options (some of them already competitive) that can deliver long-term synergies include co-firing, CHP, heat generation and sugarcane-based ethanol and bioelectricity co-production. Development of working bioenergy markets and facilitation of international bioenergy trade can help achieve these synergies.

Further improvements in power generation technologies, supply systems of biomass and production of perennial cropping systems can bring bioenergy costs down. There is clear evidence that technological learning and related cost reductions occur in many biomass technologies with learning rates comparable to other RE technologies. This is true for cropping systems where improvements in agricultural management of annual crops, supply systems and logistics, conversion technologies to produce energy carriers such as heat, electricity and ethanol from sugarcane or maize, and biogas have demonstrated significant cost reductions.

Combining biomass conversion with developing carbon capture and storage (CCS) could lead to long-term substantial removal of GHGs from the atmosphere (also referred to as negative emissions). Advanced biomaterials are promising as well from both an economic and a GHG mitigation perspective, though the relative magnitude of their mitigation potential is not well understood. The potential role of aquatic biomass (algae) is highly uncertain but could reduce land use conflict. More experience, research, development and demonstration (RD&D), and detailed analyses of these options are needed.

Multiple drivers for bioenergy systems and their deployment in sustainable directions are emerging. Examples include rapidly changing policy contexts, recent market-based activities, the increasing support for advanced biorefinery and lignocellulosic biofuel options and, in particular, development of sustainability criteria and frameworks. Sustained cost reductions of key technologies in biomass production and conversion, supply infrastructure development, and integrated systems research can lead to the implementation of strategies that facilitate sustainable land and water use and gain public and political acceptance.

2.1 Introduction

Bioenergy is embedded in complex ways in global biomass systems for food, fodder and fibre production and for forest products; in wastes and residue management; and in the everyday living of the developing countries' poor. Bioenergy includes different sets of technologies for applications in various sectors.

2.1.1 Current pattern of biomass and bioenergy use and trends

Biomass provided about 10.2% (50.3 EJ/yr) of the annual global primary energy supply in 2008, from a wide variety of biomass sources feeding numerous sectors of society (see Table 2.1; IEA, 2010a). The biomass feedstocks used for energy are shown in Figure 2.1 (top), and more than 80% are derived from wood (trees, branches, residues) and shrubs. The remaining bioenergy feedstocks came from the agricultural sector (energy crops, residues and by-products) and from various commercial and post-consumer waste and by-product streams (biomass product recycling and processing or the organic biogenic fraction of municipal solid waste[1] (MSW)).

Biomass is used (see Table 2.1) with varying degrees of energy efficiency in various sectors:

- Low-efficiency *traditional biomass*[2] such as wood, straws, dung and other manures are used for cooking, lighting and space heating, generally by the poorer populations in developing countries. This biomass is mostly combusted, creating serious negative impacts on health and living conditions. Increasingly, charcoal is becoming a secondary energy carrier in rural areas. As an indicator of the magnitude of traditional biomass use, Figure 2.1 (bottom) illustrates that the global primary energy supply from traditional biomass parallels the world's industrial roundwood production.

In the International Energy Agency's (IEA) World Energy Statistics (IEA, 2010a) and World Energy Outlook (WEO: IEA, 2010b) TPES from traditional biomass amounts to 30.7 EJ/yr based on national databases that tend to systematically underestimate fuelwood consumption. Although international forestry and energy data (FAO, 2005) are the main reference sources for policy analyses, they are

Table 2.1 | Examples of traditional and select modern biomass energy flows in 2008 according to the IEA (2010 a,b) and supplemented by Masera et al., 2005, 2006; Drigo et al., 2007, 2009.

Type	Approximate Primary Energy (EJ/yr)	Approximate Average Efficiency (%)	Approximate Secondary Energy (EJ/yr)
Traditional Biomass			
Accounted for in IEA energy statistics	30.7	10–20	3–6
Estimated for informal sectors (e.g., charcoal)	6–12		0.6–2.4
Total Traditional Biomass	37–43		3.6–8.4
Modern Bioenergy			
Electricity and CHP from biomass, MSW, and biogas	4.0	32	1.3
Heat in residential, public/commercial buildings from solid biomass and biogas	4.2	80	3.4
Road transport fuels (ethanol and biodiesel)	3.1	60	1.9
Total Modern Bioenergy	11.3	58	6.6

Notes: According to the IEA (2010a,b), the 2008 TPES from biomass of 50.3 EJ was composed primarily of solid biomass (46.9 EJ); biogenic MSW used for heat and CHP (0.58 EJ); and biogas (secondary energy) for electricity and CHP (0.41 EJ) and heating (0.33 EJ). The contribution of ethanol, biodiesel, and other biofuels (e.g., ethers) used in the transport sector amounted to 1.9 EJ in secondary energy terms. Examples of specific flows: output electricity from biomass was 0.82 EJ (biomass power plants including pulp and paper industry surplus, biogas and MSW) and output heating from CHP was 0.44 EJ. Modern residential heat consumption was calculated by subtracting the IEA estimate of traditional use of biomass (30.7 EJ) from the total residential heat consumption (33.7 EJ).

Some table numbers were taken directly from the IEA global energy statistics, such as secondary biofuels at 1.9 EJ (whereas the derived primary energy input is based on the assumed efficiency of 60% which could be lower) as well as output electricity and heat at 1.3 EJ for all feedstocks. Primary input for MSW and biogas (secondary) and the corresponding output were available and efficiencies are calculated. Solid biomass primary input was calculated from the average efficiency for MSW. Not included in the numbers above are solid biomass (3.4 EJ) used to make charcoal (1.15 EJ) for heating (0.88 EJ, traditional mostly) and industry, such as the iron/steel industry (0.22 EJ), mostly in Brazil. Heat for making charcoal is included in Figure 1.18 in the 5.2 EJ from biomass for electricity, CHP, and heat plants. Not included in Table 2.1 is the industry sector that consumed 7.7 EJ, but the electricity sold by the pulp and paper industry is included.

1 MSW is used throughout the chapter with the same meaning as the term municipal wastes as defined by EUROSTAT.

2 Traditional biomass is defined as biomass consumption in the residential sector in developing countries and refers to the often unsustainable use of wood, charcoal, agricultural residues and animal dung for cooking and heating (IEA, 2010b and Annex I). All other biomass use is defined as modern biomass; this report further differentiates between highly efficient modern bioenergy and industrial bioenergy applications with varying degrees of efficiency (Annex I). The renewability and sustainability of biomass use is primarily discussed in Sections 2.5.4 and 2.5.5, respectively (see also Section 1.2.1 and Annex I).

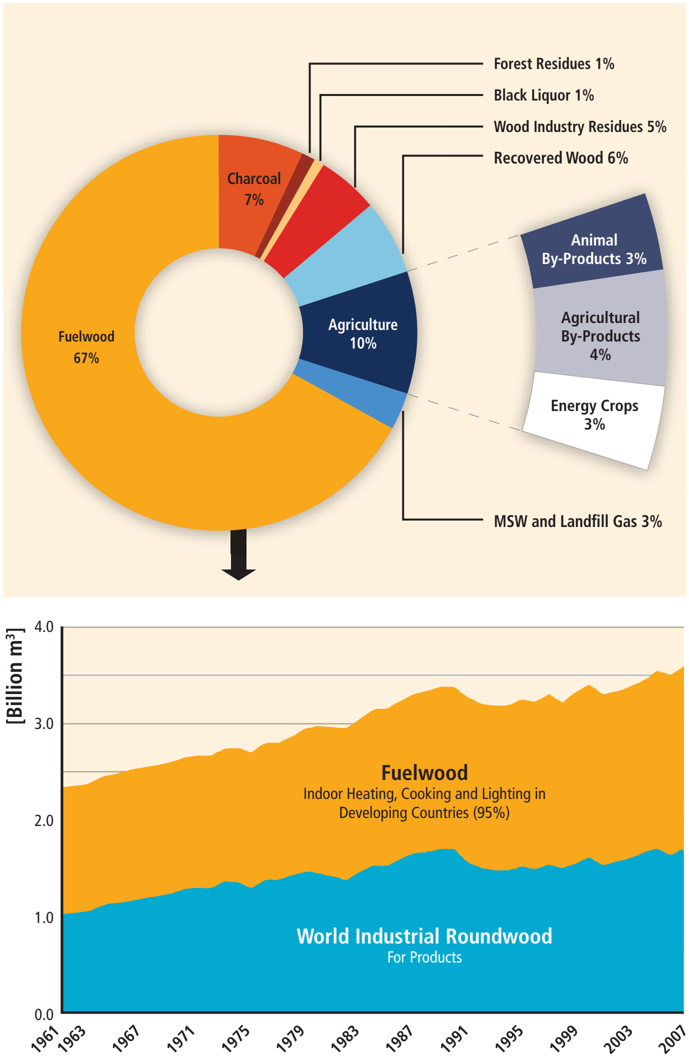


Figure 2.1 | Top: Shares of global primary biomass sources for energy (IPCC, 2007a,d; IEA Bioenergy, 2009); Bottom: Fuelwood used in developing countries parallels world industrial roundwood[1] production levels (UNECE/FAO Timber Database, 2011).

Note: 1. Roundwood products are saw logs and veneer logs for the forest products industry and wood chips that are used for making pulpwood used in paper, newsprint and Kraft paper. In 2009, reflecting the downturn in the economy, there was a decline to 3.25 (total) and 1.25 (industrial) billion m³; the data can be retrieved from a presentation on Global Forest Resources and Market Developments: timber.unece.org/fileadmin/DAM/other/GlobalResMkts300311.pdf.

often in contradiction when it comes to estimates of biomass consumption for energy, because production and trade of these solid biomass fuels are largely informal.[3] A supplement of 20 to 40% to the global TPES of biomass in Table 2.1 is based on detailed, multiscale, spatially explicit analyses performed in more than 20 countries (e.g., Masera et al., 2005, 2006; Drigo et al., 2007, 2009). Traditional biomass is discussed in later sections on feedstock logistics and supply (Section 2.3.2.2), improved technologies, practices and barriers (Sections 2.4.2.1 and 2.4.2.2), climate change effects (Section 2.5.4) and socioeconomic aspects (Section 2.5.7).

3 See the Glossary in Annex I for a definition of informal sector/economy.

- High-efficiency *modern bioenergy* uses more convenient solids, liquids and gases as secondary energy carriers to generate heat, electricity, combined heat and power (CHP) and transport fuels for various sectors (Figure 2.2). Many entities in the process industry, municipalities, districts and cooperatives generate these energy products, in some cases for their own use, but also for sale to national and international markets in the increasingly global trade. Liquid biofuels, such as ethanol and biodiesel, are used for global road transport and some industrial uses. Biomass-derived gases, primarily methane from anaerobic digestion of agricultural residues and waste treatment streams, are used to generate electricity, heat or CHP for multiple sectors. The most important contribution to these energy services is, however, based on solids, such as chips, pellets, recovered wood previously used etc. Heating includes space and hot water heating such as in district heating systems. The estimated TPES from modern bioenergy is 11.3 EJ/yr and the secondary energy delivered to end-use consumers is roughly 6.6 EJ/yr (IEA, 2010a,b). Modern bioenergy feedstocks such as short-rotation trees (poplars or willows) and herbaceous plants (*Miscanthus* or switchgrass) are discussed in Sections 2.3.1 and 2.6.1. The discussion of modern bioenergy includes biomass logistics and supply chains (Sections 2.3.2 and 2.6.2); conversion of biomass into secondary carriers or energy through existing (Section 2.3.3) or developing (Section 2.6.3) technologies; integration into bioenergy systems and supply chains (Section 2.3.4); and market and industry development (Section 2.4).

- High energy efficiency biomass conversion is found typically in the *industry* sector (with a total consumption of ~7.7 EJ/yr) associated with the pulp and paper industry, forest products, food and chemicals. Examples are fibre products (e.g., paper), energy, wood products, and charcoal for steel manufacture. Industrial heating is primarily steam generation for industrial processes, often in conjunction with power generation. The industry sector's final consumption of biomass is not shown in Table 2.1 since it cannot be unambiguously assigned. Also see Section 8.3.4, which addresses the biomass industry sector.

Global bioenergy use has steadily grown worldwide in absolute terms in the last 40 years, with large differences among countries. In 2006, China led all countries and used 9 EJ of biomass for energy, followed by India (6 EJ), the USA (2.3 EJ) and Brazil (2 EJ) (GBEP, 2008). Bioenergy provides a relatively small but growing share of TPES (1 to 4 % in 2006) in the largest industrialized countries (grouped as the G8 countries: the USA, Canada, Germany, France, Japan, Italy, the UK and Russia). The use of solid biomass for electricity production is particularly important in pulp and paper plants and in sugar mills. Bioenergy's share in total energy consumption is generally increasing in the G8 countries through the use of modern biomass forms (e.g., co-combustion or co-firing for electricity generation, space heating with pellets) especially in Germany, Italy and the UK (see Figure 2.8; GBEP, 2008).

By contrast, in 2006, bioenergy provided 5 to 27% of TPES in the largest developing countries (China, India, Mexico, Brazil and South Africa),

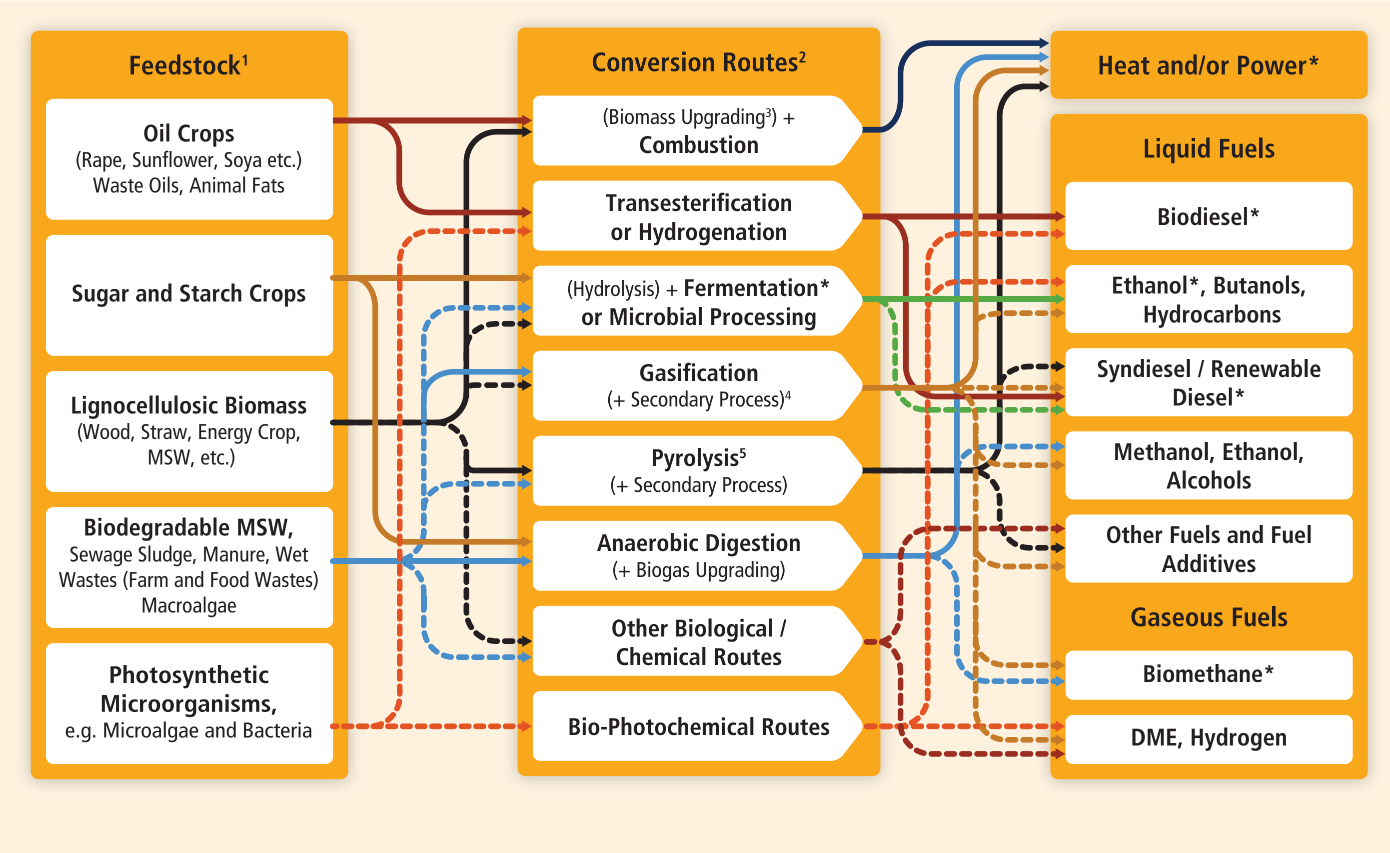


Figure 2.2 | Schematic view of the variety of commercial (solid lines, see Figure 2.6) and developing bioenergy routes (dotted lines) from biomass feedstocks through thermochemical, chemical, biochemical and biological conversion routes to heat, power, CHP and liquid or gaseous fuels (modified from IEA Bioenergy, 2009). Commercial products are marked with an asterisk.

Notes: 1. Parts of each feedstock, for example, crop residues, could also be used in other routes. 2. Each route also gives coproducts. 3. Biomass upgrading includes any one of the densification processes (pelletization, pyrolysis, torrefaction, etc.). 4. Anaerobic digestion processes release methane and CO_2 and removal of CO_2 provides essentially methane, the major component of natural gas; the upgraded gas is called biomethane. 5. Could be other thermal processing routes such as hydrothermal, liquefaction, etc. DME=dimethyl ether.

mainly through the use of traditional forms, and more than 80% of TPES in the poorest countries. The bioenergy share in India, China and Mexico is decreasing, mostly as traditional biomass is substituted by kerosene and liquefied petroleum gas within large cities. However, consumption in absolute terms continues to grow. This trend is also true for most African countries, where demand has been driven by a steady increase in wood fuels, particularly in the use of charcoal in booming urban areas (GBEP, 2008).

Turning from the technological perspectives of bioenergy to environmental and social aspects, the literature assessments in this chapter reveal positive and negative aspects of bioenergy. Sustainably produced and managed, bioenergy can provide a substantial contribution to climate change mitigation through increasing carbon stocks in the biosphere (e.g., in degraded lands), reducing carbon emissions from unsustainable forest use and replacing fossil fuel-based systems in the generation of heat, power and modern fuels. Additionally, bioenergy may provide opportunities for regional economic development (see Sections 9.3.1 and 2.5.4). Advanced bioenergy systems and end-use technologies can also substantially reduce the emissions of black carbon and other short-lived GHGs such as methane and carbon monoxide (CO), which are related to the burning of biomass in traditional open fires and kilns. If improperly designed or implemented, the large-scale expansion of bioenergy systems is likely to have negative consequences for climate and sustainability, for example, by inducing d+iLUC that can alter surface albedo and release carbon from soils and vegetation, reducing biodiversity or negatively impacting local populations in terms of land tenure or reduced food security, among other effects.

The literature on the resource potential of biomass is covered in Section 2.2, which discusses a variety of global modelling studies and the factors that influence the assessments. Section 2.2 also presents examples of resource assessments from countries and specific regions, which provide cost dimensions for these resources. The overall technology portfolio is shown in Figure 2.2 and includes commercial and developing energy carriers from modern biomass. The commercially available energy products and (conversion) technologies are discussed in Section 2.3. These are based on sugar crops (perennial sugarcane and beets), starch crops (maize, wheat, cassava etc.), and oil crops (soy, rapeseed) as feedstocks, and they expand food and fodder processing to bioenergy production. Current bioenergy production is also coupled with forest products industry residues and the pulping industry that has traditionally self generated heat and power; with dry and wet municipal wastes; with sewage sludge; and with a variety of organic wet wastes from various sectors. These wastes and residues, if left untreated, can have a major impact on climate through methane emission releases. The bioenergy market is described in Section 2.4 for traditional and modern forms, as are evolving international trade and sustainability frameworks for bioenergy. The advanced technologies for production of feedstocks and conversion to energy products are discussed in Section 2.6.

In Section 2.5, the environmental and social impacts of biomass use are addressed with emphasis on the climate change effects of bioenergy. Because of the complexity of GHG impacts and of the bioenergy chains, impacts are analyzed without and with LUC separately. These impacts span micro-, meso- and macro- scales and depend on the land cover conversion and water availability, among other factors, in specific regions. Direct land use impacts occur locally by changes in crop use or the dedication of a crop to bioenergy. The iLUC results from a market-mediated shift in land management activities (i.e., dLUC) outside the region of primary production expansion. Both are addressed in Section 2.5. The social impacts of modern and traditional biomass use are presented and related to key issues such as the impact of bioenergy on food production and sustainable development in Section 2.5.7 (also refer to Sections 9.3 and 9.4).

To reach high levels of bioenergy production and minimize environmental and social impacts, it is necessary to develop a variety of lignocellulosic biomass sources and a portfolio of conversion routes for power, heat and gaseous and liquid fuels that satisfy existing and future energy needs (Figure 2.2). With these prospects for technology improvement, innovation and integration, key conversion intermediates derived from biomass such as sugars, syngas, pyrolysis oils (or oils derived from other thermal treatments), biogas and vegetable oils (lipids) can be upgraded in conversion facilities that are capable of making a variety of products including biofuels, power and process heat, alongside other products as discussed in Section 2.6. In Section 2.7, the costs of existing commercial technologies and their trends are discussed, highlighting that over the past 25 years technological learning occurred in a variety of bioenergy systems in specific countries. Finally, Section 2.8 addresses the potential deployment of biomass for energy. It also compares biomass resource assessments from Section 2.2, informed by environmental and social impacts discussions, with the levels of deployment indicated by the scenario literature review described in Chapter 10. The role of biomass and its multiple energy products alongside food, fodder, fibre and forest products is viewed through IPCC scenario storylines (IPCC, 2000a,d) to reach significant penetration levels with and without taking into account sustainable development and climate change mitigation pathways. High and low penetration levels can be reached with (and without) climate change mitigation and sustainable development strategies. Many insights into bioenergy technology developments and integrated systems can be gleaned from these sketches, and they will be useful in further developing bioenergy sustainably with climate mitigation.

2.1.2 Previous Intergovernmental Panel on Climate Change assessments

Bioenergy has not been examined in detail in previous IPCC reports. In the most recent Fourth Assessment Report (AR4), the analysis of GHG mitigation from bioenergy was scattered among seven chapters, making it difficult to obtain an integrated and cohesive picture of the resource and mitigation potential, challenges and opportunities. The main conclusions from the AR4 report (IPCC, 2007b,d) are as follows:

- **Biomass energy demand.** Primary biomass requirements for the production of transportation fuels were largely based on the WEO (IEA, 2006) global projections, with a relatively wide range of about 14 to 40 EJ/yr of primary biomass, or 8 to 25 EJ/yr of biofuels in 2030. However, higher demand estimates of 45 to 85 EJ/yr for primary biomass in 2030 (roughly 30 to 50 EJ/yr of biofuel) were also included. For comparison, the scenario review in Chapter 10 shows biofuel production ranges of 0 to 14 EJ/yr in 2030 and 2 to 50 EJ/yr in 2050 with median values of 5 to 12 EJ/yr and 18 to 20 EJ/yr in the two GHG mitigation scenario categories analyzed. The demand for biomass-generated heat and power was stated to be strongly influenced by the availability and introduction of competing technologies such as CCS, nuclear power, wind energy, solar heating and others. The projected biomass demand in 2030 would be around 28 to 43 EJ according to the data used in the AR4. These estimates focus on electricity generation. Heat was not explicitly modelled or estimated in the WEO (IEA, 2006), on which the AR4 was based, therefore underestimating the total demand for biomass.

  Potential future demand for biomass in industry (especially new uses such as biochemicals, but also expansion of charcoal use for steel production) and the built environment (heating as well as increased use of biomass as a building material) was also highlighted as important, but no quantitative projections were included in the potential demand for biomass at the medium and longer term.

- **Biomass resource potential (supply).** According to the AR4, the largest contribution to technical potential could come from energy crops on arable land, assuming that efficiency improvements in agriculture are fast enough to outpace food demand so as to avoid increased pressure on forests and nature areas. A range of 20 to 400 EJ/yr is presented for 2050, with a best estimate of 250 EJ/yr. Using degraded lands for biomass production (e.g., in reforestation schemes: 8 to 110 EJ/yr) can contribute significantly. Although such low-yielding biomass production generally results in more expensive biomass supplies, competition with food production is almost absent and various co-benefits, such as regeneration of soils (and carbon storage), improved water retention and protection from (further) erosion may also offset part of the establishment costs. A current example of such biomass production schemes is the establishment of *Jatropha* crops (oilseeds) on marginal lands.

The technical potential in residues from forestry is estimated at 12 to 74 EJ/yr, that from agriculture at 15 to 70 EJ/yr and that from waste at 13 EJ/yr. These biomass resource categories are largely available before 2030, but also partly uncertain. The uncertainty comes from possible competing uses (e.g., increased use of biomaterials such as fibreboard production from forest residues and use of agricultural residues for fodder and fertilizer) and differing assumptions about sustainability criteria deployed with respect to forest management and agricultural intensity. The technical potential for biogas fuel from waste, landfill gas and digester gas is much smaller.

- **Carbon mitigation potential.** The mitigation potential for electricity generation from biomass reaches 1,220 Mt CO_2eq for the year 2030, a substantial fraction of it at costs lower than USD_{2005} 19.5/t CO_2. From a top-down assessment, the economic mitigation potential of biomass energy supplied from agriculture is estimated to range from 70 to 1,260 Mt CO_2eq/yr at costs of up to USD_{2005} 19.5/t CO_2eq, and from 560 to 2,320 Mt CO_2eq/yr at costs of up to USD_{2005} 48.5/t CO_2eq. The overall mitigation from biomass energy coming from the forest sector is estimated to reach 400 Mt CO_2/yr up to 2030.

2.2 Resource potential

2.2.1 Introduction

Bioenergy production interacts with food, fodder and fibre production as well as with conventional forest products in complex ways. Bioenergy demand constitutes a benefit to conventional plant production in agriculture and forestry by offering new markets for biomass flows that earlier were considered to be waste products; it can also provide opportunities for cultivating new types of crops and integrating bioenergy production with food and forestry production to improve overall resource management. However, biomass for energy production can intensify competition for land, water and other production factors, and can result in overexploitation and degradation of resources. For example, too-intensive biomass extraction from the land can lead to soil degradation, and water diversion to energy plantations can impact downstream and regional ecological functions and economic services.

As a consequence, the magnitude of the biomass resource potential depends on the priority given to bioenergy products versus other products obtained from the land—notably food, fodder, fibre and conventional forest products such as sawn wood and paper—and on how much total biomass can be mobilized in agriculture and forestry. This in turn depends on natural conditions (climate, soils, topography), on agronomic and forestry practices, and on how societies understand and prioritize nature conservation and soil/water/biodiversity protection and on how production systems are shaped to reflect these priorities (Figure 2.3).

This section focuses on long-term biomass resource potential and how it has been estimated based on considerations of the Earth's biophysical resources (ultimately net primary production: NPP) and restrictions on their energetic use arising from competing requirements, including non-extractive requirements such as soil quality maintenance/improvement and biodiversity protection. Additionally, approaches to assessing biomass resource potentials—and results from selected studies—are presented with an account of the main determining factors. These factors are treated explicitly, including the constraints on their utilization. The section ends by summarizing conclusions about biomass resource assessments, including uncertainties.

2.2.1.1 Methodology assessment

Studies quantifying biomass resource potential have assessed the resource base in a variety of ways. They differ in the extent to which the influence of natural conditions (and how these can change in the future) are considered as well as in the extent to which the types and details of important additional factors are taken into account, such as socioeconomic considerations, the character and development of agriculture and forestry, and factors connected to nature conservation and soil/water/biodiversity preservation (Berndes et al., 2003). Different types of resource potentials are assessed but the following are commonly referred to (see Glossary in Annex I):

- **Theoretical potential** refers to the biomass supply as limited only by biophysical conditions (see discussion below in this same sub-section);

- **Technical potential** considers the limitations of the biomass production practices assumed to be employed and also takes into account concurrent demand for food, fodder, fibre, forest products and area requirements for human infrastructure. Restrictions connected to nature conservation and soil/water/biodiversity preservation can also be considered. In such cases, the term *sustainable potential* is sometimes used (see Section 2.2.2); and

- **Market potential** refers to the part of the technical potential that can be produced given a specified requirement for the level of economic profit in production. This depends not only on the cost of production but also on the price of the biomass feedstock, which is determined by a range of factors such as the characteristics of biomass conversion technologies, the price of competing energy technologies and the prevailing policy regime (see Section 2.2.3).

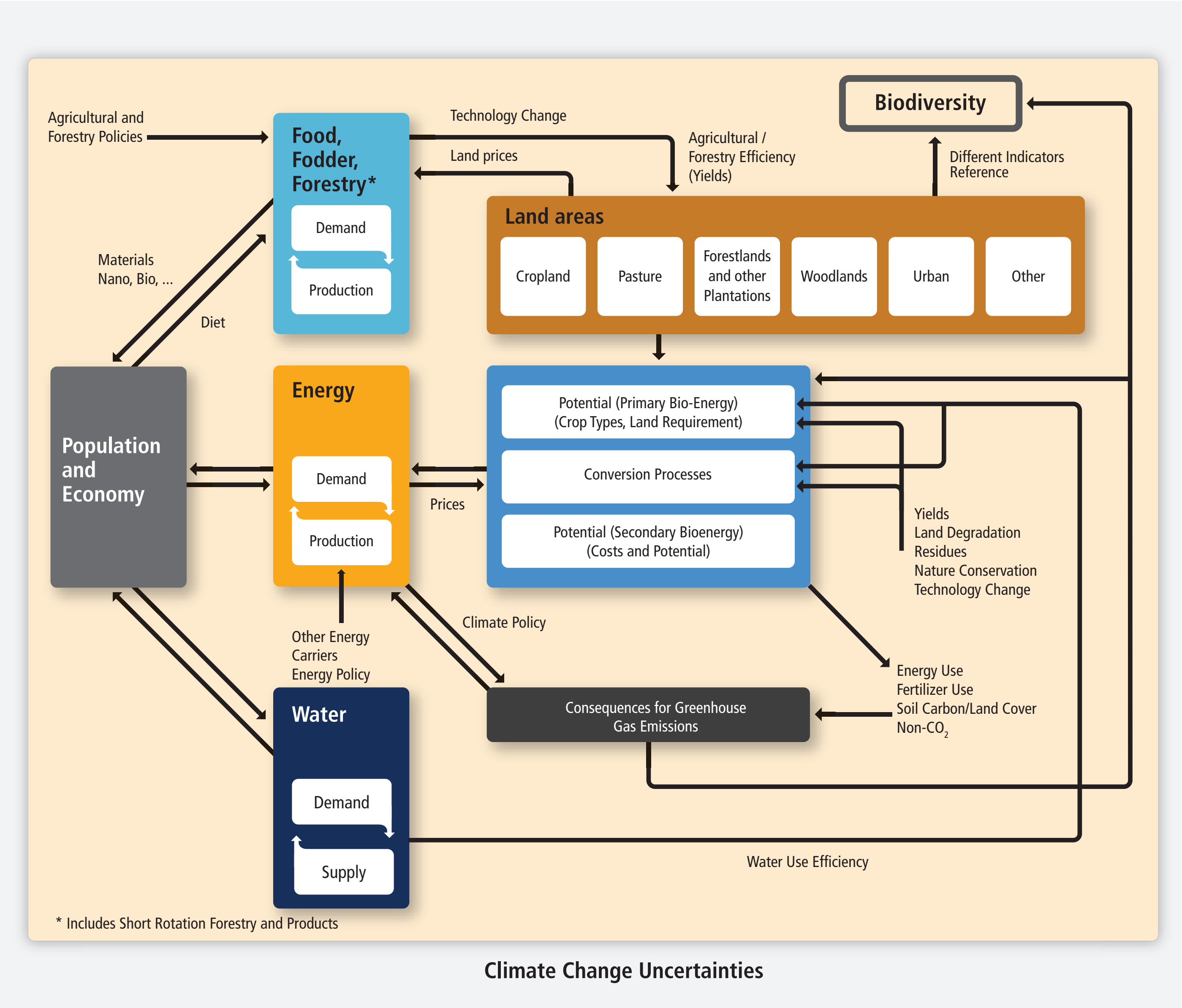


Figure 2.3 | Overview of key relationships relevant to assessment of biomass resource potentials (modified from Dornburg et al., 2010). Indirect land use and social issues are not displayed. Reproduced with permission from the Royal Society of Chemistry.

Three principal categories are—more or less comprehensively—considered in assessments of biomass resource potentials (see also Section 2.3.1.1):

- Primary residues from conventional food and fibre production in agriculture and forestry, such as cereal straw and logging residues;
- Secondary and tertiary residues in the form of organic food/forest industry by-products and retail/post consumer waste; and
- Plants produced for energy supply, including conventional food/fodder/industrial crops, surplus roundwood forestry products, and new agricultural, forestry or aquatic plants.

Given that resource potential assessments quantify the availability of residue flows in the food and forest sectors, the definition of how these sectors develop is central for the outcome. As discussed below, consideration of various environmental and socioeconomic factors as a rule reduces the assessed resource potential to lower levels.

Most assessments of the biomass resource potential considered in this section are variants of technical/market potentials employing a 'food/fibre first principle', applied with the objective of quantifying biomass resource potentials under the condition that global requirements for food and conventional forest products such as sawn wood and paper are met with priority (see, e.g., WBGU, 2009; Smeets and Faaij, 2007).

Studies that start out from such principles should not be understood as providing guarantees that a certain level of biomass can be supplied for energy purposes without competing with food or fibre production. They quantify how much bioenergy could be produced in a certain future year based on using resources not required for meeting food and fibre demands, given a specified development in the world or in a region. But they do not analyze how bioenergy expansion towards such a future level of production would—or should—interact with food and fibre production.

Studies using integrated energy/industry/land use cover models (see, e.g., Leemans et al., 1996; Strengers et al., 2004; Johansson and Azar, 2007; van Vuuren et al., 2007; Fischer et al., 2009; Lotze-Campben, 2009; Melillo et al., 2009; Wise et al., 2009; Figure 2.4) can provide insights into how an expanding bioenergy sector interacts with other sectors in society including land use and the management of biospheric carbon stocks. Studies focused on sectors can contain more detailed information on interactions with other biomass uses. Restricted scope (only selected biofuel/land uses and/or regions covered) or lack of sufficiently detailed empirical data can limit the confidence in results—especially in prospective studies. This is further discussed in Sections 2.5 and 2.8.

By considering the upper level of productivity of biomass plantations on land while assuming theoretical potentials also for worldwide agriculture and fully taking into account conservation of a viable biosphere, global modelling studies by Smeets et al. (2007) derived a maximum global potential of biomass for energy of 1,548 EJ/yr.[4] In this chapter, this figure is considered to be an estimate of theoretical potential.

2.2.1.2 Total aboveground net primary production of biomass

A first qualitative understanding of biomass technical potentials can be gained from considering the total annual aboveground net primary production (NPP: the net amount of carbon assimilated in a time period by vegetation) on the Earth's terrestrial surface. This is estimated to be about 35 Gt carbon, or 1,260 EJ/yr assuming an average carbon content of 50% and 18 GJ/t average heating value (Haberl et al., 2007), which can be compared to the current world primary energy supply of about 500 EJ/yr (IEA, 2010a). This comparison shows that total terrestrial aboveground NPP is larger, but by no more than a factor of around three, than what is required to meet society's energy demand. Establishing bioenergy as a major source of future primary energy requires that a significant part of global terrestrial NPP takes place within production systems that provide bioenergy feedstocks (removing their NPP from the trophic chains of ecosystems). In addition, total terrestrial NPP may have to be increased through fertilizer, irrigation and other inputs on lands managed for food, fodder, fibre, forest products and bioenergy.

4 Smeets et al. (2007) model a scenario with a fully landless animal production system with globally high feed conversion efficiency and a 4.6-fold increase in global agricultural productivity by 2050 due to technological progress and deployment that is considerably faster than has historically ever been achieved (a 1.9-fold increase for Europe and a 7.7-fold increase in sub-Saharan Africa). In that case, 72% of current agricultural area could be used for bioenergy production in 2050 and supply a theoretical potential of 1,548 EJ/yr, which is of the same magnitude as the total energy content of the world's natural aboveground net primary production on land.

2.2.1.3 Human appropriation of terrestrial net primary production

A comparison with biomass production in agriculture and forestry can give a perspective on the potential bioenergy supply in relation to what is presently harvested. Today's global industrial roundwood production corresponds to 15 to 20 EJ/yr, and the global harvest of major crops (cereals, oil crops, sugar crops, roots, tubers and pulses) corresponds to about 60 EJ/yr (FAOSTAT, 2011). One immediate conclusion from this comparison is that biomass extraction by agriculture and forestry will have to increase substantially in order to provide feedstocks for a bioenergy sector large enough to make a significant contribution to the future energy supply.

Studies estimating the overall human appropriation of terrestrial NPP across all human uses of biomass (HANPP, taking into account all NPP gained or lost due to human activities, including harvesting and backflows) suggest that societies already appropriate a substantial share of the world's aboveground terrestrial NPP. This provides a context for prospective future biomass extraction for bioenergy. Estimates of HANPP vary depending on its definition as well as the models and data used for the calculations. A spatially explicit calculation by Haberl et al. (2007) estimated that in the year 2000, aboveground HANPP amounted to nearly 29% of the modelled global aboveground NPP. Total human biomass harvest alone was estimated to amount to about 20% (including utilized residues and grazing), with all harvested biomass used by humans containing an energy of 219 EJ/yr (Krausmann et al., 2008).

Other HANPP estimates range from a similar level down to about half of this level (D. Wright, 1990; Imhoff et al., 2004). The HANPP concept cannot directly be used to define a certain level of biomass use that would be 'safe' or 'sustainable' because the impacts of human land use depend on how agriculture and forestry systems are shaped (Bai et al., 2008). However, it can be used as a measure of the human domination of the biosphere and provide a reference for assessing the comparative magnitude of prospective additional biomass resource potentials.

Besides biophysical factors, socioeconomic conditions also influence the biomass resource potential by defining how—and how much—biomass can be produced without causing socioeconomic impacts that might be considered unacceptable. Socioeconomic restrictions vary around the world, change as society develops and depend on how societies prioritize bioenergy in relation to other socioeconomic objectives (see also Sections 2.5 and 2.8).

2.2.2 Global and regional technical potential

2.2.2.1 Literature assessment

In an assessment of technical potential based on an analysis of the literature available in 2007 and additional modelling, Dornburg et al. (2008, 2010) arrived at the conclusion that the upper bound of the technical potential in 2050 can amount to about 500 EJ. The study assumes policy frameworks that secure good governance of land use and major improvements in agricultural management and takes into account water limitations, biodiversity protection, soil degradation and competition with food. Residues originating from forestry, agriculture and organic wastes (including the organic fraction of MSW, dung, process residues etc.) are estimated to amount to 40 to 170 EJ/yr, with a mean estimate of around 100 EJ/yr. This part of the technical potential is relatively certain, but competing applications may push net availability for energy applications to the lower end of the range. Surplus forestry other than from forestry residues has an additional technical potential of 60 to 100 EJ/yr.

The findings of the Dornburg et al. (2008, 2010) reviews for biomass produced via cropping systems is that a lower estimate for energy crop production on possible surplus, good quality agricultural and pasture lands is 120 EJ/yr. The potential contribution of water-scarce, marginal and degraded lands could amount up to an additional 70 EJ/yr. This would comprise a large area where water scarcity provides limitations and soil degradation is more severe. Assuming strong learning in agricultural technology for improvements in agricultural and livestock management would add 140 EJ/yr. The three categories added together lead to a technical potential from this analysis of up to about 500 EJ/yr (Dornburg et al., 2008, 2010). For example, Hoogwijk et al. (2005, 2009) estimate that the biomass technical potential could expand from 290 to 320 EJ/yr in 2020 to 330 to 400 EJ/yr in 2030. Developing the technical potential would require major policy efforts; therefore, actual deployment is likely to be lower and the biomass resource base will be largely constrained to a share of the biomass residues and organic wastes, some cultivation of bioenergy crops on marginal and degraded lands, and some regions where biomass is a cheaper energy supply option compared to the main reference options (e.g., sugarcane-based ethanol production), amounting to a minimum of about 50 EJ/yr (Dornburg et al., 2008, 2010).

Table 2.2 shows ranges in the assessed global technical potential for the year 2050 explicitly for various biomass categories. The wide ranges shown are due to differences in the studies' approaches to considering important factors, which are in themselves uncertain: population, economic and technology development assumed or computed can vary and evolve at different regional paces; biodiversity, nature conservation and other environmental requirements are difficult to assess and depend on numerous factors and social preferences; and the magnitude and pattern of climate change and land use can strongly influence the biophysical capacity of the environment. Furthermore, technical potentials cannot be determined precisely while uncertainties remain regarding societal preferences with respect to trade-offs in environmental impacts and the implications of increased intensification in food and fibre production, and regarding potential synergies between different forms of land use.

Although assessments employing improved data and modelling capacity have not succeeded in providing narrow distinct estimates of the technical potential of biomass, they do indicate the most influential factors that affect this technical potential. This is further discussed below, where approaches used in the assessments are treated in more detail.

2.2.2.2 The contribution from residues, dung, processing by-products and waste

As can be seen in Table 2.2, biomass resource assessments indicate that retail/post-consumer waste, dung and primary residues/processing by-products in the agriculture and forestry sectors have prospects for providing a substantial share of the total global biomass supply in the longer term. Yet, the sizes of these biomass resources are ultimately determined by the demand for conventional agriculture and forestry products and the sustainability of the land resources.

Assessments of the potential contribution from these sources to the future biomass supply combine data on future production of agriculture and forestry products obtained from food/forest sector scenarios, the possibility of use of degraded lands, and the residue factors that account for the amount of residues generated per unit of primary product produced. For example, harvest residue generation in agricultural crops cultivation is estimated based on harvest index data, that is, the ratio of harvested product to total aboveground biomass (e.g., Wirsenius, 2003; Lal, 2005; Krausmann et al., 2008; Hakala et al., 2009). The generation of logging residues in forestry, and of additional biomass flows such as thinning wood and process by-products, is estimated using similar methods (see Ericsson and Nilsson, 2006; Smeets and Faaij, 2007).

The shares of the biomass flows that are available for energy (i.e., recoverability fractions) are then estimated based on consideration of other extractive uses and requirements (e.g., soil conservation, animal feeding or bedding in agriculture, and fibre board production in the forest sector).

2.2.2.3 The contribution from unutilized forest growth

In addition to the residue flows that are linked to industrial roundwood production and processing into conventional forest products, forest growth currently not harvested is considered in some studies. This biomass resource is quantified based on estimates of the biomass increment in parts of forests that are assessed as being available for wood supply. This increment is compared with the estimated level of forest biomass extraction for conventional industrial roundwood production—and sometimes for traditional biomass, notably heating and cooking—to obtain the unutilized forest growth. Smeets and Faaij (2007) provide illustrative quantifications showing how this technical potential of biomass can vary from being a major source of bioenergy to being practically zero as a consequence of competing demand and economic and ecological considerations. A comparison with the present industrial roundwood production of about 15 to 20 EJ/yr shows that a drastic increase in forest biomass output is required to reach the higher-end technical potential assessed for the forest biomass category in Table 2.2. A special case that can play a role is forest growth that becomes available after extensive tree mortality from insect outbreaks or fires (Dymond et al., 2010).

2.2.2.4 The contribution from biomass plantations

Table 2.2 indicates that substantial supplies from biomass plantations are required for reaching the high end of the technical potential range. Land availability (and its suitability) for dedicated biomass plantations and the biomass yields that can be obtained on the available lands are two critical determinants of the technical potential. Given that surplus agricultural land is commonly identified as the major land resource for the plantations, food sector development is critical. Methods for determining land availability and suitability should consider requirements for maintaining the economic, ecological and social value of ecosystems. There are different approaches for considering such requirements, as described for a selection of studies below.

Most earlier assessments of biomass resource potentials used rather simplistic approaches to estimating the technical potential of biomass plantations (Berndes et al., 2003), but the continuous development of modelling tools that combine databases containing biophysical information (soil, topography, climate) with analytical representations of relevant crops and agronomic systems and the use of economic and full biogeochemical vegetation models has resulted in improvements over time (see, e.g., van Vuuren et al., 2007; Fischer et al., 2008; Lotze-Campen et al., 2009; Melillo et al., 2009; WBGU, 2009; Wise et al., 2009;

Table 2.2 | Global technical potential overview for a number of categories of land-based biomass supply for energy production (primary energy numbers have been rounded). The total assessed technical potential can be lower than the present biomass use of about 50 EJ/yr in the case of high future food and fibre demand in combination with slow productivity development in land use, leading to strong declines in biomass availability for energetic purposes.

Biomass category	Comment	2050 Technical potential (EJ/yr)
Category 1. **Residues from agriculture**	By-products associated with food/fodder production and processing, both primary (e.g., cereal straw from harvesting) and secondary (e.g., rice husks from rice milling) residues.	15 – 70
Category 2. **Dedicated biomass production on surplus agricultural land**	Includes both conventional agriculture crops and dedicated bioenergy plants including oil crops, lignocellulosic grasses, short-rotation coppice and tree plantations. Only land not required for food, fodder or other agricultural commodities production is assumed to be available for bioenergy. However, surplus agriculture land (or abandoned land) need not imply that its development is such that less total land is needed for agriculture: the lands may become excluded from agriculture use in modelling runs due to land degradation processes or climate change (see also 'marginal lands' below). Large technical potential requires global development towards high-yielding agricultural production and low demand for grazing land. Zero technical potential reflects that studies report that food sector development can be such that no surplus agricultural land will be available.	0 – 700
Category 3. **Dedicated biomass production on marginal lands**	Refers to biomass production on deforested or otherwise degraded or marginal land that is judged unsuitable for conventional agriculture but suitable for some bioenergy schemes (e.g., via reforestation). There is no globally established definition of degraded/marginal land and not all studies make a distinction between such land and other land judged as suitable for bioenergy. Adding categories 2 and 3 can therefore lead to double counting if numbers come from different studies. High technical potential numbers for categories 2 and 3 assume biomass production on an area exceeding the present global cropland area (ca. 1.5 billion ha or 15 million km^2). Zero technical potential reflects low potential for this category due to land requirements for, for example, extensive grazing management and/or subsistence agriculture or poor economic performance if using the marginal lands for bioenergy.	0 – 110
Category 4. **Forest biomass**	Forest sector by-products including both primary residues from silvicultural thinning and logging, and secondary residues such as sawdust and bark from wood processing. Dead wood from natural disturbances, such as fires and insect outbreaks, represents a second category. Biomass growth in natural/semi-natural forests that is not required for industrial roundwood production to meet projected biomaterials demand (e.g., sawn wood, paper and board) represents a third category. By-products provide up to about 20 EJ/yr implying that high forest biomass technical potentials correspond to a much larger forest biomass extraction for energy than what is presently achieved in industrial wood production. Zero technical potential indicates that studies report that demand from sectors other than the energy sector can become larger than the estimated forest supply capacity.	0 – 110
Category 5. **Dung**	Animal manure. Population development, diets and character of animal production systems are critical determinants.	5 – 50
Category 6. **Organic wastes**	Biomass associated with materials use, for example, organic waste from households and restaurants and discarded wood products including paper, construction and demolition wood; availability depends on competing uses and implementation of collection systems.	5 – >50
Total		**<50 – >1000**

Notes: Based on Fischer and Schrattenholzer (2001); Hoogwijk et al. (2003, 2005, 2009); Smeets and Faaij (2007); Dornburg et al. (2008, 2010); Field et al. (2008); Hakala et al. (2009); IEA Bioenergy (2009); Metzger and Huttermann (2009); van Vuuren et al. (2009); Haberl et al. (2010); Wirsenius et al. (2010); Beringer et al. (2011).

Beringer et al., 2011). Important conclusions are: a) the effects of LUC associated with bioenergy expansion can considerably influence the climate benefit of bioenergy (see Section 2.5) and b) biofuel yields from crops have frequently been overestimated by neglecting spatial variations in productivity (Johnston et al., 2009).

Figure 2.4—representing one example (Fischer et al., 2009)—shows the modelled global land suitability for selected first-generation biofuel feedstocks and for lignocellulosic plants (see caption to Figure 2.4 for information about plants included). By overlaying spatial data on global land cover derived from the best available remote sensing data combined

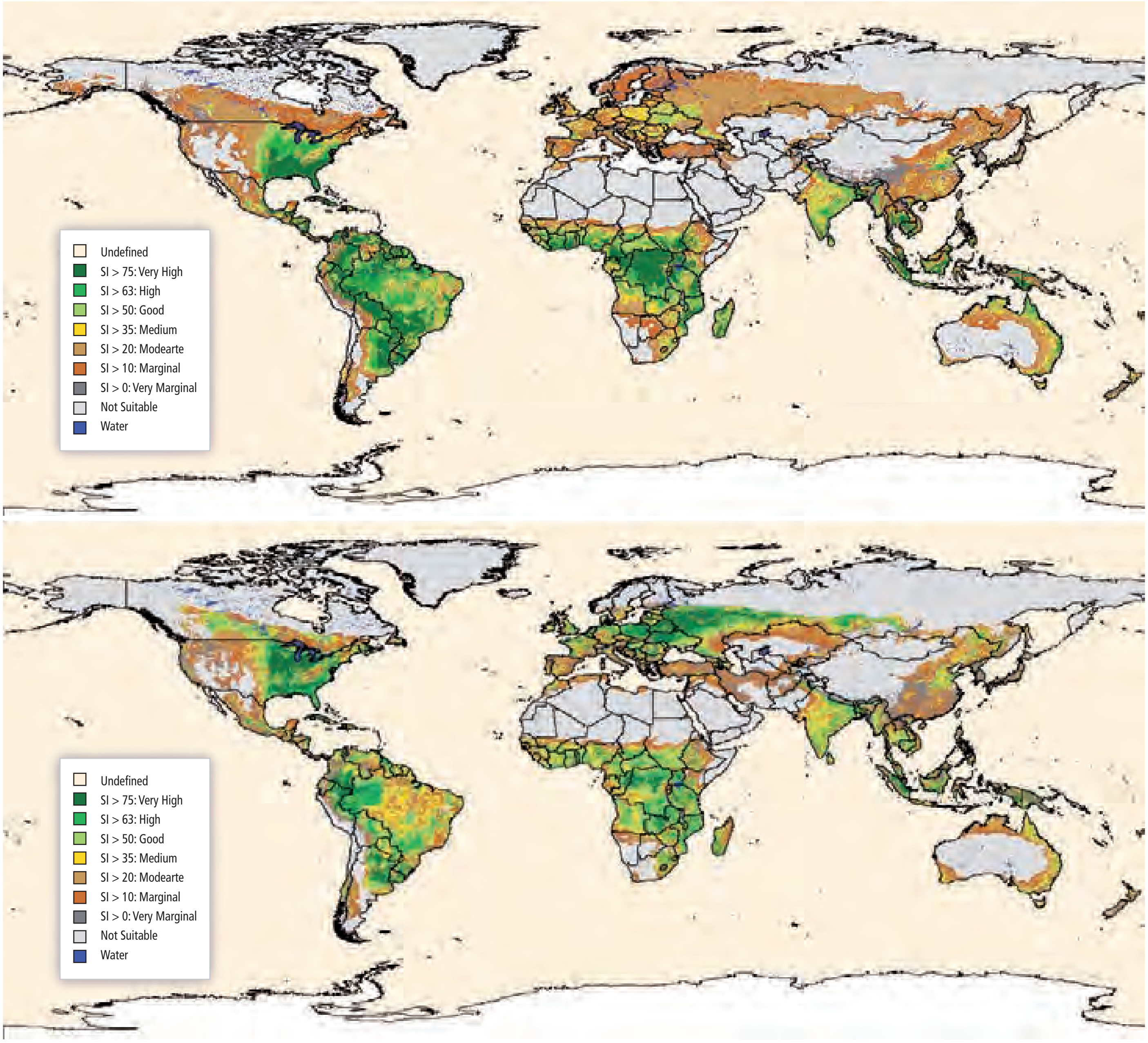


Figure 2.4 | Global land suitability for bioenergy plantations. The upper map shows suitability for herbaceous and woody lignocellulosic plants (*Miscanthus*, switchgrass, reed canary grass, poplar, willow, eucalyptus) and the lower map shows suitability for first-generation biofuel feedstocks (sugarcane, maize, cassava, rapeseed, soybean, palm oil, *Jatropha*). The suitability index (SI)[1] describes the spatial suitability of each pixel and reflects the match between crop requirements and prevailing climate, soil and terrain conditions. The map shows suitability under rain-fed cultivation and advanced management systems that assume availability of sufficient nutrients, adequate pest control and mechanization, and other practices. Results for irrigated conditions or low-input management systems would result in different pictures (Fischer et al., 2009; reproduced with permission from the International Institute for Applied Systems Analysis (IIASA)).

Note: 1. SI: suitability index. The SI used reflects the spatial suitability of each pixel and is calculated as SI = VS*0.9+S*0.7+MS*0.5+mS*0.3, where VS, S, MS and mS correspond to yield levels at 80–100%, 60–80%, 40–60% and 20–40% of the modelled maximum, respectively (Fischer et al., 2009).

with statistical information and data on protected areas, it is possible to quantify suitable lands for different land cover types. A suitability index has been used in order to represent both yield potentials[5] and suitability (see caption to Figure 2.4). For instance, almost 700 Mha (7,000 km^2), or about 20%, of currently unprotected grasslands and woodlands are assessed as suitable for soybean while less than 50 Mha (500 km^2) are assessed as suitable for oil palm (note that these land suitability numbers cannot be added because areas overlap). Considering unprotected forest land, an area roughly 10 times larger (almost 500 Mha or 5,000 km^2) is suitable for oil palm cultivation (Fischer et al., 2009, their Annex 5 and 6). However, converting large areas of forests into biomass plantations would negatively impact biodiversity and might—depending on the carbon density of converted forests—also lead to large initial CO_2 emissions that can drastically reduce the annual accumulated climate benefit of substituting fossil fuels with the bioenergy derived from such plantations. Converting grass- and woodlands with high soil carbon content to intensively cultivated annual crops can similarly lead to large CO_2 emissions, while if degraded and C-depleted pastures are cultivated with herbaceous and woody lignocellulosic plants soil carbon may instead accumulate, enhancing the climate benefit. This is further discussed in Section 2.5.

Technical potentials of biomass plantations can thus be calculated based on assessed land availability and corresponding yield levels. Based on the results as shown in Figure 2.4, Fischer et al. (2009) estimated regional land balances of unprotected grassland and woodland potentially available for rain-fed lignocellulosic biofuel feedstock production under a 'food and environment first' paradigm excluding forests and land currently used for food and fodder production. The latter includes estimates of unprotected grassland and woodland required today for ruminant livestock feeding. Calculations are based on FAOSTAT data on fodder utilization of crops, and national livestock numbers, estimated fodder energy requirements of the national herds and derived fodder gaps filled by grassland and pastures. Grassland and woodland with very low productivity or steep sloping conditions were considered unsuitable for lignocellulosic feedstock production. The results, shown in Table 2.3, represent one example of estimates of regional technical potentials of biomass resulting from a specific set of assumptions with respect to nature protection requirements, biofuel feedstock crop choice and agronomic practice determining attainable yield levels and livestock production systems determining grazing requirements. Furthermore, the results represent current agriculture practice and productivity, population, diets, climate etc. Quantifications of the technical potential of the future biomass resource need to consider how such parameters change over time.

A similar analysis (WBGU, 2009; Beringer et al., 2011) reserved current and near-future agricultural land for food and fibre production and also excluded unmanaged land from bioenergy production if its conversion to biomass plantations would lead to large net CO_2 emissions to the atmosphere, or if the land was degraded, a wetland, environmentally protected or rich in biodiversity. If dedicated biomass plantations were established in the available lands, an estimated 26 to 116 EJ/yr could be produced (52 to 174 EJ with irrigation). The spatial variation of technical potential was computed from biogeochemical principles, that is, photosynthesis, transpiration, soil quality and climate. Haberl et

Table 2.3 | Example of the technical potential of rain-fed lignocellulosic plants on unprotected grassland and woodland (i.e., forests excluded) where land requirements for food production, including grazing, have been considered at 2000 levels. Calculated based on Fischer et al. (2009); reproduced with permission from the International Institute for Applied Systems Analysis (IIASA).

Region	Total grass- and woodland area (Mha) [million km^2]	Protected areas (Mha) [million km^2]	Unproductive or very low productive areas (Mha) [million km^2]	Bioenergy area also excluding grazing land (Mha) [million km^2]	Technical potential (average yield,[1] GJ/ha/yr) [GJ/km^2/yr]	Technical Potential[2] (total, EJ/yr)
North America	659 [6.59]	103 [1.03]	391 [3.91]	111 [1.11]	165 [16,500]	19
Europe and Russia	902 [9.02]	76 [0.76]	618 [6.18]	122 [1.22]	140 [14,000]	17
Pacific OECD	515 [5.15]	7 [0.07]	332 [3.32]	97 [0.97]	175 [17,500]	17
Africa	1,086 [10.68]	146 [1.46]	386 [3.86]	275 [2.75]	250 [2,500]	69
South and East Asia	556 [5.56]	92 [0.92]	335 [3.35]	14 [0.14]	285 [28,500]	4
Latin America	765 [7.65]	54 [0.54]	211 [2.11]	160 [1.6]	280 [28,000]	45
Middle East and North Africa	107 [1.07]	2 [0.02]	93 [0.93]	1 [0.01]	125 [12,500]	0.2
World	**4,605 [46.05]**	**481 [4.81]**	**2,371 [23.71]**	**780 [7.80]**	**220 [22,000]**	**171**

Notes: 1. Calculated based on average yields of rain-fed lignocellulosic feedstocks on grass- and woodland area given in Fischer et al. (2009, p.174) and assuming an energy content of 18 GJ/t dry matter (rounded numbers). 2. If livestock grazing area can be freed up by intensification of agricultural practices and pasture use, these areas could be used for additional bioenergy production. The technical potential in this case could increase from 171 up to 288 EJ/yr.

5 Yield potential is the yield obtained when an adapted cultivar (cultivated variety of a plant) is grown with the minimal possible stress that can be achieved with best management practices, a functional definition by Cassman (1999).

al. (2010) considered the land available after meeting prospective future food, fodder and nature conservation targets, also taking into account spatial variation in projected future productivity of bioenergy plantations, and arrived at a technical potential in 2050 in the range of 160 to 270 EJ/yr. Of the 210 EJ/yr average technical potential, 81 EJ/yr are provided by dedicated plantations, 27 EJ/yr by residues in forestry and 100 EJ/yr by crop residues, manure and organic wastes, emphasizing the importance of process optimization and cascading biomass use.

Water constraints are highlighted in the literature for agriculture (UN-Water, 2007) and for bioenergy (Berndes, 2002; Molden, 2007; De Fraiture et al., 2008; Sections 9.3.4.4 and 2.5.5.1). In a number of regions the technical potential can decrease to lower levels than what is assessed based on approaches that do not involve explicit geo-hydrological modelling (Rost et al., 2009). Such modelling can lead to improved quality bioenergy potential assessments. Planting of trees and other perennial vegetation can decrease erosive water run-off and replenish groundwater but may lead to substantial reductions in downstream water availability (Calder et al., 2004; Farley et al., 2005).

Illustrative of this, Zomer et al. (2006) report that large areas deemed suitable for afforestation within the Clean Development Mechanism (CDM) would exhibit evapotranspiration increases and/or decreases in runoff if they become forested, that is, a decrease in water potentially available offsite for other uses. This would be particularly evident in drier areas, the semi-arid tropics, and in conversion from grasslands and subsistence agriculture. Similarly, based on a global analysis of 504 annual catchment observations, Jackson et al. (2005) report that afforestation dramatically decreased stream flow within a few years of planting. Across all plantation ages in the database, afforestation of grasslands, shrublands or croplands decreased stream flow by, on average, 38%. Average losses for 10- to 20-year-old plantations were even greater, reaching 52% of stream flow.

Studies by Hoogwijk et al. (2003), Wolf et al. (2003), Smeets et al. (2007) and van Minnen et al., (2008) also illustrate the importance of biomass plantations for reaching a higher global technical potential, and how different determining parameters greatly influence the technical potential. For instance, in a scenario with rapid population growth and slow technology progress, where agriculture productivity does not increase from its present level and little biomass is traded, Smeets et al. (2007) found that no land would be available for bioenergy plantations. In a contrasting scenario where all critical parameters were instead set to be very favourable, up to 3.5 billion hectares (35 million km^2) of former agricultural land—mainly pastures and with large areas in Latin America and sub-Saharan Africa—were assessed as not required for food in 2050. A substantial part of this area was assessed as technically suitable for bioenergy plantations.

2.2.3 Economic considerations in biomass resource assessments

Some studies exclude areas where attainable yields are below a certain minimum level. Other studies exclude biomass resources judged as being too expensive to mobilize, given a certain biomass price level. These assessments address biomass resource availability and cost for given levels of production so that an owner of a facility for secondary energy production from modern biomass could assess a location and the size of a facility for a cost-effective business with a guaranteed supply of biomass throughout the year. Costs models are based on combining land availability, yield levels and production costs to obtain plant- and region-specific cost-supply curves (Walsh, 2008). These are based on projections or scenarios for the development of cost factors, including opportunity cost of land, and can be produced for different contexts and scales—including feasibility studies of supplying individual bioenergy plants and estimating the future global cost-supply curve. Studies using this approach at different scales include Dornburg et al. (2007), Hoogwijk et al. (2009), de Wit et al. (2010) and van Vuuren et al. (2009). P. Gallagher et al. (2003) exemplify the production of cost-supply curves for the case of crop harvest residues and Gerasimov and Karjalainen (2009) for the case of forest wood.

The biomass production costs can be combined with technological and economic data for related logistic systems and conversion technologies to derive market potentials at the level of secondary energy carriers such as bioelectricity and biofuels for transport (e.g., Gan, 2007; Hoogwijk et al., 2009; van Dam et al., 2009c). Using biomass cost and availability data as exogenously defined input parameters in scenario-based energy system modelling can provide information about levels of implementation in relation to a specific energy system context and possible climate and energy policy targets. Cost trends are discussed further in Section 2.7.

Figure 2.5(a) shows projections of European market potential estimated based on food sector scenarios for 2030, considering also nature protection requirements and infrastructure development (Fischer et al., 2010). Estimated production cost supply curves shown in Figure 2.5(b) were subsequently produced including biomass plantations and forest/agriculture residues (de Wit and Faaij, 2010). The key factor determining the size of the market potential was the development of agricultural land productivity, including animal production.

Figure 2.5(c) data for the USA are based on recent assessments of lignocellulosic feedstock supply cost curves conducted at county-level resolution (Walsh, 2008; Perlack et al., 2005; US DOE, 2011). Figure 2.5(d) illustrates the delivered price of biomass to the conversion facility under the baseline conditions for various production levels of lignocellulosic feedstocks.[6] Total market potential for crop-based ethanol and

6 For instance, at a biomass feedstock price of USD_{2005} 3/GJ delivered to the conversion facility, the three types of feedstocks shown in Figure 2.5(d) would provide 5.5 EJ. At higher prices there is more feedstock up to a point, for example, 1.5 EJ for the forest residues in the figure.

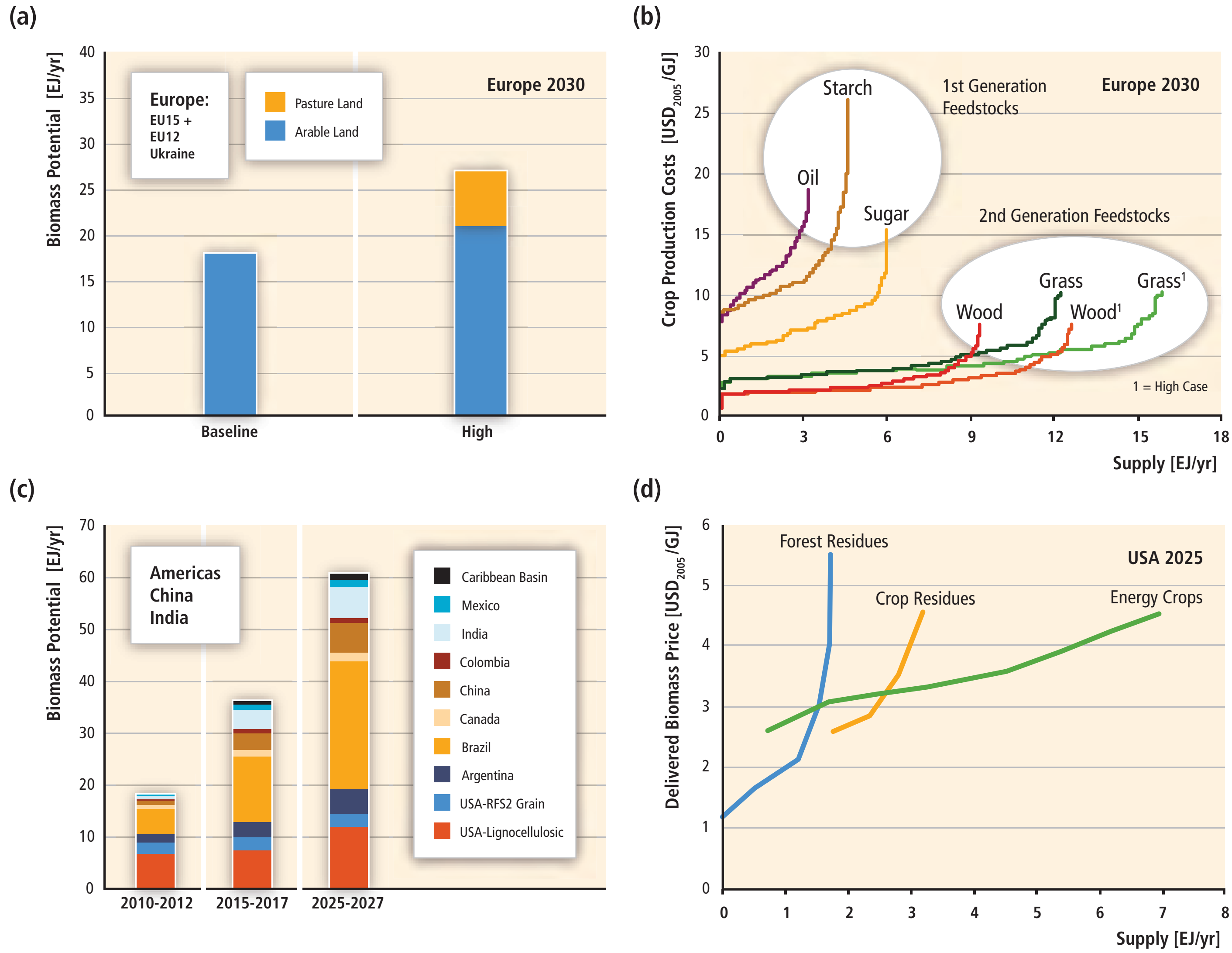


Figure 2.5 | Examples of preliminary market potentials based on feedstock cost supply curves shown in (b) for European countries and (d) for the USA. The feedstock cost supply curves for these assessments are from recent studies conducted at levels of: (a) region; (c) country based on state/province except for the USA, which is performed at a county level. In (c) the US data are for the baseline case and the other countries' cases are for a high-growth scenario (a total of 45 EJ/yr, which would decrease to 25 EJ/yr in the base case and to around 8 EJ/yr in the low case) by 2025. See text for further information. Sources: (a) Fischer et al. (2010); (b) de Wit and Faaij (2010); (c) Kline et al. (2007); Walsh (2008); EPA (2010); (d) Walsh (2008), US DOE (2011).

biodiesel are from EPA (2010) projections. In addition, Figure 2.5(c) includes preliminary estimates of high-growth scenarios of market potentials for the Americas, China and India based on historic production trends and average production costs at the state/province level (Kline et al., 2007), considering multiple crops, residues and perennial biomass crops. Market potentials were estimated based on arable land availability for bioenergy plants and some degree of environmental protection and infrastructure. High-growth market potentials are shown for years 2012, 2017 and 2027 (Kline et al., 2007). The largest supplier, Brazil, is using AgroEcological Zoning (EMBRAPA, 2010) to limit expansion to unrestricted areas with appropriate soil and climate, with no or low irrigation requirements, and low slopes for mechanized harvesting. Similar zoning is available for oil palm.[7] These steps are recommended by several of the organizations developing sustainability criteria (van Dam et al., 2010, and see Section 2.4.5).

2.2.4 Factors influencing biomass resource potentials

As described briefly above, many studies that quantify the biomass resource potential consider a range of factors that reduce it to lower levels than if they are not included. These factors are also connected to impacts arising from the exploitation of biomass resources, which are further discussed in Section 2.5. The most important factors are

7 DECRETO Nº 7172, DE 07 DE MAIO DE 2010, Brazil.

discussed below in relation to how they influence the future biomass resource potential.

2.2.4.1 Residue supply in agriculture and forestry

Soil conservation and biodiversity requirements influence technical potentials for both agriculture and forestry residues. In forestry, the combination of residue harvest and nutrient (including wood ash) input can avoid nutrient depletion and acidification and can in some areas improve environmental conditions due to reduced nutrient leaching from forests (Börjesson, 2000; Eisenbies et al., 2009). Even so, organic matter at different stages of decay plays an important ecological role in conserving soil quality as well as for biodiversity in soils and above ground (Grove and Hanula, 2006). Thresholds for desirable amounts of dead wood in forest stands are difficult to set and the most demanding species require amounts of dead wood that are difficult to reach in managed forests (Ranius and Fahrig, 2006). Dymond et al. (2010) report that estimates from studies taking into account the need for on-site sustainability can be several times lower than those that do not. Large differences were also reported by Gronowska et al. (2009). Titus et al. (2009) report wide ranges (0 to 100%) in allowed residue recovery rates for large-scale logging residue inventories and propose a 50% retention proportion as an appropriate level, noting that besides soil sustainability additional aspects (e.g., biodiversity and water quality) need to be considered.

Development of technologies for stump harvesting after felling increases the availability of residues during logging (Näslund-Eriksson and Gustavsson, 2008). Stump harvesting can also reduce the cost of site preparation for replanting (Saarinen, 2006). It can reduce damage from insects and spreading of root rot fungus, but can also lead to negative effects including reduced forest soil carbon and nutrient stocks, increased soil erosion and soil compaction (Zabowski et al., 2008; Walmsley and Godbold, 2010).

In agriculture, overexploitation of harvest residues is one important cause of soil degradation in many places in the world (Wilhelm et al., 2004; Ball et al., 2005; Blanco-Canqui et al., 2006; Lal, 2008). Fertilizer inputs can compensate for nutrient removals connected to harvest and residue extraction, but maintenance or improvement of soil fertility, structural stability and water-holding capacity requires recirculation of organic matter to the soil (Lal and Pimentel, 2007; Wilhelm et al., 2007; Blanco-Canqui and Lal, 2009). Residue recirculation leading to nutrient replenishment and carbon storage in soils and dead biomass not only contributes positively to climate change mitigation by withdrawing carbon from the atmosphere but also by reducing soil degradation and improving soil productivity. This leads to higher yields and consequently less need to convert land to croplands for meeting future food/fibre/bioenergy demand (i.e., fewer GHG emissions arising from vegetation removal and ploughing of soils). Residue removal can, all other things being equal, be increased when total biomass production per hectare becomes higher and if 'waste' from processing of crop residues that is rich in refractory compounds such as lignin is returned to the field (J. Johnson et al., 2004; Reijnders, 2008; Lal, 2008).

Principles, criteria and indicators are developed to ensure ecological sustainability (e.g., van Dam et al., 2010; Lattimore et al., 2009; Section 2.4.3) but these cannot easily be used to derive sustainable residue extraction rates. Large uncertainties are also linked to the possible future development of several factors determining residue generation rates. Population growth, economic development and dietary changes influence the demand for products from agriculture and forestry, and materials management strategies (including recycling and cascading use of material) influence how this demand translates into demand for basic food commodities and industrial roundwood.

Furthermore, changes in food and forestry sectors influence the residue/waste generation per unit of product output up or down: crop breeding leads to improved harvest index, reducing residue generation rates; implementation of no-till/conservation agriculture requires that harvest residues are left on the fields to maintain soil cover and increase organic matter in soils (Lal, 2004); shifts in livestock production to more confined and intensive systems can increase recoverability of dung but reduce overall dung production at a given level of livestock product output; and increased occurrence of silvicultural treatments such as early thinning to improve stand growth will lead to increased availability of small roundwood suitable for energy uses.

Consequently, the longer-term technical potential connected to residue/waste flows will continue to be uncertain even if more comprehensive assessment approaches are used. It should be noted that it does not necessarily follow that more comprehensive assessments of determining factors will lead to a lower technical potential of residues; earlier studies may have used conservative residue recovery rates as a precaution in the face of uncertainties (S. Kim and Dale, 2004). However, modelling studies indicate that the cost of soil productivity loss may restrict residue removal intensity to much lower levels than the quantity of biomass physically available in forestry (Gan and Smith, 2010).

2.2.4.2 Dedicated biomass production in agriculture and forestry

Studies indicate significant potential for intensifying conventional long-rotation forestry to increase forest growth and total biomass output—for instance, by fertilizing selected stands and using shorter rotations (Nohrstedt, 2001; Saarsalmi and Mälkönen, 2001)—especially in regions of the world with large forest areas that currently practice extensive forest management. Yet, the prospects for intensifying conventional long-rotation forestry to increase forest growth are not thoroughly investigated in the assessed studies of biomass resource potentials. Instead, the major source of increased forest biomass output is assumed to be fast-growing tree plantations. Besides tree plantations, short-rotation coppicing plants such as willow and perennial grasses such as switchgrass and *Miscanthus* are considered candidate bioenergy plants to become established on these lands.

It is commonly assumed that biomass plantations are established on surplus agricultural land. Intensification in agriculture is therefore a key aspect in essentially all of the assessed studies because it influences both land availability for biomass plantations (indirectly by determining the land requirements in the food sector) and the biomass yield levels obtained. High assessed technical potentials for energy plantations rely on high-yielding agricultural systems and international bioenergy trade leading to the result that biomass plantations are established globally where the production conditions are most favourable. Increasing yields from existing agricultural land is also proposed as a key component for agricultural development (Ausubel, 2000; Fischer et al., 2002; Tilman et al., 2002; Cassman et al., 2003; Evans, 2003; Balmford et al., 2005; Green et al., 2005; D. Lee et al., 2006; Bruinsma, 2009). Studies also point to the importance of diets and the food sector's biomass use efficiency in determining land requirements (both cropland and grazing land) for food (Gerbens-Leenes and Nonhebel, 2002; Smil, 2002; Carlsson-Kanyama and Shanahan, 2003; de Boer et al., 2006; Elferink and Nonhebel, 2007; Stehfest et al., 2009; Wirsenius et al., 2010).

Studies of agricultural development (e.g., Koning, 2008; Alexandratos, 2009; IAASTD, 2009) show lower expected yield growth than studies of the biomass resource potential that report very high technical potentials for biomass plantations (Johnston et al., 2009). Some observations indicate that it can be a challenge to maintain yield growth in several main producer countries and that much cropland and grazing land undergoes degradation and productivity loss as a consequence of improper land use (Cassman, 1999; Pingali and Heisey, 1999; Fischer et al., 2002). The possible consequences of climate change for crop yields are not firmly established but indicate net global negative impact, where damages will be concentrated in developing countries that will lose agriculture production potential while developed countries might gain (Fischer et al., 2002; Cline, 2007; Easterling et al., 2007; Schneider et al., 2007; Lobell et al., 2008; Fischer et al., 2009). Water scarcity can limit both intensification possibilities and the prospects for expansion of bioenergy plantations (Berndes, 2008a,b; de Fraiture et al., 2008; de Fraiture and Berndes, 2009; Rost et al., 2009; van Vuuren et al., 2009) but can be partially alleviated through on-site water management (Rost et al., 2009). Biomass resource potential studies that use biophysical data sets and modelling are able to consider water limitations on land productivity. However, assumptions about productivity growth in land use may implicitly presume irrigation development that could lead to problems in regional water availability, use and distribution among users. Empirical data are needed for use in hydrological process models to better understand and predict the hydrological effects of various land use options at the landscape level (Malmer et al., 2010). Water and land use-related aspects are further discussed in Section 2.5.

Conversely, some observations indicate that rates of gain obtained from breeding have increased in recent years after previous stagnation and that yields might increase faster again as newer hybrids are adopted more widely (Edgerton, 2009). Theoretical limits also appear to leave scope for further increasing the genetic yield potential (Fischer et al., 2009). It should be noted that studies finding high technical potential for bioenergy plantations point primarily to tropical developing countries as major contributors. These countries still have substantial yield gaps to exploit and large opportunities for productivity growth—not the least in livestock production (Fischer et al., 2002; Edgerton, 2009; Wirsenius et al., 2010). There is also a large yield growth potential for dedicated bioenergy plants that have not been subject to the same breeding efforts as the major food crops. Selection and development of suitable plant species and genotypes for given locations to match specific soil types, climate and conversion technologies are possible, but are at an early stage of understanding for some energy plants (Bush and Leach, 2007; Chapple et al., 2007; Lawrence and Walbot, 2007; Carpita and McCann, 2008; Karp and Shield, 2008). Traditional plant breeding, selection and hybridization techniques are slow, particularly for woody plants but also for grasses, but new biotechnological routes to produce both genetically modified (GM) and non-GM plants are possible (Brunner et al., 2007). GM energy plant species may be more acceptable to the public than GM food crops, but there are concerns about the potential environmental impacts of such plants, including gene flow from non-native to native plant relatives (Chapotin and Wolt, 2007; Firbank, 2008; Warwick et al., 2009; see Section 2.5.6.1).

There can be limitations on and negative aspects of further intensification aiming at farm yield increases, for example, high crop yields depending on large inputs of nutrients, fresh water and pesticides can contribute to negative ecosystem effects, such as changes in species composition in the surrounding ecosystems, groundwater contamination and eutrophication with harmful algal blooms, oxygen depletion and anoxic 'dead' zones in oceans (Donner and Kucharik, 2008; Simpson et al., 2009; Sections 2.5.5.1 and 2.6.1.2). However, intensification is not necessarily equivalent to an industrialization of agriculture, as agricultural productivity can be increased in many regions and systems with conventional or organic farming methods (Badgley et al., 2007). The potential to increase the currently low productivity of rain-fed agriculture exists in large parts of the world through improved soil and water conservation (Lal, 2003; Rockström et al., 2007, 2010), fertilizer use and crop selection (Cassman, 1999; Keys and McConnell, 2005). Available best practices[8] are not at present applied in many world regions (Godfray et al., 2010), due to a lack of dissemination, capacity building, availability of resources and access to capital and markets, with distinct regional differences (Neumann et al., 2010).

8 For example, mulching, low tillage, contour ploughing, bounds, terraces, rainwater harvesting and supplementary irrigation, drought adapted crops, crop rotation and fallow time reduction.

Conservation agriculture and mixed production systems (double-cropping, crop with livestock and/or crop with forestry) hold potential to sustainably increase land productivity and water use efficiency as well as carbon sequestration and to improve food security and efficiency in the use of limited resources such as phosphorous (Kumar, 2006; Heggenstaller et al., 2008; Herrero et al., 2010). Integration can also be based on integrating feedstock production with conversion—typically producing animal feed that can replace cultivated feed such as soy and corn (Dale et al., 2009, 2010) and also reduce grazing requirements (Sparovek et al., 2007).

Investment in agricultural research, development and deployment could produce a considerable increase in land and water productivity (Rost et al., 2009; Herrero et al., 2010; Sulser et al., 2010) as well as improve robustness of plant varieties (Reynolds and Borlaug, 2006; Ahrens et al., 2010). Multi-functional systems (IAASTD, 2009) providing multiple ecosystem services (Berndes et al., 2004, 2008a,b; Folke et al., 2004, 2009) represent alternative options for the production of bioenergy on agricultural lands that could contribute to development of farming systems and landscape structures that are beneficial for the conservation of biodiversity (Vandermeer and Perfecto, 2006).

2.2.4.3 Use of marginal lands

Biomass resource potential studies also point to marginal/degraded lands—where productive capacity has declined temporarily or permanently—as lands that can be used for biomass production. Advances in plant breeding and genetic modification of plants not only raise the genetic yield potential but also may adapt plants to more challenging environmental conditions (Fischer et al., 2009). Improved drought tolerance can improve average yields in drier areas and in rain-fed systems in general by reducing the effects of sporadic drought (Nelson et al., 2007; Castiglioni et al., 2008) and can also reduce water requirements in irrigated systems. Thus, besides reducing land requirements for meeting food and materials demand by increasing yields, plant breeding and genetic modification could make lands initially considered unsuitable available for rain-fed or irrigated production.

Some studies show a significant technical potential of marginal/degraded land, but it is uncertain how much of this technical potential can be realized. The main challenges in relation to the use of marginal/degraded land for bioenergy include (1) the large efforts and long time periods required for the reclamation and maintenance of more degraded land; (2) the low productivity levels of these soils; and (3) ensuring that the needs of local populations that use degraded lands for their subsistence are carefully addressed. Studies point to the benefits of local stakeholder participation in appraising and selecting appropriate measures (Schwilch et al., 2009) and suggest that land degradation control could benefit from addressing aspects of biodiversity and climate change and that this could pave the way for funding via international financing mechanisms and major donors (Knowler, 2004; Gisladottir and Stocking, 2005). In this context, the production of properly selected plant species for bioenergy can be an opportunity, where additional benefits involve carbon sequestration in soils and aboveground biomass and improved soil quality over time.

2.2.4.4 Biodiversity protection

Considerations regarding biodiversity can limit residue extraction as well as intensification and expansion of agricultural land area. WBGU (2009) shows that the way biodiversity is considered can have a larger impact on technical potential than either irrigation or climate change. The common way of considering biodiversity requirements as a constraint is by including requirements for land reservation for biodiversity protection. Biomass resource potential assessments commonly exclude nature conservation areas from being available for biomass production, but the focus is as a rule on forest ecosystems and takes the present level of protection as a basis. Other natural ecosystems also require protection—not least grassland ecosystems—and the present status of nature protection for biodiversity may not be sufficient for given targets. While many highly productive lands have low natural biodiversity, the opposite is true for some marginal lands and, consequently, the largest impacts on biodiversity could occur with widespread use of marginal lands.

Some studies indirectly consider biodiversity constraints on productivity by assuming a certain expansion of alternative agriculture production (to promote biodiversity) that yields less than conventional agriculture and therefore requires more land for food production (EEA, 2007; Fischer et al., 2009). However, for multi-cropping systems a general assumption of lower yields from alternative cropping systems is not consistent. Biodiversity loss may also occur indirectly, such as when productive land use displaced by energy crops is re-established by converting natural ecosystems into croplands or pastures elsewhere. Integrated energy system and land use/vegetation cover modelling have better prospects for analyzing these risks.

Bioenergy plantations can play a role in promoting biodiversity, particularly when multiple species are planted and mosaic landscapes are established in uniform agricultural landscapes and in some currently poor or degraded areas (Hartley, 2002). Agro-forestry systems combining biomass and food production can support biodiversity conservation in human-dominated landscapes (Bhagwat et al., 2008). Biomass resource potential assessments, however, as a rule assume yield levels corresponding to those achieved in monoculture plantations and therefore provide little insight into how much biomass could be produced if a significant part of the biomass plantation were shaped to contribute to biodiversity preservation.

2.2.5 Possible impact of climate change on resource potential

Technical potentials are influenced by climate change. The magnitude and spatial pattern of climate change remain uncertain[9] despite high scientific confidence that global warming and an intensification of the hydrological cycle will be a consequence of increased GHG concentrations in the atmosphere (IPCC, 2007c). Furthermore, the effect of unhistorical new changes in temperature, irradiation and soil moisture on the growth of agricultural plants is frequently uncertain (Lobell and Burke, 2008), as is the adaptive response of farmers. As a consequence, the overall magnitude and pattern of climate change effects on agricultural production, including bioenergy plantations, remain uncertain. While positive effects on plant growth may occur, detrimental impacts on productivity cannot at present be precluded for many important regions.

Uncertainty also remains about the concurrent ecophysiological effect of elevated atmospheric CO_2 concentration on plant productivity—the CO_2 fertilization effect. Under elevated CO_2 supply, the growth of plants with C_3 photosynthesis is increased unless it is hampered by increased water stress or nutrient depletion (Oliver et al., 2009). The long-term magnitude of the carbon fertilization effect is disputed, with increases in annual NPP of around 25% possible and observed in some field experiments for a doubling of atmospheric CO_2 concentration (the effect levels off at higher CO_2 concentrations), while some expect smaller gains due to co-limitations and eventual adaptations (Ainsworth and Long, 2005; Körner et al., 2007). The magnitude of the effect under agricultural management and breeding conditions may be different and is not well known.

Under climate warming, the increased requirement for transpiration water by vegetation is partially countered by increased water use efficiency (increased stomatal closure) under elevated atmospheric CO_2 concentrations, with variable regional patterns (Gerten et al., 2005). Changes in precipitation patterns and magnitude can increase or decrease plant production depending on the direction of change. Generally, some semi-arid marginal lands are projected to be more productive due to increased water use efficiency under CO_2 fertilization (Lioubimtseva and Adams, 2004). As crop production is projected to mostly decline with warming of more than 2°C (Easterling et al., 2007), particularly in the tropics, biomass for energy production could be similarly affected. Overall, the effects of climate change on biomass technical potential are found to be smaller than the effects of management, breeding and area planted (WBGU, 2009), but in any particular region they can be strong. Which regions will be most affected remains uncertain, but tropical regions are most likely to see the strongest negative impact.

9 Uncertainties arise because future GHG emission trajectories cannot be known (and are therefore studied using a variety of scenarios), the computed sensitivities of climate models to GHG forcing vary (i.e., the amount of warming that follows from a given emission scenario), and the spatial pattern and seasonality of changes in precipitation vary greatly between models, particularly for some tropical and subtropical regions (Li et al., 2006).

2.2.6 Synthesis

As discussed, narrowing down the technical potential of the biomass resource to precise numbers is not possible. A number of studies show that between less than 50 and several hundred EJ per year can be provided for energy in the future, the latter strongly conditional on favourable developments. From an assessment of the findings, it can be concluded that:

- The size of the future technical potential is dependent on a number of factors that are inherently uncertain and will continue to make long-term technical potentials unclear. Important factors are population and economic/technology development and how these translate into fibre, fodder and food demand (especially share and type of animal food products in diets) and development in agriculture and forestry.

- Additional important factors include (1) climate change impacts on future land use including its adaptation capability; (2) considerations set by biodiversity and nature conservation requirements; and (3) consequences of land degradation and water scarcity.

- Studies point to residue flows in agriculture and forestry and unused (or extensively used) agricultural land as an important basis for expansion of biomass production for energy, both in the near term and in the longer term. Consideration of biodiversity and the need to ensure maintenance of healthy ecosystems and avoid soil degradation set bounds on residue extraction in agriculture and forestry (further discussed in Section 2.5.5).

- Grasslands and marginal/degraded lands are considered to have potential for supporting substantial bioenergy production, but biodiversity considerations and water shortages may limit this potential. The possibility that conversion of such lands to biomass plantations reduces downstream water availability needs to be considered.

- The cultivation of suitable plants can allow for higher technical potentials by making it possible to produce bioenergy on lands less suited for conventional food crops—also when considering that the cultivation of conventional crops on such lands can lead to soil carbon emissions (further discussed in Section 2.5.2).

- Landscape approaches integrating bioenergy production into agriculture and forestry systems to produce multi-functional land use systems could contribute to the development of farming systems and landscape structures that are beneficial for the conservation of biodiversity and help restore/maintain soil productivity and healthy ecosystems.

- Water constraints may limit production in regions experiencing water scarcity. But the use of suitable energy crops that are drought tolerant can also help adaptation in water-scarce situations. Assessments of biomass resource potentials need to more carefully consider constraints and opportunities in relation to water availability and competing uses.

Based on this expert review of the available scientific literature, deployment levels of biomass for energy could reach a range of 100 to 300 EJ/yr around 2050 (see Section 2.8.4.1 for more detail). This can be compared with the present biomass use for energy of about 50 EJ/yr. While recent assessments employing improved data and modelling capacity have not succeeded in providing narrow, distinct estimates of the biomass resource potential, they have advanced the understanding of how influential various factors are on the resource potential and that both positive and negative effects may follow from increased biomass use for energy. One important conclusion is that the effects of LUC associated with bioenergy expansion can considerably influence the climate benefit of bioenergy (Section 2.5.5). The insights from the resource assessments can improve the prospects for bioenergy by pointing out the areas where development is most crucial and where research is needed. A summary is given in Section 2.8.4.3.

2.3 Technologies and applications

This section reviews commercial technologies for biomass feedstock production, pretreatment of solid biomass and logistics of supply chains bringing feedstocks to direct users. The users can be individuals (e.g., fuelwood for cooking or heating) or firms (e.g., industrial users or processors). Pretreated and converted energy carriers are more convenient and can be used in more applications than the original biomass and are modern solid (e.g., pellets), liquid (e.g., ethanol) and gaseous (e.g., methane) fuels from which electricity and/or heat or mobility services are produced (see Figure 2.2). The integration of modern biomass with existing and evolving electricity, natural gas, heating (residential and district, commercial and public services), industrial, agriculture/forestry, and fossil liquid fuels systems is discussed thoroughly in Chapter 8.

This section is organized along the supply chain of bioenergy and thus discusses feedstock production and the synergies with related sectors before turning to pretreatment, logistics and supply chains of solid biomass. The section then explains different state-of-the-art conversion technologies for energy carriers from modern biomass before discussing the costs, directly available from relevant literature, of these broader bioenergy systems and supply chains. Section 2.6 provides prospects for technology improvement, innovation and integration before Section 2.7 addresses relevant cost information in terms of levelized cost of production for many world regions.

2.3.1 Feedstocks

2.3.1.1 Feedstock production and harvest

The performance characteristics of major biomass production systems, dedicated plants or primary residues across the world regions are summarized in Table 2.4. The management of energy plants includes the provision of seeds or seedlings, stand establishment and harvest, soil tillage, irrigation, and fertilizer and pesticide inputs. The latter depend on crop requirements, target yields and local pedo-climatic conditions, and may vary across world regions for similar species (Table 2.4). Strategies such as integrated pest management or organic farming may alleviate the need for synthetic inputs for a given output of biomass (Pimentel et al., 2005).

Wood for energy is obtained as fuelwood or as residue. While fuelwood is derived from the logging of natural or planted forests or trees and shrubs grown in agriculture fields, residues are derived from wood waste and by-products. While natural forests are not managed for production per se, problems arise if fuelwood extraction exceeds the regeneration capacity of the forests, which is the case in many parts of the world. The management of planted forests involves silvicultural techniques similar to those used in cropping systems and includes stand establishment and tree felling (Nabuurs et al., 2007).

Biomass may be harvested several times per year (for forage-type feedstocks such as hay or alfalfa), once per year (for annual species such as wheat or perennial grasses), or every 2 to 50 years or more (for short-rotation coppice and conventional forestry, respectively). Sugarcane is harvested annually but planted every 4 to 7 years and grown in ratoons; it is considered a perennial grass. Harvested biomass is typically transported to a collection point on the farm or at the edge of the road before being transported to the bioenergy unit or to an intermediate storage facility. It may be preconditioned and densified to facilitate storage, transport and handling (see Section 2.3.2).

The species listed in Table 2.4 have different possible energy end uses and require diverse conversion technologies (see Figure 2.6). Starch and oil crops are grown and harvested annually as feedstocks for what are called first-generation liquid biofuels (ethanol and biodiesel, see Section 2.3.3). Only a fraction of the total aboveground biomass is used for biofuels, with the rest being processed for animal feed or lignocellulosic residues. Sugarcane plants are feedstocks for the production of sugar and ethanol and, increasingly, sugarcane bagasse and straw, which serve as sources of process heat and extra power in many sugar- and ethanol-producing countries (Macedo et al., 2008; Dantas et al., 2009; Seabra et al., 2010) resulting in favourable environmental footprints for these biorefinery products. Lignocellulosic plants such as perennial grasses or short-rotation coppice may be entirely converted to energy, and feature two to five times higher

Table 2.4 | Typical characteristics of the production technologies for dedicated species and their primary residues. Yields are expressed as GJ of energy content in biomass prior to conversion to energy, or of the ethanol end product for sugar and starch crops. Costs refer to private production costs or market price when costs were unavailable (data from 2005 to 2009). Key to management inputs: +: low; ++: moderate; +++: high requirements.

Feedstock type	Region	Yield	Management			Co-products	Costs	Refs.
		GJ/ha/yr [$TJ/km^2/yr$]	Fertilizer use[1]	Water needs	Pesticides		Examples (2005-2009) USD/GJ	
OIL CROPS		**As oil**						
Oilseed rape	Europe	60–70 [6.7–7.0]	+++	+	+++	Rape cake, straw	7.2–16.0	1,2,3,22
Soybean	North America	16–19 [1.6–1.9]	++	+	+++	Soy cake, straw	11.7	3,12
	Brazil	18–21 [1.8–2.1]	++	+	+++		N/A	
Palm oil	Asia	135–200 [13.5–20.0]	++	+	+++	Fruit bunches, press fibres	N/A	
	Brazil	169 [16.9]	++	+	+++		12.6[2]	3
Jatropha	World	17–88 [1.7–8.8]	+/++	+	+	Seed cake (toxic), wood, shells	3.2	3,4,5,10,11
STARCH CROPS		**As ethanol**						
Wheat	Europe	54–58 [5.4–5.8]	+++	++	+++	Straw, DDGS[3]	5.2	3
Maize	North America	72–79 [7.2–7.9]	+++	+++	+++	Corn stover, DDGS	10.9	3
Cassava	World	43 [4.3]	++	+	++	DDGS	3.3–4	3
SUGAR CROPS		**As ethanol**						
Sugarcane	Brazil	116–149 [11.6–14.9]	++	+	+++	Bagasse, straw	1.0–2.0[2]	3,17
	India	95–112 [9.5–11.2]					N/A	3
Sugar beet	Europe	116–158 [11.6–15.8]	++	++	+++	Molasses, pulp	5.2–9.6	3,13,22
Sorghum (sweet)	China	105–160 [10.5–16.0]	+++	+	++	Bagasse	4.4	2,21
LIGNOCELLULOSIC CROPS		**As ethanol**						
Miscanthus	Europe	190–280 [19.0–28.0]	+/++	++	+		4.8–16	6,8
Switchgrass	Europe	120–225 [12.0–22.5]	++	+	+		2.4–3.2	10,14
	North America	103–150 [10.3–15.0]	++	+	+		4.4	
Short rotation (SR)	Southern Europe	90–225 [9.0–22.5]	+	++	+	Tree bark	2.9–4	10,14
Eucalyptus	South America	150–415 [15.0–41.5]	+/++	+	+		2.7	16,19
SR Willow	Europe	140 [14.0]					4.4	2,7
Fuelwood (chopped)	Europe	110 [11.0]				Forest residues	3.4–13.6	15
Fuelwood (renewable, native forest)	Central America	80–150 [8.0–15.0]					1.8–2.0	23
PRIMARY RESIDUES								
Wheat straw	Europe	60 [6.0]	+			Not Applicable	1.9	2
	USA	7–75 [0.7–7.5]					N/A	14, 20
Sugarcane straw	Brazil	90–126 [9.0–12.6]	+				N/A	17
Corn stover	North America	15–155 [1.5–15.5]	+				N/A	9,14
	India	22–30 [2.2–3.0]	+				0.9	18
Sorghum stover	World	85 [8.5]	+				N/A	9
Forest residues	Europe	2–15 [0.2–1.5]					1–7.7	15

Notes: 1. Nitrogen, phosphorus, and potassium; 2. Market price; 3. DDGS: Dried Distillers Grain with Solubles. These are illustrative cost figures or market prices from the literature. See Annex II for ranges of costs for specific commercial feedstocks over a year period.

References: 1: EEA (2006); 2: Edwards et al. (2007); 3: Bessou et al. (2010); 4: Jongschaap et al. (2007); 5: Openshaw (2000); 6: Clifton-Brown et al. (2004); 7: Ericsson et al. (2009); 8: Fagernäs et al. (2006); 9: Lal (2005); 10: WWI, (2006); 11: Maes et al. (2009); 12: Gerbens-Leenes et al. (2009);13: Berndes (2008a,b); 14: Perlack et al. (2005); 15: Asikainen et al. (2008); 16: Scolforo (2008); 17: Folha (2005); 18: Guille (2007); 19: Diaz-Balteiro and Rodriguez (2006); 20: Lal (2005); 21: Grassi et al. (2006); 22: Faaij (2006); 23: T. Johnson et al. (2009). See Bessou et al. (2010) for specific biofuel volumes per hectare for various countries; see also IEA Renewable Energy Division (2010) for additional country information.

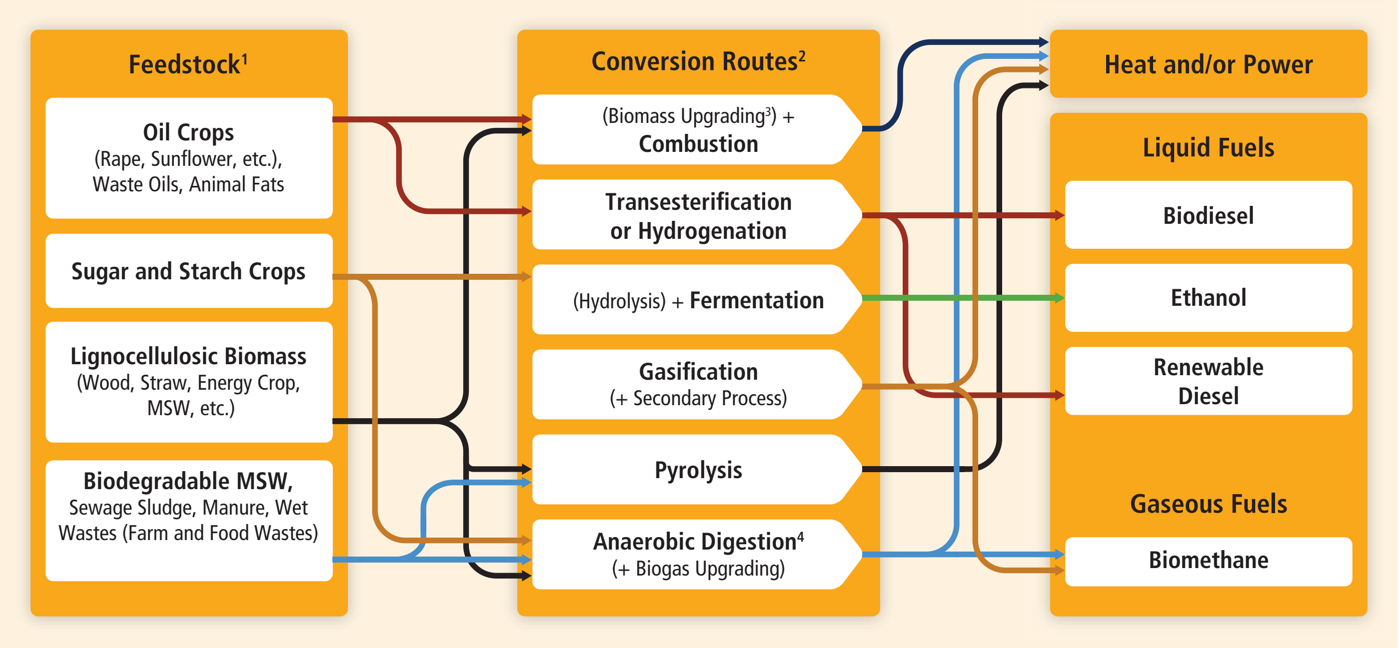


Figure 2.6 | Schematic view of commercial bioenergy routes (modified from IEA, Bioenergy, 2009).

Notes: 1. Parts of each feedstock, for example, crop residues, could also be used in other routes. 2. Each route also gives co-products. 3. Biomass upgrading includes any one of the densification processes (pelletization, pyrolysis, etc.). 4. Anaerobic digestion processes release methane and CO_2 and removal of CO_2 provides essentially methane, the main component of natural gas; the upgraded gas is called biomethane.

yields per hectare than most of the other feedstock types, while requiring far fewer synthetic inputs when managed carefully (Hill, 2007). However, their impact on soil organic matter after the removal of stands is not well understood (Wilhelm et al., 2007; Anderson-Teixeira et al., 2009). Research is underway to assess site-specific removal levels as a function of time and strategies to mitigate weather impacts on residue removal (e.g., Karlen, 2010; Zhang et al., 2010). With technologies that are currently commercial, lignocellulosic feedstocks are only providing heat and power whereas the harvest products of oil, sugar and starch crops are being converted readily to liquid biofuels and in some cases together with heat and power.

Production and harvest costs for dedicated plants vary widely according to the prices of inputs, machinery, labour and land-related costs (Ericsson et al., 2009; Table 2.4). If energy plantations are to compete with land dedicated to food production, the opportunity cost of land (the price that a farmer needs to receive in order to switch from the known annual crop cultivation to an energy crop) could be quite significant and may escalate proportionally with the demand for energy feedstocks (Bureau et al., 2010). Cost-supply curves scaling from farm to the regional level are needed to account for possible large-scale deployment scenario effects (see examples in Figures 2.5(b) and 2.5(d) for feedstock supplies in Europe (cost) and the USA (delivered price), respectively, as a function of feedstock production level, with the unit price per GJ growing several-fold as the total demand for biomass increases).

The cost of forest products depends heavily on harvesting and other logistical practices. In particular labour costs, machinery and the distance from the logging site to the conversion plant are important (Asikainen et al., 2008). This favours local, non-centralized markets especially in developing countries where forests are the dominant fuel source for households (Bravo et al., 2010).

2.3.1.2 Synergies with the agriculture, food and forest sectors

As emphasized in Section 2.2.1, bioenergy feedstock production competes with other uses for resources, chiefly land, with possible negative effects on biodiversity, water availability, soil quality and climate (see Sections 2.2.4 and 2.5). However, synergistic effects may also emerge through the design of integrated production systems, which also provide additional environmental services. Intercropping and mixed cropping are options to maximize the output of biomass per unit area farmed (WWI, 2006). Mixed cropping systems result in increased yields compared to single crops, and may provide both food/fodder and energy feedstocks from the same field (Jensen, 1996; Tilman et al., 2006b). Double-cropping systems have the potential to generate additional feedstocks for bioenergy and livestock utilization and potentially higher yields of biofuel from two crops in the same area in a year (Heggenstaller et al., 2008).

Agro-forestry systems make it possible to use land for food, fodder, timber and energy purposes with mutual benefits for the associated species (R. Bradley et al., 2008). The associated land equivalent ratios may reach up to 1.5, meaning a 50% saving in land area when combining trees with arable crops compared to monocultures (Dupraz and Liagre, 2008) and therefore an equal reduction in indirect LUC effects (see Section

2.5.3). Another option is growing an understory food crop and coppicing the lignocellulosic species to produce residual biomass for energy, similarly to short-rotation coppice (Dupraz and Liagre, 2008). Perennial plants create positive externalities such as erosion control, improved fertilizer use efficiency and reduction in nitrate leaching relative to annual plants (see Section 2.2.4.2). Lastly, the revenues generated from growing bioenergy feedstocks may provide access to technologies or inputs enhancing the yields of food crops, drive additional investments in the agricultural sector and contribute to productivity gains (De La Torre Ugarte and Hellwinckel, 2010), provided feedstock benefits are distributed to local communities (Practical Action Consulting, 2009).

2.3.2 Logistics and supply chains for energy carriers from modern biomass

Because biomass is mostly available in low-density form, it demands more storage space, transport and handling than fossil equivalents, with consequent cost implications. Biomass often needs to be processed (pretreated) to improve handling. For most bioenergy systems and chains, handling and transport of biomass from the source location to the conversion plant is an important contributor to the overall costs of energy production. Crop harvesting, storage, transport, pretreatment and delivery can amount to 20 to 50% of the total costs of energy production (J. Allen et al., 1998).

Use of a single agricultural biomass feedstock for year-round energy generation requires relatively large storage because biomass is only available for a short time following harvest in many places. In addition to such seasonal variations in biomass availability, other characteristics complicate the biomass supply chain and should be taken into account. These include multiple feedstocks with their own complex supply chains, and storage challenges such as space constraints, fire hazards, moisture control and health risks from fungi and spores (Junginger et al., 2001; Rentizelas et al., 2009).

2.3.2.1 Solid biomass supplies and market development for utilization

Over time, several stages may be observed in biomass utilization and market developments in biomass supplies. Different countries seem to follow these stages over time, but clearly differ in their respective stages of development (Faaij, 2006; Sims et al., 2010).

1. Waste treatment (e.g., MSW and use of process residues (paper industry, food industry) onsite at production facilities) is generally the starting phase of a developing bioenergy system. Resources are available and often have a disposal cost (could have a negative value) making utilization profitable and simultaneously solving waste management problems. Large- and small-scale developments are evolving along with integrated resource management.

2. Local utilization of resources from forest management and agriculture. Such resources are more expensive to collect and transport, but usually still economically attractive. Infrastructure development is needed.

3. Biomass market development at regional scale; larger-scale conversion units with increasing fuel flexibility are deployed; increasing average transport distances further improves economies of scale. Increasing costs of biomass supplies make more energy-efficient conversion facilities necessary as well as feasible. Policy support measures such as feed-in tariffs (FITs) are usually needed to develop into this stage.

4. Development of national markets with increasing numbers of suppliers and buyers; creation of a marketplace; increasingly complex logistics. Availability often increases due to improved supply systems and access to markets. Price levels may therefore decrease (see, e.g., Junginger et al., 2005).

5. Increasing scale of markets and transport distances, including cross-border transport of biofuels; international trade in biomass resources (and energy carriers derived from biomass). Biomass is increasingly becoming a globally traded energy commodity (see, e.g., Junginger et al., 2008). Bio-ethanol trade has come closest to that situation (see, e.g., Walter et al., 2008).

6. Growing role for dedicated fuel supply systems (biomass production largely or only for energy purposes). So far, most energy crops are grown because of agricultural interests and support (subsidies for farmers, use of set-aside subsidies), which concentrate on oil crops (such as rapeseed) and surplus food crops (cereals and sugar beets).

Countries that have gained substantial commercial experience with biomass supplies and biomass markets are generally able to obtain substantial cost reductions in biomass supply chains over time. In Finland and Sweden, delivery costs decreased from USD_{2005} 12 to 5/GJ from 1975 to 2003, due to factors such as scale increases, technological innovations or increased competition (Junginger et al., 2005). Similar trends are observed in the corn ethanol industry in the USA and the sugarcane ethanol industry in Brazil (see Table 2.17).

Analyses of regional and international biomass supply chains show that road transport of untreated and bulky biomass becomes uncompetitive and energy-inefficient when crossing distances of 50 to 150 km (Dornburg and Faaij, 2001; McKeough et al., 2005). When long-distance transport is required, early pretreatment and densification in the supply chain (see Sections 2.3.2.3 and 2.6.2) pays off to minimize transport costs. Taking into account energy use and related GHG emissions, well-organized logistic chains can require less than 10% of the initial energy content of the biomass (Hamelinck et al., 2005b; Damen and Faaij, 2006), but this requires substantial scale in transport, efficient pretreatment and minimization of road transport of untreated biomass.

Such organization is observed in the rapidly developing international wood pellet markets (see Sections 2.3.2.3 and 2.4.4). Furthermore, (long distance) transport costs of liquid fuels such as ethanol and vegetable oils contribute only a minor fraction of overall costs and energy use of bioenergy chains (Hamelinck et al., 2005b).

2.3.2.2 Solid biomass and charcoal supplies in developing countries

The majority of poorest households in the developing world depend on solid biomass fuels such as charcoal for cooking, and millions of small industries (such as brick and pottery kilns) generate process heat from these fuels (FAO, 2010a; IEA, 2010b; see Section 1.4.1.2). Despite this pivotal role of biomass, the sector remains largely unregulated, poorly understood, and the supply chains are predominantly in the hands of the informal sector (Sepp, 2008).

When fuelwood is marketed, trees are usually felled and cut into large pieces and transported to local storage facilities where they are collected by merchants and delivered to wholesale and retail facilities, mainly in rural areas. Some of the wood is converted to charcoal in kilns, packed into large bags and transported by hand, animal-drawn carts and small trucks to roadside sites where it is collected by trucks and sent to urban wholesale and retail sites. Thus charcoal making is an enterprise for rural populations to supply urban markets. Crop residues and dung are normally used by animal owners as a seasonal supplement to fuelwood (FAO 2010a).

Shredded biomass residues may be densified by briquetting or pelletizing, typically in screw or piston presses that compress and extrude the biomass (FAO, 1985). Briquettes and pellets can be good substitutes for coal, lignite and fuelwood because they are renewable and have consistent quality and size, better thermal efficiency, and higher density than loose biomass.

There are briquetting plants in operation in India and Thailand, using a range of secondary residues and with different capacities, but none as yet in other Asian countries. There have been numerous, mostly development agency-funded, briquetting projects in Africa, and most have failed technically and/or commercially. The reasons for failure include deployment of new test units that were not proven technically, selection of very expensive machines that did not make economic sense given the location, low local capacity to fabricate components and provide maintenance, and lack of markets for the briquettes due to uncompetitive cost and low acceptance (Erikson and Prior, 1990).

Wood pellets are made of wood waste such as sawdust and grinding dust. Pelletization machines are based on fodder-making technology and produce somewhat lighter and smaller pellets of biomass compared to briquetting. Wood pellets are easy to handle and burn because their shape and characteristics are uniform, transportation efficiency is high and energy density is high. Wood pellets are used as fuel in many countries for cooking and heating applications (Peksa-Blanchard et al., 2007).

Chips are mainly produced from plantations' waste wood and wood residues (branches and presently even spruce stumps) as a by-product of conventional forestry. They require less processing and are cheaper than pellets. Depending on end use, chips may be produced onsite, or the wood may be transported to the chipper. Chips are commonly used in automated heating systems, and can be used directly in coal-fired power stations or for CHP production (Fagernäs et al., 2006).

Charcoal is obtained by heating woody biomass to high temperatures in the absence of oxygen, and has a twice higher calorific value than the original feedstock. It burns without smoke and has a low bulk density, which reduces transport costs. In rural areas in many African countries, charcoal is produced in traditional kilns with efficiencies as low as 10% (Adam, 2009), and typically sold to urban households while rural households use fuelwood. Hardwoods are the most suitable raw material for charcoal, because softwoods incur possibly high losses during handling/transport. Charcoal from granular materials like coffee shells, sawdust and straw is in powder form and needs to be briquetted with or without a binder. Charcoal is also used in large-scale industries, particularly in Brazil from high-yielding eucalyptus plantations (Scolforo, 2008), and in many cases, in conjunction with sustainably produced wood, and also increasingly as a co-firing feedstock in oil-based electric power plants. The projected costs for charcoal production from Brazilian eucalyptus plantations are USD_{2005} 5.7 to 9.8/GJ (Fallot et al., 2009) using industrial carbonizing process.

Charcoal in Africa is predominantly produced in inefficient traditional kilns in the informal sector, often illegally. Current production, packaging and transport of charcoal are characterized by low efficiencies and poor handling, leading to losses. Introducing change to this industry requires that it be recognized and legalized, where it is found to be sustainable and not contradictory to environmental protection goals. Once legalized, it would be possible to regulate it and introduce standards addressing fuel quality, packaging and production kiln standards and better enforcement of which tree species should be used to produce charcoal (Kituyi, 2004).

2.3.2.3 Wood pellet logistics and supplies

Wood pellets are one of the most successful bioenergy-based commodities traded internationally. Wood pellets offer several advantages over other solid biomass fuels: they generally have a low moisture content and a relatively high heating value (about 17 GJ/t), which allow long-distance transport by ship without affecting the energy balance (Junginger et al., 2008). Local transport is carried out by trucks, which sets a feasible upper limit for transportation of 50 km for raw biomass (150 km for pellets) and together with the necessary storage usually represents more than 50% of the final cost. Bulk delivery of pellets is very similar to delivery of home heating oil and is carried out by the lorry driver blowing pellets into the storage space, while a suction pump takes away any dust. Storage solutions include underground tanks, container units, silos or storage within the boiler room. Design of more efficient pellet storage, charging and combustion systems for domestic users is ongoing (Peksa-Blanchard et al., 2007). International trade by ships to ports that are properly equipped for handling pellets is a major logistical barrier.[10] Freight costs are another barrier very sensitive to international trade demand. For instance, in 2004, the average price of pellets at a mill in Canada was USD_{2005} 3.4/GJ; shipped to the Netherlands, USD_{2005} 4.1/GJ (Free on Board); and delivered to the Rotterdam harbour, USD_{2005} 7.5/GJ (Junginger et al., 2008; see also Sikkema et al., 2011).

2.3.3 Conversion technologies to electricity, heat, and liquid and gaseous fuels

Commercial bioenergy routes are shown in Figure 2.6 and start with feedstocks such as forest- or agriculture-based crops or industrial, commercial or municipal waste streams and by-products. These routes deliver electricity or heat from biomass directly or as CHP, biogas and liquid biofuels, including ethanol from sugarcane or corn and biodiesel from oilseed crops. Current biomass-based commercial processes produce a limited range of liquid fuels compared to the variety of petroleum-based fuels and products.

Figure 2.2 presented a complex set of developing technological options based on second- (lignocellulosic herbaceous or woody species) and higher- (aquatic plants) generation feedstocks and a variety of second- (or higher-) generation conversion processes.[11] It also included the commercial (Figure 2.6) first-generation (oil, sugar and starch crops) and solid biomass feedstocks and conversion processes (fermentation, transesterification, combustion, gasification, pyrolysis and anaerobic digestion). Second-generation feedstocks and conversion processes can produce higher-efficiency electricity and heat, as well as a wider range of liquid hydrocarbon fuels, alcohols (including some with higher energy density), ethers, chemical products and polymers (biobased materials) in the developing biorefineries that are discussed in more detail in Section 2.6.3.4. Initial R&D on producing hydrocarbon fuels is starting with sugar and starch crops and covers the range of gasoline, diesel and jet fuel with an increasing focus on chemicals. Both improved first-generation crops (e.g., perennial sugarcane-derived) and second-generation plants suited to specific geographic regions have the potential to provide a variety of energy products, along with high-volume chemicals and materials traditionally derived from the petrochemical industry, maximizing the outputs of end products per unit of feedstock.

10 In most countries with export potential, ports are not yet equipped with storage and modern handling equipment or are poorly managed, which implies high shipping costs.

11 Biofuels produced via new processes are also called advanced or next-genereation biofuels, e.g. from lignocellulosic biomass.

2.3.3.1 Development stages of conversion technologies

The development stages of selected thermochemical, biochemical and chemical routes from solid lignocellulosic biomass, wet waste streams, sugars from sugarcane or starch crops, and vegetable oils are shown in Table 2.5 for the production of heat, power and fuels. For instance, while biomass combustion coupled with electricity generators such as turbines using steam cycles is a commercial system for electricity production (or CHP), coupling with the Stirling engine is still developing, and the Organic Rankine Cycle (ORC) is just starting commercial penetration (van Loo and Koppejan, 2002). Generally, solid wood or waste biomass is processed by thermochemical routes, and wet feedstocks and sugar or starch crops are processed biochemically or chemically and, in the case of the vegetable oils, after a mechanical pressing step (Bauen et al., 2009a). The development stages are roughly divided into R&D, demonstration, early commercial and full commercial products and processes. Precise allocation to these different stages is difficult and somewhat arbitrary, because many developments are taking place in industry and are not often documented in the peer-reviewed literature (Regalbuto, 2009; Bacovsky et al., 2010a,b). Usually, those processes that are deployable throughout the world are fully commercial technologies because their technical risk is small and financing can be obtained (Kirkels and Verbong, 2011).

Synergies between biomass industries and waste management are already established and additional synergies are evolving with the petroleum refining, chemicals, natural gas and coal industries (King et al., 2010; Kirkels and Verbong, 2011). Many bioenergy systems that are moving towards commercialization still have a high technical risk. Section 2.6.3 will describe these additional advancing conversion processes in more detail.

2.3.3.2 Thermochemical processes

Biomass combustion is a process where carbon and hydrogen in the fuel react with excess oxygen to form CO_2 and water and release heat. Direct burning of biomass is popular in rural areas for cooking. Wood and charcoal are also used as a fuel in the industry. Combustion processes are well understood and a wide range of existing commercial technologies are tailored to the characteristics of the biomass and the scale of their applications. Biomass can also be co-combusted with coal in coal-fired plants (van Loo and Koppejan, 2002; Faaij, 2006; Egsgaard et al., 2009).

Pyrolysis is the thermal decomposition of biomass occurring in the absence of oxygen (anaerobic environment) that produces a solid (charcoal), a liquid (pyrolysis oil or bio-oil) and a gas product. The relative amounts of the three co-products depend on the operating temperature and the residence time used in the process. High heating rates of the biomass feedstocks at moderate temperatures (450°C to 550°C) result in oxygenated oils as the major products (70 to 80%), with the remainder split between a biochar and gases. Slow pyrolysis (also known

Table 2.5 | Examples of stages of development of bioenergy: thermochemical (orange), biochemical (blue), and chemical routes (red) for heat, power, and liquid and gaseous fuels from solid lignocellulosic and wet waste biomass streams, sugars from sugarcane or starch crops, and vegetable oils (IEA Bioenergy, 2009; Alper and Stephanopoulos, 2009; Regalbuto, 2009).

Type of Plant	Type of Product	Process	Stage of Development of Process for Product(s) or System(s): Basic and Applied R&D	Demonstration	Early Commercial	Commercial
Low Moisture Lignocellulosic	Densified Biomass		Torrefaction	Hydrothermal Oil (Hy Oil)	Pyrolysis Oil (Py Oil)	Pelletization
	Charcoal			Pyrolysis (Biochar)		Carbonization
	Heat				Small Scale Gasification	Combustion Stoves
		Combustion			Py/Hy Oil	Home/District/Industrial
	Power or CHP	Combustion Coupled with		Stirling Engine	ORC[1]	Steam Cycles
		Co-Combustion or Co-Firing with Coal		Indirect	Parallel	Direct
		Gasification (G) or Integrated Gasification (IG)		IG-Fuel Cell IG-Gas Turbine		
				IG-Combined Cycle	G and Steam Cycle	
Wet Waste	Heat or Power or Fuel	Anaerobic Digestion to Biogas		2-Stage		Landfills (1-Stage)
			Microbial Fuel Cell		Reforming to Hydrogen (H_2)	Small Manure Digesters
					Biogas Upgrading to Methane	
				Hydrothemal Processing to Oils or Gaseous Fuels		
Sugar or Starch Crops	Fuels	Sugar Fermentation		Butanol		Ethanol
		Microbial Processing[2]	H_2; Gasoline/ Diesel/ Jet Fuel	Biobutanol/Butanols[3]		
Vegetable or Waste Oils		Extraction and Esterification				Biodiesel
		Extraction and Hydrogenation			Renewable Diesel	
		Extraction and Refining		Jet Fuel		

Notes: 1. ORC: Organic Rankine Cycle; 2. genetically engineered yeasts or bacteria to make, for instance, isobutanol (or hydrocarbons) developed either with tools of synthetic biology or through metabolic engineering. 3. Several four-carbon alcohols are possible and isobutanol is a key chemical building block for gasoline, diesel, kerosene and jet fuel and other products.

as carbonization) is practiced throughout the world, for example, in traditional stoves in developing countries, in barbecues in Western countries, and in the Brazilian steel industry (Bridgwater et al., 2003; Laird et al., 2009).

Biomass Gasification occurs when a partial oxidation of biomass happens upon heating. This produces a combustible gas mixture (called producer gas or fuel gas) rich in CO and hydrogen (H_2) that has an energy content of 5 to 20 MJ/Nm^3 (depending on the type of biomass and whether gasification is conducted with air, oxygen or through indirect heating). This energy content is roughly 10 to 45% of the heating value of natural gas. Fuel gas can then be upgraded to a higher-quality gas mixture called biomass synthesis gas or syngas (Faaij, 2006). A gas turbine, a boiler or a steam turbine are options to employ unconverted gas fractions for electricity co-production. Coupled with electricity generators, syngas can be used as a fuel in place of diesel in suitably designed or adapted internal combustion engines. Most commonly available gasifiers use wood or woody biomass and specially designed gasifiers can convert non-woody biomass materials (Yokoyama and Matsumura, 2008). Biomass gasifier stoves are also being used in many rural industries for heating and drying, for instance, in India and China (Yokoyama and Matsumura, 2008; Mukunda et al., 2010). Compared to combustion, gasification is more efficient, providing better controlled heating, higher efficiencies in power production and the possibility for co-producing chemicals and fuels (Kirkels and Verbong, 2011).

2.3.3.3 Chemical processes

Transesterification is the process through which alcohols (often methanol) react in the presence of a catalyst (acid or base) with triglycerides contained in vegetable oils or animal fats to form an alkyl ester of fatty acids and a glycerine by-product. Vegetable oil is extracted from the seeds, usually with mechanical crushing or chemical solvents prior to transesterification. The fatty acid alkyl esters are typically referred to as 'biodiesel' and can be blended with petroleum-based diesel fuel. The protein-rich residue, also known as cake, is typically sold as animal feed or fertilizer, but may also be used to synthesize higher-value chemicals (WWI, 2006; Bauen et al., 2009a; Demirbas, 2009; Balat, 2011).

The **hydrogenation** of vegetable oil, animal fats or recycled oils in the presence of a catalyst yields a renewable diesel fuel—hydrocarbons that can be blended in any proportion with petroleum-based diesel and propane as products. This process involves reacting vegetable oil or animal fats with H_2 (typically sourced from an oil refinery) in the presence of a catalyst (Bauen et al., 2009a). Although at an earlier stage of development and deployment than transesterification, hydrogenation of vegetable oils and animal fats can still be considered a first-generation route as it is demonstrated at a commercial scale.[12] Hydrogenated biofuels have a high cetane number, low sulphur content and high viscosity (Knothe, 2010).

2.3.3.4 Biochemical processes

Biochemical processes use a variety of microorganisms to perform reactions under milder conditions and typically with greater specificity compared to thermochemical processes. These reactions can be part of the organisms' metabolic functions or they can be modified for a specific product through metabolic engineering (Alper and Stephanopoulos, 2009). For instance, *fermentation* is the process by which microorganisms such as yeasts metabolize sugars under low or no oxygen to produce ethanol. Among bacteria, the most commonly employed is *Escherichia (E.) coli*, often used to perform industrial synthesis of biochemical products, including ethanol, lactic acid and others. *Saccharomyces cerevisiae* is the most common yeast used for industrial ethanol production from sugars. The major raw feedstocks for biochemical conversion today are sugarcane, sweet sorghum, sugar beet and starch crops (such as corn, wheat or cassava) and the major commercial product from this process is ethanol, which is predominantly used as a gasoline substitute in light-duty transport.

Anaerobic digestion (AD) involves the breakdown of organic matter in agricultural feedstocks such as animal dung, human excreta, leafy plant materials, urban solid and liquid wastes, or food processing waste streams by a consortium of microorganisms in the absence of oxygen to produce biogas, a mixture of methane (50 to 70%) and CO_2. In this process, the organic fraction of the waste is segregated and fed into a closed container (biogas digester). In the digester, the segregated biomass undergoes biodegradation in the presence of methanogenic bacteria under anaerobic conditions, producing methane-rich biogas and effluent. The biogas can be used either for cooking and heating or for generating motive power or power through dual-fuel or gas engines, low-pressure gas turbines, or steam turbines. The biogas can also be upgraded through enrichment to a higher heat content biomethane (85 to 90% methane) gas and injected in the natural gas grid (Bauen et al., 2009a; Petersson and Wellinger, 2009). The residue from AD, after stabilization, can be used as an organic soil amendment or a fertilizer. The residue can be sold as manure depending upon the composition of the input waste.

Many developing countries, for example India and China, are making use of AD technology extensively in rural areas. Many German and Swedish companies are market leaders in large biogas plant technologies (Faaij, 2006; Petersson and Wellinger, 2009). In Sweden, multiple wastes and manures (co-digestion) are also used and the biogas is upgraded to biomethane, a higher methane content gas, which can be distributed via natural gas pipelines and can also be used directly in vehicles.[13]

2.3.4 Bioenergy systems and chains: Existing state-of-the-art systems

Literature examples of relevant commercial bioenergy systems operating in various countries today by type of energy product(s), feedstock, major process, current and estimated future (2020 to 2030) efficiency, and estimated current and future (2020) production costs are presented in Tables 2.6 and 2.7. Current markets and potential are reviewed in Section 2.4.

Production costs presented in Tables 2.6 and 2.7 are taken directly from the available literature with no attempt to harmonize the literature data because the underlying techno-economic parameters are not always sufficiently transparent to assess the specific conditions under which

12 Many companies throughout the world have patents, demonstration plants, and have tested this technology at a commercial scale for diesel, including Neste Oil's commercial facility in Singapore (Bauen et al., 2009a; Bacovsky et al., 2010b).

13 See, for instance, the Linköping example at www.iea-biogas.net/_download/linkoping_final.pdf (IEA Bioenergy Task 37 success story).

comparable production costs can be achieved, except in cases analyzing multiple products. Section 2.7 presents complementary information on the levelized costs of various bioenergy systems and discusses specific cost determinants based on the methods specified in Annex II and the assumptions summarized in Annex II (note that only a few of the underlying assumptions included in Tables 2.6 and 2.7 were used as inputs to the data presented in Annex III).

2.3.4.1 Bioenergy chains for power, combined heat and power, and heat

Liquid biofuels from biomass have higher production costs than solid biomass (at USD_{2005} ~2 to 5/GJ) used for heat and power. Unprocessed solid biomass is less costly than pre-processed types (via densification, e.g., delivered wood pellets at USD_{2005} 10 to 20/GJ), but entails higher logistic costs and is a reason why both types of solid biomass markets developed (Sections 2.3.2.2 and 2.3.2.3). Because of economies of scale, some of the specific technologies that have proven successful at a large scale (such as combustion for electricity generation) cannot be directly applied to small-scale applications in a cost-effective fashion, making it necessary to identify suitable alternative technologies, usually adapting existing technologies used with carbonaceous fuels. This is the case for ORC technologies, which are entering the commercial stage, and Stirling engine technologies, which are still in developmental phase, or moving from combustion to gasification, coupled to an engine (IEA, 2008a).

An intermediate liquid fuel from pyrolysis is part of evolving heating and power in co-firing applications because it is a transportable fuel (see Table 2.6) and is under investigation for stationary power and for upgrading to transport fuel (see Sections 2.3.3.2 and 2.6.3.1). Pyrolysis oils are a commercial source of low-volume specialty chemicals (see Bridgwater et al., 2003, 2007).

Many bioenergy chains employ cogeneration in their systems where the heat generated as a by-product of power generation is used as steam to meet process heating requirements, with an overall efficiency of 60% or even higher (over 90%) in some cases (IEA, 2008a; Williams et al., 2009). Technologies available for high-temperature/high-pressure steam generation using bagasse as a fuel, for example, make it possible for sugar mills to operate at higher levels of energy efficiency and generate more electricity than what they require. Sugarcane bagasse and now increasingly sugarcane field residues from cane mechanical harvesting are used for process heat and power (Maués, 2007; Macedo et al., 2008; Dantas et al., 2009; Seabra et al., 2010) to such an extent that in 2009, 5% of Brazil's electricity was provided by bagasse cogeneration (EPE, 2010). Similarly, black liquor, an organic pulping product containing pulping chemicals, is produced in the paper and pulp industry and is being burnt efficiently in boilers to produce energy that is then used as process heat (Faaij, 2006). Cogeneration-based district heating in Nordic and European countries is also very popular.

A significant number of electricity generation routes are available, including co-combustion (co-firing) with non-biomass fuels, which is a relatively efficient use of solid biomass compared to direct combustion. Due to economies of scale, small-scale plants usually provide heat and electricity at a higher production cost than do larger systems, although that varies somewhat with location. Heat and power systems are available in a variety of sizes and with high efficiency. Biomass gasification currently provides an annual supply of about 1.4 GW_{th} in industrial applications, CHP and co-firing (Kirkels and Verbong, 2011). Small-scale systems ranging from cooking stoves and anaerobic digestion systems to small gasifiers have been improving in efficiency over time. Several European countries are developing digestion systems using a mixture of solid biomass, municipal waste and manures, producing either electricity or high-quality methane. At the smallest scales, the primary use of biomass is for lighting, heating and cooking (see Table 2.6).

Many region-specific factors determine the production costs of bioenergy carriers, including land and labour costs, biomass distribution density, and seasonal variation. Also, other markets and applications partly determine the value of biomass. For many bioenergy systems, biomass supply costs represent a considerable proportion of total production costs. The scale of biofuel conversion technologies, local legislation and environmental standards can also differ considerably from country to country. Even the operation of conversion systems (e.g., load factor) varies, depending on, for example, climatic conditions (e.g., winter district heating) or crop harvesting cycles (e.g., sugarcane harvest cycles and climate impact). The result is a wide range of production costs that varies not only by technology and resource type, but also by numerous regional and local factors (see examples of such ranges in Section 2.7 and Annex III).

2.3.4.2 Bioenergy chains for liquid transport fuels

Bioenergy chains for liquid transportation fuels are similarly diverse and are described below under three subsections: (1) integrated ethanol, power, and sugar from sugarcane; (2) ethanol and fodder products; and (3) biodiesel. Also covered here are 2008 to 2009 biofuels production costs by feedstock and region. Though liquid biofuels are mainly used in the transport sector, in many developing and in some developed countries they are also used to generate electricity or peak power.

Integrated ethanol, power and sugar from sugarcane
Ethanol from sugarcane is primarily made from pressed juices and molasses or from by-products of sugar mills. The fermentation takes place in single-batch, fed-batch or continuous processes, the latter becoming widespread and being more efficient because yeasts can be recycled. The ethanol content in the fermented liquor is 7 to 10% in Brazil (BNDES/CGEE, 2008), and is subsequently distilled to increase purity to about 93%. To be blended with gasoline in most applications,

Table 2.6 | Current and projected estimated production costs and efficiencies of bioenergy chains at various scales in world regions for power, heat, and biomethane from wastes directly taken from available literature data.

Feedstock/ Country/ Region	Major Process	Efficiency, Application and Production Costs; Eff. = bioenergy/biomass energy Component costs in USD_{2005}/GJ	Estimated Production Costs USD_{2005}/GJ US $cents_{2005}$/kWh	Potential Advances USD_{2005}/GJ US $cents_{2005}$/kWh
Wood log, residues, chips/ Ag. Wastes/ Worldwide	Co-combustion with coal	5 to 100 MW_e, Eff. ~30 to 40%.[1,2] >50 power plants operated or carried on experimental operation using wood logs/ residues, of which 16 are operational and using coal. More than 20 pulverized coal plants in operation.[3] Wood chips (straw) used in at least 5 (10) operating power plants in co-firing with coal.[3]	8.1 – 15 2.9 – 5.3 Inv. Cost (USD/kW): 100 – 1,300[1]	Reduce fuel cost by improved pretreatment, characterization and measurement methods.[4] Torrefied biomass is a solid uniform product with low moisture and high energy content and more suitable for co-firing in pulverized coal plants.[3] Cost reduction and corrosion-resistant materials for coal plant needed.[5]
Wood log, residues, chips/ Ag. Wastes/ Worldwide	Direct combustion	10 to 100 MW_e, Eff. ~20 to 40%.[1,2] Well deployed in Scandinavia and North America; various advanced concepts give high efficiency, low costs and high flexibility.[2] Major variable is biomass supply costs.[2]	20 – 25 7.2 – 9.2 Inv. Cost (USD/kW): 1,600 – 2,500[1]	U.S. 2020 cost projections:[6] 6.3 – 7.8 Stoker fired boilers: 7.5 – 8.1
MSW/ Worldwide	Direct combustion (gasification and co-combustion with coal	50 to 400 MW_e, Eff. ~22%, due to low-temperature steam to avoid corrosion.[7,8] Commercially deployed incineration has higher capital costs and lower (average) efficiency.[2] Four coal-based plants co-fire MSW.[3]	9.1 – 26 3.3 – 9.4[7]	New CHP plant designs using MSW are expected to reach 28 to 30% electrical efficiency, and above 85 to 90% overall efficiency in CHP.[8]
Wood/ Ag. Wastes/ Worldwide	Small scale/gas engine gasification	5 to 10 MW_e, Eff. ~15 to 30%.[1,2] First-generation concepts prove capital intensive.[2]	29 – 38 10 – 14 Inv. Cost (USD/kW): 2,500 – 5,600[1]	Increased efficiency of the gasification and performance of the integrated system. Decrease tars and emissions.[1]
Wood pellets/ EU	Direct coal co-firing or co-gasification	12.5 to 300 MW_e.[9] Used in 2 operating power plants in co-firing with coal.[3] Costs highly dependent on shipment size and distances.[9]	14 – 36 5.0 – 13[9,10]	See PELLETS@LAS Pellet Handbook and www.pelletsatlas.info.
Pyrolysis oil /EU	Coal co-combustion/ gasification	12.5 to 1,200 MW_e.[9] Costs highly dependent on shipment size and distances.[9]	19 – 42 7.0 – 15[9,10]	Develop direct conventional oil refinery integrated and/or upgrading processes allowing for direct use in diesel blends.[1]
Fuelwood/ Mostly in developing countries	Combustion for heat	0.005 to 0.05 MW_{th}, Eff. ~10 to 20%.[2] Traditional devices are inefficient and generate indoor pollution. Improved cook stoves are available that reduce fuel use (up to 60%) and cut 70% of indoor pollution. Residential use (cooking) application.[2]	Inv. Cost (USD/kW): 100[2]	New stoves with 35 to 50% efficiency also reduce indoor air pollution more than 90%.[2] See Section 2.5.7.2.
		1 to 5 MW_{th}, Eff. ~70 to 90% for modern furnaces.[2] Existing industries have highly polluting low-efficiency kilns.[11]	Inv. Cost (USD/kW): 300 – 800[2]	More widespread use of improved kilns to cut consumption by 50 to 60% and reduce pollution.[11]
Organic Waste/MSW/ Worldwide	Landfill with methane recovery	Eff. ~10 to 15% (electricity).[2] Widely applied for electricity and part of waste treatment policies of many countries.[2]	Biogas: 1.3 – 1.7[12]	Continued efficiency increases are expected.
Organic Waste/MSW/ Manures/ Sweden/ EU in expansion	Anaerobic co-digestion, gas clean up, compression, and distribution	Widely applied for homogeneous wet organic waste streams and waste water.[2] To a lesser extent used for heterogeneous wet wastes such as organic domestic wastes.[2]	Fuel: 2.4 – 6.6[13] Elec.: 48 – 59[1] 17 – 21[1]	Improvements in biomass pretreatment, the biogas cleansing processes, the thermophilic process, and biological digestion (already at R&D stage).[1, 17]
		Costs do not include credits for sale of fertilizer by-product.[14]	Fuel: 15 – 16 Inv. Cost (USD/kW): 13,000[14]	In commercial use in Sweden, other EU countries. State of California study shows potential for the augmentation of natural gas distribution.[14]
Manures/ Worldwide	Household digestion	Cooking, heating and electricity applications. By-product liquid fertilizer credit possible.	1 to 2 years payback time	Large reductions in costs by using geomembranes. Improved designs and reduction in digestion times.[15]

Continued next Page →

Feedstock/ Country/ Region	Major Process	Efficiency, Application and Production Costs; Eff. = bioenergy/biomass energy Component costs in USD_{2005}/GJ	Estimated Production Costs USD_{2005}/GJ US $cents_{2005}$/kWh	Potential Advances USD_{2005}/GJ US $cents_{2005}$/kWh
Manures/Finland	Farms	Biogas from farms 0.018 to 0.050 MW_e.[16]	Elec.: 77 – 110 Inv. Cost (USD/kW): 14000 – 23000[16]	Improved designs and reduction in digestion times. Improvements in the understanding of anaerobic digestion, metagenomics of complex consortia of microorganisms.[12]
Manures/Food residues	Farms/Food Industry	Biogas from farm animal residues and food processing residues at 0.15 to 0.29 MW_e.[16]	Elec.: 70 – 89 Inv. Cost (USD/kW): 12000 – 15000[16]	

Abbreviations: Inv. = Investment; Elec. = Electricity. References: 1. Bauen et al. (2009a); 2. IEA Bioenergy (2007); 3. Cremers (2009) (see IEA co-firing database at www.ieabcc.nl/database/cofiring.php); 4. Econ Poyry (2008); 5. Egsgaard et al. (2009); 6. NRC (2009b); 7. Koukouzas et al. (2008); 8. IEA (2008a); 9. Hamelinck (2004); 10. Uslu et al. (2008); 11. REN21 (2007); 12. Cirne et al. (2007); 13. Sustainable Transport Solutions (2006); 14. Krich et al. (2005); 15. Müller, (2007); 16. Kuuva and Ruska (2009); 17. Petersson and Wellinger, 2009.

ethanol should be anhydrous and the mixture has to be further dehydrated to reach a grade of 99.8 to 99.9% (WWI, 2006).

Ethanol and fodder products

The dominant dry mill (or dry grind) process (88% of US production) for ethanol fuel manufactured from corn starts with hammer milling the whole grain into a coarse flour, which is cooked into a slurry, then hydrolyzed with alpha amylase enzymes to form dextrins, next hydrolyzed by gluco-amylases to form glucose that is finally fermented by yeasts (the last two processes can be combined). The byproduct is distillers' grains with solubles, an animal feed (McAloon et al., 2000; Rendleman and Shapouri, 2007) that can be sold wet to feedlots near the biorefinery or be dried for stabilization and sold. The most common source of process heat is natural gas. From the early 1980s to 2005, the energy intensity of average dry mill plants in North America has been reduced by 14% for every cumulative doubling of production (learning rate, see Table 2.17; Hettinga et al., 2007, 2009). Since then, 10 cumulative doublings (see also Section 2.7.2) have occurred and the industry continues to improve its energy performance with, for instance, CHP ((S&T)[2] Consultants, 2009). The impacts of this and other process improvements have been estimated to continue such that, by 2022, the projected production cost is USD_{2005} 16/GJ, reduced from USD_{2005} 17.5/GJ in 2009 (EPA, 2010). Table 2.7 presents examples of process improvements from membrane separation for ethanol to enzymes operating at lower temperature, etc. A similar process to corn dry milling is wheat-to-ethanol processing, starting with a malting step, and either enzyme or acid hydrolysis leading to sugars for fermentation.

Biodiesel

Biodiesel is produced from oil seed crops like rapeseed or soybeans, or from trees such as oil seed palms. It is also produced from a variety of greases and wastes from cooking oils or animal fats. This wide range of feedstocks, from low-cost wastes to more expensive vegetable oils, produces biodiesel fuels with more variable properties that follow those of the starting oil seed plant. Fuel standards' harmonization is still under development as are a variety of non-edible oil seed plants (Knothe, 2010; Balat, 2011). Examples of producing regions are shown in Figure 2.7.

Snapshot of 2008 to 2009 biofuels costs from multiple feedstocks and world regions

A snapshot of ranges of biofuels production costs for 2008 to 2009 (primarily 2009) is shown in Figure 2.7 for various world regions based on a variety of feedstocks including wastes and processing streams from the manufacture of sugar (molasses). The snapshot is based on various literature sources such as the recent comparison of costs for Asian Pacific Economic Countries (Milbrandt and Overend, 2008, updated),[14] and data from Table 2.7.[15] For production volumes of these countries see Figure 2.9. For ethanol production, feedstock costs represent about 60 to 80% of the total production cost while, for biodiesel from oil seeds, the proportion is higher (80 to 90%) (data from 2008 to 2009). Latin and Central American sugarcane ethanol is found to have had the lowest production costs over this period, followed by Asian, Pacific and North American starch crops, then by European Union (EU) sugar beet and finally EU grains. Molasses production costs are lower in India and Pacific countries than in Other Asia countries. For biodiesel production, Latin America has the lowest costs, followed by Other Asia countries palm oil, Other Asia rapeseed and soybean, and then North American soybean and EU rapeseed. Biodiesel production costs are generally somewhat higher than for ethanol, but can reach those of ethanol for countries with higher-productivity plants or a lower cost base such as Indonesia/Malaysia and Argentina.

There is significant room for feedstock improvement, mainly its productivity (see also Section 2.6.1), and also for its conversion to products based on the projected increases in efficiency shown in Table 2.7. In an analysis of US biofuel production, the US Environmental Protection Agency (EPA) projected costs based on the Forest and Agricultural Sector Optimization Model (FASOM) and found significant room for improvement (see

14 The study addressed biofuels production, feedstock availability, economics, refuelling infrastructure, use of alternative fuel vehicles, trade, and policies.

15 The ranges of production costs shown here include a variety of waste streams and feedstocks with a broader geographic distribution than those summarized in Section 2.7 and detailed in Annex III. Data in Annex III cover broad ranges of a few feedstocks varying their costs, investment capital, co-products, and financial assumptions. From these transparent techno-economic data, it is possible for the reader to change assumptions and recalculate approximate production costs in specific regions.

Table 2.7 | Current and projected estimated production costs and efficiencies of commercial biofuels in various countries directly taken from available literature data. Also provided is the range of direct reductions of GHG emissions from these routes compared to the fossil fuel replaced (see Section 2.5 for detailed GHG emissions discussion). Parts A and B address ethanol and biodiesel fuels, respectively.

A: Ethanol

Feedstock/ Process	Country/ Region	Efficiency, Application and Production Costs; Eff. = bioenergy/ biomass energy Component costs in USD_{2005}/GJ	Estimated Production Costs USD_{2005}/GJ	Direct GHG Reduction (%) from Fossil Reference (FR)	Potential Advances in Cost Reductions and Efficiency USD_{2005}/GJ
Sugarcane pressed, juice fermented to ethanol, bagasse to process heat and power, and increasingly sale of electricity.	Brazil	Eff. ~38%,[1] ~41% (ethanol only);[2] 170 million l/yr, FC: 11.1; CC*: 3.7 w/o CR.[2]	14.8 w/o CR.[2]	79 to 86% (w/o and w/ CPC); FR: gasoline.[4]	9 – 10.[1] Eff. ~50%.[5] Mechanized harvest and efficient use of sugarcane straw and leaves.[6] Biorefineries with multiple products.[5] Improved yeasts.
	Australia	Eff. ~38%, ~41% (ethanol only), FC: 24.8; CC*: 7 w/o CR.[3]	31.8 w/o CR.[3]		
Corn grain dry milling process for ethanol, fodder (DGS) for animal feed		Eff. ~62%;[2,8] 89% of production.[5] 30% co-product feed DGS sold wet.[5,8] 250 million l/yr plant, FC: 14.1[2] – 29.4[11]; CC*: 6 and CR: 3.8 – 4.4.[2]	20–21 w/ CR[2,15,19] 17.5[5] 31 w/ CR.[11]	35 to 56% for various CPC methods; FR: gasoline 35% (system expansion); Process Heat: NG.[12,13]	Eff. ~64%.[11] Industry Eff. ~65 to 68%. Estimated production cost:16.[5,8] US projected low temperature starch enzyme hydrolysis/fermentation, corn dry fractionation, biodiesel from oil in 90% of mills, membrane ethanol separation, and CHP.[5]
	France	170 million l/yr, FC: 29.3; CC*: 10.5 and CR: 5.[11]	34.8 w/ CR.[11]	60%[9,14]	
Wheat similar to corn to ethanol, fodder (DGS)	EU (UK)	Eff. ~53 to 59%.[11,16] 250 million l/yr plant, FC: 36.2; CC*: 10.5 and CR: 6.[11]	40.7 w/ CR.[11]	40%, DGS to energy.[17] 2 to 80% w/ DGS to energy -8 to 70% w/ DGS to feed.[18]	2020 Eff. ~64%.[11]
	Australia (from waste)	30 million l/yr plant, FC: 14.4; CC*: 8.6 and CR: 0.2.[3]	22.8 w/ CR.[3]	55% wheat starch NG, 27% wheat-coal, 59% wheat w/ straw firing.[3]	
Sugar beet crushing, ferment sugar to ethanol and residue	EU (UK)	Eff. ~12%.[1,16,19] 250 million l/yr plant, FC: 21.6; CC*: 11 and CR: 8.2.[11]	24.4 w/ CR.[11]	28 to 66%, alternate co-product use.[17,18]	2020 Eff. ~15%.[1]
Cassava mashing, cooking, fermentation to ethanol	Thailand/ China	Thailand's process with 38 million l, and feed productivity 20 to 21 t/ha.[16,20,21] China ethanol plant operating at partial capacity.[22]	Thailand: 26[23]	Thailand: 45%.[24] China: 20% with anaerobic digestion energy.[25]	
Molasses by-product of sugar production	Thailand/ Australia	About 3% of molasses could be used for ethanol in Thailand. FC: 10.9 and 10; CC*: 10.1 and CR: 5.7.[23]	Thailand: 21[23] Australia: 16[3]	27 to 59% depending on co-product credit method (Australia).[26,27]	

Continued next Page →

Table 2.7; EPA, 2010). The IEA has similarly estimated cost reductions for Organisation for Economic Co-operation and Development (OECD) countries' rapeseed biodiesel by 2030 (IEA Bioenergy, 2007). Further discussions of historical and future cost expectations are provided in Section 2.7.

2.3.5 Synthesis

The key currently commercial technologies are heat production (ranging from home cooking to district heating), power generation from biomass via combustion, CHP, co-firing of biomass and fossil fuels, and first-generation liquid biofuels from oil crops (biodiesel) and sugar and starch crops (ethanol). Several bioenergy systems have been deployed competitively, most notably sugarcane ethanol and heat and power generation from wastes and residues. Other biofuels have also undergone cost and environmental impact reductions and reached significant scales but still require government subsidies.

Modern bioenergy systems involve a wide range of feedstock types, residues from agriculture and forestry, various streams of organic waste, and dedicated crops or perennial systems. Existing bioenergy systems rely mostly on wood, residues and waste for heat and power production, and agricultural crops for liquid biofuels. The economics and yields of feedstocks vary widely across world regions and feedstock types. Energy yields per unit area range from 16 to 200 GJ/ha (1.6 to 20 TJ/km^2) for

B: Biodiesel

Feedstock/ Process	Country	Efficiency, Application and Production Costs; Eff. = bioenergy/biomass energy Component costs in USD_{2005}/GJ	Estimated Production Costs USD_{2005}/GJ	Direct GHG Reduction (%) from Fossil Reference (FR)	Potential Advances in Cost Reductions and Efficiency USD_{2005}/GJ
Rape seed	Germany	Eff. ~29%; for the total system it is assumed that surpluses of straw are used for power production.[27]	31 – 50.[1]	31 to 70%, alternate co-product use.[9,17,28]	25 – 37 for OECD.[1] New methods using bio-catalysts; Supercritical alcohol processing. Heterogeneous catalysts or bio-catalysts. New uses for glycerine. Improved feedstock productivity.[30]
	France	55 GJ/ha/yr (EU), 220 million l/yr plant, FC: 40.5; CC*: 2.7 and CR: 1.7.[11]	41.5 w/ CR.[11]		
	UK	220 million l/yr plant, FC: 35.6; CC*: 4.2 and CR: 11.3.[11]	28.5 w/ CR.[11]		
Oil palm	Indonesia Malaysia Asian countries[20]	163 GJ/ha/yr. 220 million l/yr plant, FC: 25.1; CC*: 2.7 and CR: 1.7.[11]	26.1 w/ CR.[11]	35 to 66%, alternate co-product use.[31] (tropical fallow land, residue to power, good management).[28]	
Vegetable oils	109 countries	Costs neglect some countries with high production costs. FC: 0.6 – 21; CC*: 2.3 – 3.7 and CR: 0 – 6.2.[3,11,29]	4.2 – 17.9.[3,11,31]	N/A	US projected 2020 waste oil ester cost 14.[5] About 50 billion l projected from 119 countries.[29]

Abbreviations: *Conversion costs (CC) include investment costs and operating expenses; CR = Co-product Revenue; CPC = coproduct credit; FC = feedstock cost; FR = fossil reference; N/A = not available.

References: 1. IEA Bioenergy (2007a); 2. Tao and Aden (2009); 3. Beer and Grant 2007; 4. Macedo et al. (2008); 5. EPA (2010); 6. Seabra et al. (2010); 7. UK DfT (2003); 8. Rendleman and Shapouri (2007); 9. Bessou et al. (2010); 10. Wang et al. (2011); 11. Bauen et al. (2009a); 12. Wang et al. (2010); 13. Plevin (2009); 14. Ecobilan (2002); 15. Bain (2007); 16. Fulton et al. (2004); 17. Edwards et al. (2008); 18. Edwards et al. (2007); 19. Hamelinck (2004); 20. Koizumi and Ohga (2008); 21. Milbrandt and Overend (2008); 22. GAIN (2009a; for China); 23. GAIN (2009c; for Thailand); 24. Nguyen and Gheewala et al. (2008); 25. Leng et al. (2008); 26. Beer et al. (2001); 27. Beer et al. (2000); 28. Reinhardt et al. (2006); 29. Johnston and Holloway (2007); 30. Bhojvaid (2007); 31. Wicke et al. (2008).

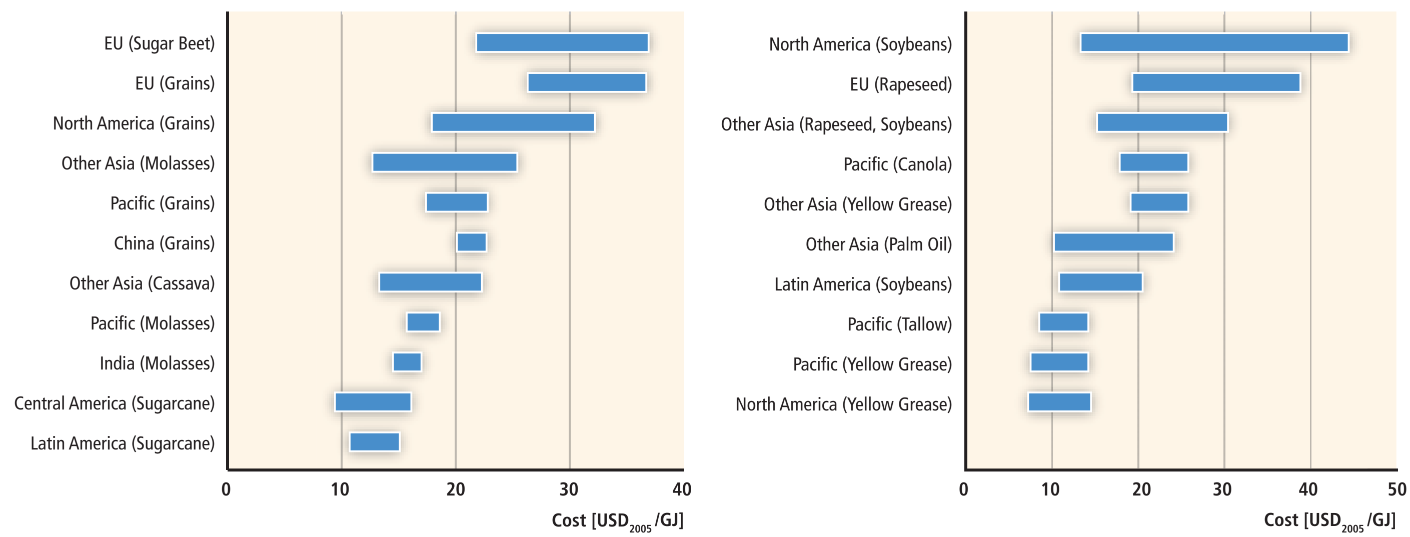


Figure 2.7 | Snapshots of regional ranges of current (2008-2009) estimated production costs for ethanol and biodiesel from various biomass feedstocks and wastes based on Milbrandt and Overend (2008) and Table 2.7.

Notes: The upper value of the range of soybean diesel in North America is due to the single point estimate of Bauen et al. (2009a). Other estimates are in the USD_{2005} 12 to 32/GJ range.

biofuel feedstocks, from 80 to 415 GJ/ha (8 to 41.5 TJ/km^2) for lignocellulosic feedstocks, and from 2 to 155 GJ/ha (0.2 to 15.5 TJ/km^2) for residues, while costs range from USD_{2005} 0.9 to 16/GJ/ha (USD_{2005} 0.09 to 1.6/TJ/km^2). Feedstock production competes with the forestry and food sectors, but the design of integrated production systems such as agro-forestry or mixed cropping may provide synergies along with additional environmental services.

Handling and transport of biomass from production sites to conversion plants may contribute 20 to 50% of the total costs of bioenergy production. Factors such as scale increases, technological innovation and increased competition have contributed to decrease the economic and energy costs of supply chains by more than 50%. Densification via pelletization or briquetting is required for transport distances over 50 km. International costs of delivering densified feedstocks are sensitive to trade and are in the USD_{2005} 10 to 20/GJ range for pellet fuels, and competitive with other market fuels in several regions, thus explaining why such markets are increasing. Charcoal made from biomass is a major fuel in developing countries, and should benefit from the adoption of higher-efficiency kilns and densification technologies.

A significant number of electricity generation routes are available and co-combustion (co-firing) is a relatively efficient way to use solid biomass compared to direct combustion. Small-scale plants usually provide heat and electricity at a higher production cost than larger systems, although this varies somewhat with location. Heat and power systems are available in a variety of sizes and efficiencies. Biomass gasification currently provides about 1.4 GW_{th} of industrial applications, CHP and co-firing. Small-scale systems ranging from cooking stoves and anaerobic digestion systems to small gasifiers have been improving in efficiency over time. Several European countries are developing digestion systems using a mixture of solid biomass, municipal waste and manures, producing either electricity or high-quality methane from upgrading. Many applications, including transport systems, are developing and have the potential to further increase their effectiveness. Technologies at small scales, primarily stoves for heating, continue to improve but diffusion is slow.

Sugarcane-, sugar beet-, and cereal grain-derived ethanol production reached a high level of energy efficiency in major producing countries such as Brazil, the USA, and the EU. The ethanol industry in Center South Brazil significantly increased its cogeneration efficiency and supplied 5% of the country's electricity in 2009. Development of ethanol from waste streams from sugar processing is occurring in India, Pacific and other Asian countries that produce relatively low-cost ethanol but with limited production volumes. Biodiesel production from waste fats and greases has a lower feedstock cost than from rapeseed and soybean but waste fat and grease volumes are limited.

Biofuel production economics is of key importance for future expansion of the biofuels industry. The future development of sustainable biofuels also depends on a balanced scorecard that includes economic, environmental, and social metrics (see Section 2.5). Resolution of technical, economic, social, environmental and regulatory issues remains critical to further development of biofuels. The development of a global market and industry is described in the next section.

2.4 Global and regional status of market and industry development

2.4.1 Current bioenergy production and outlook[16]

Biomass provides about 10% (50.3 EJ in 2008) of the annual global primary energy supply. As presented in Table 2.1, about 60% (IEA accounted) to 70% (including unaccounted informal sector) of this biomass is used in rural areas and relates to charcoal, wood, agricultural residues and manure used for cooking, lighting and space heating, generally by the poorer part of the population in developing countries. Modern bioenergy use (for power generation and CHP, heat or transport fuels) accounted for a primary biomass supply of 11.3 EJ (IEA, 2010a,b; see Table 2.1) in 2008, up from 9.6 EJ[17] in 2004 (IPCC, 2007d), and a rough estimate of 8 EJ in 2000 (IEA Bioenergy, 2007).

The use of solid biomass for energy increased at an average annual growth rate of 1.5%, but secondary energy carriers from modern biomass such as liquid and gaseous fuels increased at 12.1 and 15.4% average annual growth rates, respectively, from 1990 to 2008 (IEA, 2010a). As a result, biofuels' share of global road transport fuel use was 2% in 2008. In 2009, the production of ethanol and biodiesel increased by 10 and 9%, respectively, to 90 billion litres; biofuels provided nearly 3% of global road transport fuel use in 2009, as oil demand decreased for the first time since 1980 (IEA, 2010b). Government policies in various countries led to a five-fold increase in global biofuels production from 2000 to 2008. Biomass and renewable waste power generation was 259 TWh (0.93 EJ) in 2007 and 267 TWh (0.96 EJ) in 2008, representing 1% of the world's electricity, which doubled since 1990 (from 131 TWh or 0.47 EJ). Industrial biomass heating accounts for 8 EJ while space and water heating for building applications account for 3.4 EJ (IEA, 2010b; see Table 2.1).

Most of the increase in the use of biofuels in 2007 and 2008 occurred in the OECD, mainly in North America and Europe. Excess capacity was installed in expectation of increased demand with mandates and subsidies in many countries; however, feedstock and oil price increases and the worsening overall economic conditions during and after the credit crunch made many of these facilities unprofitable. As a result, some are underutilized, more so in biodiesel than in ethanol production. Some plants are not in operation and some businesses failed. Asia Pacific and Latin American markets are growing, primarily

16 This sub-section is largely based on the WEO 2009 (IEA, 2009b) and 2010 (IEA, 2010b) and the Global Biofuels Center assessments, web-based biofuels news, reports, trade, and market information (Hart Energy Publishing, LP, www.globalbiofuelscenter.com/).

17 The 9.6 EJ is an estimated equivalent primary biomass energy deducting the non-biogenic MSW that was included in the AR4 study (IPCC, 2007d), or about 0.4 EJ of plastics (estimated based on subsequent IEA 2005 data).

in developing countries due to economic development. Despite this anticipated short-term downturn, world use of biofuels for road transport is projected to recover in the next few years (IEA, 2010b).

The WEO (IEA, 2010b) projections for 2020 to 2035 are summarized in Table 2.8 (in terms of global TPES from biomass); Table 2.9 (in terms of global biofuel demand, i.e., secondary energy); and Table 2.10 (in terms of global electricity generation)—all of them comparing a baseline case (Current Policies) and a mitigation scenario reaching an atmospheric CO_2 concentration of 450 ppm by 2100.

The overall TPES from biomass in the 450 ppm CO_2 stabilization scenario increases to 83 (95) EJ/yr in 2030 (2035) adding 14 (12) EJ to the Reference (Current Policies) scenario (see Table 2.8).

and many of the technologies needed are at the demonstration to early commercialization stages of development in 2011 (see Tables 2.5 and 2.15; IEA Renewable Energy Division, 2010).

Global biomass and renewable waste electricity generation is also projected to increase in both scenarios, reaching 5.6% of global electricity generation by 2035 in the 450-ppm scenario as shown in Table 2.10. The climate change driver nearly doubles the anticipated penetration levels of biopower compared to the projected levels owing to continuation of current policies.

In the WEO (IEA, 2010b), biomass industrial heating applications for process steam and space and hot water heating for buildings would each double in absolute terms from 2008 levels by 2035, offsetting some of the expected decrease in the major component of the heating category, traditional biomass, as the total heating demand is projected to decrease in 2035. Industrial and building heating is seen as an area for continued biomass growth. In fact, biomass is very efficiently used in CHP plants, supplying a district heating network. Biomass combustion to produce electricity and heat in CHP plants is an efficient and mature technology and is already competitive with fossil fuels in certain locations (IEA, 2008a).

Table 2.8 | IEA WEO scenarios: global TPES from biomass projections (EJ/yr) for 2020 to 2035 (IEA, 2010b).

Year	2007	2008	2020		2030		2035	
Scenario	Actual	Actual	Baseline	450 ppm	Baseline	450 ppm	Baseline	450 ppm
EJ/yr	48	50	60	63	66	83	70	95
Delta, EJ	2		3		17		25	

Table 2.9 | IEA WEO scenarios: global biofuels demand projections (EJ/yr) for 2020 to 2035 reported in secondary energy terms of the delivered product according to IEA data (IEA, 2010b).

Year	2008	2009	2020		2030		2035	
Scenario	Actual	Actual	Baseline	450 ppm	Baseline	450 ppm	Baseline	450 ppm
EJ/yr	1.9	2.1	4.5	5.1	5.9	11.8	6.8	16.2
% Global road transport	2	3	4.4	7	4.4	11 (and air)	5	14 (and air)
% Advanced biofuels			Deployment			60		66

Table 2.10 | IEA WEO scenarios: primary biomass and renewable waste electricity generation projections for 2030 (IEA, 2009, 2010b) and 2035 (IEA, 2010b).

Year	2008	2030		2035	
Scenario	Actual	Baseline, Reference case	450 ppm Scenario	Current Policies	450 ppm Scenario
TWh/yr (EJ/yr)	267 (0.96)	825 (3.0)	1380 (5.0)	1052 (3.8)	1890 (6.8)
% Global electricity	0.96	2.4	4.5	2.7	5.6
TWh/yr (EJ/yr)		840 (3.0)	1450 (5.2)		
% Global electricity		2.4	4.8		

The use of liquid and gaseous energy carriers from modern biomass is growing, in particular biofuels, with a 37% increase from 2006 to 2009 (IEA, 2010c). Regions that currently have strong policy support for biofuels are projected to take the largest share of the eight-fold increase in the market for biofuels that occurs from 2008 to 2035. This is led by the USA (where one-third of the increase occurs), followed by Brazil, the EU and China. To highlight the scale, 7 EJ of advanced biofuels (second generation) is greater than, for example, India's 2007 oil consumption,

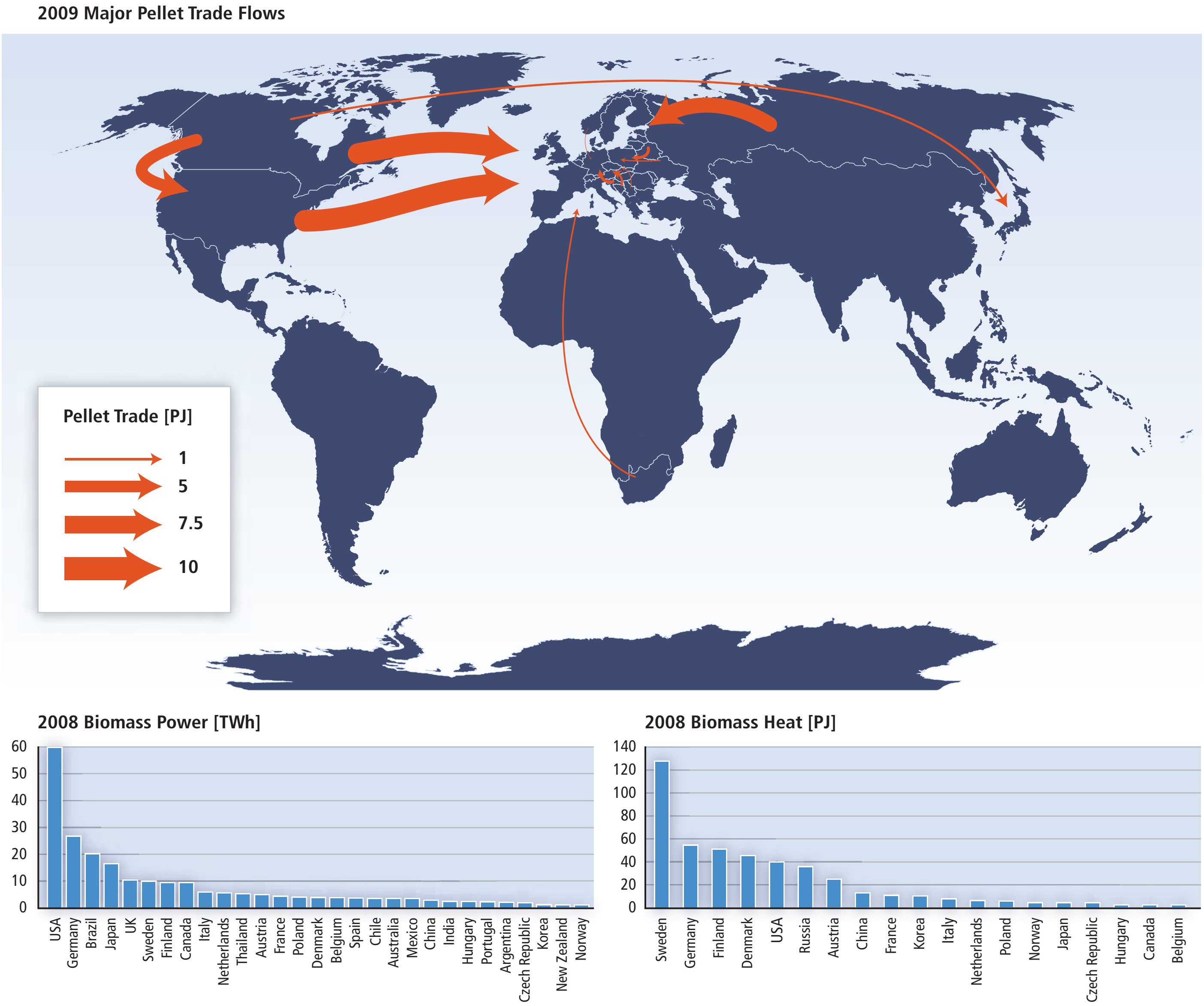


Figure 2.8 | Examples of biomass electricity generation and heating for select countries in 2008 and of the 2009 global trade in wood pellets. Sources: bar chart data from IEA (2010c); trade flow data reproduced from Sikkema et al. (2011) with permission from the Society of Chemical Industry and John Wiley & Sons, Ltd.

The use of solid biomass for electricity production is important, especially from pulp and paper plants and sugar mills. Bioenergy's share of total energy consumption is increasing in the G8 countries (e.g., co-combustion for electricity generation, building heating with pellets), especially in Germany, Italy and the UK (IEA, 2009b). The electricity generation and biomass heating are shown in Figure 2.8. Worldwide biomass heating statistics are uncertain (Sims, 2007) for developed countries. In Europe, biomass heating applications in the building sector are cost competitive and are shown in Figure 2.8. For developing countries, the statistics are less developed, as tools to collect data from informal sectors are lacking (see Table 2.1).

2.4.2 Traditional biomass, improved technologies and practices, and barriers

Biomass is an important traditional fuel in developing countries, where on average it accounts for 22% of the energy mix;[18] in the poorest countries it accounts for more than 80% (see IEA, 2010c). Traditional sources of biomass include mostly wood fuels but also agriculture residues and dung, and they contribute essentially to domestic heating and cooking. The number of people dependent on biomass for cooking is estimated at

18 Average contribution to the energy mix from renewable and waste combustibles was 48, 20, 24, 27, and 10% for Africa, Latin America, India, Non-OECD Asia, and China, respectively, while only 4% for the OECD countries in 2008 (IEA, 2010c).

2.7 billion (for 2008) and is projected to increase to 2.8 billion by 2030 (IEA, 2010b). Many thousand biomass-based small industries—such as brick making, food, charcoal, bakeries and others—provide employment and income to people. Most of these technologies are resource intensive, highly polluting and exhibit low efficiencies (see Tables 2.1 and 2.6; FAO, 2010b). However, there is currently a significant and growing market for improved technologies. Also, several programmes at the global, national and local levels are in place to disseminate more efficient technology options.

2.4.2.1 Improved biomass cook stoves

Most developing countries have initiated some type of improved cook stove (ICS) programme since the 1980s. The World Bank Energy Sector Management Assistance Program (World Bank, 2010) reviewed in depth the international experience on improved stoves and summarized significant lessons learned for developing countries and, in particular, for Bangladesh, the objective of the study. For Eastern African countries, see Karekezi and Turyareeba (1995). Many programmes are in operation, sponsored by development agencies, governments, nongovernmental organizations (NGOs) and the private sector. By the end of 2009, 173 million energy saving stoves were in use in China. Other countries were not very successful in disseminating ICS. Over the past 10 years, a whole new generation of advanced biomass stoves and dissemination approaches have been developed, and the field is now bursting with innovations (World Bank, 2010).

A variety of technologies are used, including direct combustion, small-scale gasification, small-scale anaerobic digestion, direct use of a liquid fuel (ethanol) or combinations of technologies.[19] As a result, combustion efficiency has been greatly improved relative to the alternative open fires. The cost ranges from less than USD 10 for the simpler models to more than USD 100 or more for more sophisticated models and USD 100 to 300 for institutional stoves (e.g., schools, hospitals, and barracks) according to 2007 to 2009 cost range data. Fuel savings are 30 to 60%, measured in field conditions, to more than 90%, measured in pilot testing of the most advanced models (Berrueta et al., 2008; World Bank, 2010). There are also significant reductions in GHG emissions and indoor air pollutants (Section 2.5.4).

By 2008 an estimated 820 million people (around 30% of the 2.7 billion that rely on traditional biomass for cooking, see Section 1.4.1.2) in the world were using some type of improved cook stove for cooking (Legros et al., 2009), and more than 160 stove programmes are in place worldwide, with recently launched large-scale national programmes in India, Mexico and Peru, as well as large donor-based programmes in Africa. The UN Foundation-led Global Alliance for Clean Cookstoves started in 2010 to promote the dissemination and adoption of 100 million advanced cook stoves by 2020.[20]

Two main lines of technology development have been followed. Mass-scale approaches—some of which use state-of-the-art manufacturing facilities—rely on centralized production of stoves or critical components, with distribution channels that can even include different countries. As a result, there are companies that produce more than 100,000 stoves per year (Bairiganjan et al., 2010). A second approach relies more on strengthening regional capabilities, giving more emphasis to local employment creation; sometimes the stoves are built onsite rather than sold on markets, such as the Patsari Stove in Mexico and Groupe Energies Renouvelables, Environnement et Solidarités (GERES) in Cambodia (Bairiganjan et al., 2010). Improved stove designs to appeal to consumers, market segmentation and microfinance mechanisms have also been developed (Hilman et al., 2007).

Incentives and barriers

Cookstove programmes have been successful in countries where proper assessment was made of the local needs in terms of technology, cooking devices, user needs and institutional setting. Financial incentives have helped with the dissemination, while an enabling institutional environment by governments—such as in China—has also helped promote new technologies. Finally, accurate monitoring and evaluation has been critical for successful stove adoption and use (Bairiganjan et al., 2010; Venkataraman et al., 2010). Other drivers for increased adoption of ICS have included: (1) cooking environments where users feel smoke is a health problem and annoyance; (2) a short consumer payback (few months); (3) donor or government support extended over at least five years; and (4) financial support to build local institutions and develop local expertise. Government assistance has been more effective in technical advice and quality control. Carbon offset projects are increasingly providing new financing for these activities, either through the Voluntary Market (Gold Standard) or, increasingly, through the CDM. Successful programmes with low-cost but efficient ICS report that local poor residents purchased cookstoves without support of programmes because of fuel savings (World Bank, 2010).

Several barriers need to be overcome for a rapid diffusion of ICS. There are needs for (1) substantial increases in R&D;[21] (2) more field testing and stove customization for users' needs; and (3) strict product specifications and testing and certification programmes. Finally, it is important to better understand the patterns of stove adoption given the multiple devices and fuels as well as mechanisms to foster their long-term use.

19 These ICS technologies include improvements in the combustion chamber (such as the Rocket 'elbow'), insulation materials, heat transfer ratios, stove geometry and air flow (Still et al., 2003). The most reliable of these use small electric blowers to stabilize the combustion, but there are also designs using natural air flow (World Bank, 2010).

20 See www.cleancookstoves.org.

21 Particularly for new insulating materials as well as robust designs that endure several years of rough use, and small-scale gasification.

2.4.2.2 Biogas systems

Convenient cooking and lighting are also provided by biogas production using household-scale biodigesters.[22] Biodigesters have the distinct co-benefits of enhancing the fertilizer value of the dung in addition to reducing the pathogen risks of human waste. Early stage results have been mixed because of quality control and management problems, which have resulted in a large number of failures. Smaller-scale biogas experience in Africa has been often disappointing at the household level as the capital cost, maintenance and management support required have been higher than expected. The experience gained, new technology developments (such as the use of geo-membranes), better understanding of the resources available to users, such as dung, and better market segmentation are improving the success of new programmes (Kishore et al., 2004).[23]

Incentives and barriers

Key factors for project success include a proper understanding of users' needs and resources.[24] For example, the role of NGOs, networks and associations in transfer, capacity building, extension and adoption of biogas plants in rural India was found to be very important (Myles, 2001). Financial mechanisms, including microfinance schemes and carbon offset projects under the CDM, are also important in the implementation of household biogas programmes. Barriers to increased biogas adoption include lack of proper technical standards; insufficient financial mechanisms to achieve desired profits relative to the digesters' investment, installation and equipment costs; and relatively high costs of technologies and of labour (e.g., geological investigations into proper site installations). Other related barriers include poor reliability and performance of the designs and construction, and limited application of knowledge gained from the operation of existing plants to the design of new plants.

Many other small-scale bioenergy applications are emerging, including systems aimed at transport and productive uses of energy and electricity. The market penetration is still limited, but many of these systems show important benefits in terms of livelihood, new income, revenues and efficiency (Practical Action Consulting, 2009).

22 By the end of 2009, there were 35 million household biodigesters in China and in India (Gerber, 2008; REN21, 2009, 2010). There is also significant experience with commercial biogas use in Nepal. Müller (2007) reviewed existing biogas technologies and case studies with contributions from China, Thailand, India, South Africa, Kenya, Rwanda, and Ghana.

23 For example, the high first cost (which can run up to USD 300 for some systems, including the digestion chamber unit) of traditional systems is being reduced considerably by new designs that reduce the digestion time, increase the specific methane yield and use alternate or multiple feedstocks (such as leafy material and food wastes), substantially reducing the size and cost of the digestion unit (Lehtomäki et al., 2007).

24 The Hedon Household Network provides references to the experience in the field at www.hedon.info. One example is www.hedon.info/docs/20060531_Report_(final)_on_Biogas_Experts_Network_Meeting_Hanoi.pdf.

2.4.3 Modern biomass: Large-scale systems, improved technologies and practices, and barriers

The deployment of large-scale bioenergy systems faces a wide range of barriers. Economic barriers appear most prominent for currently commercial technologies constrained by feedstock availability and by meeting sustainability requirements (Fagernäs et al., 2006; Mayfield et al., 2007), while technical barriers predominate for developing technologies such as second-generation biofuels (Cheng and Timilsina, 2010). Non-technical barriers are related to deployment policies (fiscal incentives, regulations and public finance), market creation, supply chain, infrastructure development, community engagement, collaboration and education (Mayfield et al., 2007; Adams et al., 2011). No single barrier appears to be most critical, but the interactions among different individual barriers seem to impede rapid bioenergy expansion. The relative importance of the barriers hinges on the particular value chain and context considered. In particular, national regulations, such as price-driven FITs for bioelectricity and quantity-driven blending level mandates for biofuels, play a major role in the emergence of large-scale projects, alongside public finance through government loans or guarantee programmes (Table 2.11; Section 11.5.3; Chum and Overend, 2003; Fagernäs et al., 2006). The priorities also depend on the stakeholder groups involved in the value chain and differ from feedstock producers to fuel producers and through to end users (Adams et al., 2011). Scale also matters, because barriers perceived by national governments differ from those perceived by stakeholders and communities in the vicinity of bioenergy projects.[25]

Technical and non-technical barriers may be overcome by appropriate policy frameworks, economic instruments such as government support tied to private investment support for first-of-a kind commercial plants to decrease investment risk,[26] sustained RD&D efforts, and catalysis of coordinated multiple private sector activities[27] (IATA, 2009; Regalbuto, 2009; Sims et al., 2010). In 2009, global public RD&D efforts were USD 0.6 billion and 0.2 billion for biofuels and biomass to energy, respectively, and biofuels public funding increased by 88% from 2008. Corporate RD&D efforts were USD 0.2 billion each for the two areas (UNEP/SEFI/Bloomberg, 2010). Venture capital and private equity investing was

25 For instance, the impacts of bioenergy development on landscapes are a barrier to adoption of new bioenergy conversion plants by some farmers as local acceptance decreases with increased local traffic to supply biomass (van der Horst and Evans, 2010). Some governments are more sensitive to increased efficiencies in GHG abatement and competitiveness of bioenergy with other energy sources, which often means increased scale (Adams et al., 2011) unless technologies succeed in increasing their throughput to accommodate smaller-scale applications without as large of a cost penalty (see Section 2.6.2).

26 See, for instance, the US Department of Energy's integrated biorefinery projects, including first-of-a-kind commercial plants, www1.eere.energy.gov/biomass/integrated_biorefineries.html; see also the IEA Bioenergy Task 39 interactive site with pilot, demonstration and commercial biofuels plants: biofuels.abc-energy.at/demoplants/projects/mapindex.

27 See, for instance, the European Industrial Bioenergy Initiative, a multi-industry partnership across the bioenergy value chains, www.biofuelstp.eu/eibi.html.

Table 2.11 | Key policy instruments in selected countries where E = electricity, H = heat, T = transport, Eth = ethanol and BD = biodiesel (modified after GBEP, 2008; updated with data from the REN21 global interactive map (see note 4 to Figure 2.9); reproduced with permission from GBEP).

Country	Policy Instruments							
	Binding Targets/ Mandates[1]	Voluntary Targets[1]	Direct Incentives[2]	Grants	Feed-in Tariffs	Compulsory grid connection	Sustainability Criteria	Tariffs
Brazil	E, T		T					removed
China		E, T[4]	T	E, T	E, H	E, H		n/a
India	T, (E[3])	T(BD)	E	E, H, T	E			n/a
Mexico	(E[3])	(T)	(E)			(E)		Eth
South Africa	T, E	E, (T)	(E), T					n/a
Canada	E, T, H	E[4], T[4]	T	E, H, T				Eth
France		E[3], H[3], T	E, H, T		E			as EU below
Germany	E[3], T		H	H	E	E	(E, H, T)	as EU below
Italy	E[3]	E[3], T	T	E, H, T	E	E		as EU below
Japan		E, H, T				E		Eth, B-D
Russia		(E, H, T)	(T)					n/a
UK	E[3], T[3]	E[3], T	E, H, T	E, H, T	E		T	as EU below
USA	T, T[4], E[4]	E[4]	E, H, T	E, T	E			Eth
EU	E[3], T	E[3], H[3], T	T	E, H, T		E	(T)	Eth, B-D

Notes: 1. blending or market penetration; 2. fiscal incentives: tax reductions; public finance: loan support/guarantees; 3. target applies to all RE sources; 4. target is set at a sub-national level.

estimated at USD 1.1 billion and 0.4 billion for biofuels and biomass to energy, respectively (UNEP/SEFI/Bloomberg, 2010). A significant fraction of the venture capital investment was in the USA (Curtis, 2010). There was significant first-generation biofuels industry consolidation in the USA and in Brazil. Major global oil company investments occurred in both countries and in the EU (IATA, 2009; Curtis, 2010; IEA, 2010b; UNEP/SEFI/Bloomberg, 2010).

Addressing knowledge gaps in the sustainability of bioenergy systems, as discussed in Section 2.5, is reported as crucial to enable public and private decision making and increase public acceptance. Those gaps are mostly related to feedstock production and the associated impacts on land use, biodiversity, water, and food prices (WWI, 2006; Adams et al., 2011). Other suggested R&D avenues include more sustainable feedstocks and conversion technologies (WWI, 2006), increased conversion efficiency (Cheng and Timilsina, 2010) and overall chain optimization (Fagernäs et al., 2006).

Integrating bioenergy production with other industries/sectors (such as forest, food/fodder, power, or chemical industries) should improve competitiveness and utilize raw materials more efficiently (Fagernäs et al., 2006). For instance, industrial symbiosis evolved over 50 years in the city of Kalundborg, Denmark, as a community of businesses located together on a common property voluntarily entered into several bilateral contracts to enhance environmental, economic and social performance in managing environmental and resource issues by sharing resources in close cooperation with government authorities (Grann, 1997).[28] The Kalundborg experience increased the viability of the businesses involved over the years and developed a community thinking systems approach that could be applied to many other industrial settings (Jacobsen, 2006).

2.4.4 Global trade in biomass and bioenergy

Global trade in biomass feedstocks (e.g., wood chips, raw vegetable oils, agricultural residues) and especially of energy carriers from modern

28 The latest addition is a wheat straw-to-ethanol demonstration plant to the complex of a coal power plant, an oil refinery, biotechnology companies, district heating, fish aquaculture, landfill plant with gas collection, fertilizer production, gypsum (plaster), soil remediation and water treatment facilities, and others. Waste products (e.g., heat, gas and sulphur, ash, hot water, yeasts, fertilizers, waste slurries, solid wastes) from one company become a resource for use by one or more companies, and a nearby town, in a well-functioning industrial ecosystem. (See, for instance, www.kalundborg.dk/Erhvervsliv/The_Green_Industrial_Municipality/Cluster_Biofuels_Denmark_(CBD).aspx and www.inbicon.com/Biomass Refinery/Pages/Inbicon_Biomass_Refinery_at_Kalundborg.aspx.)

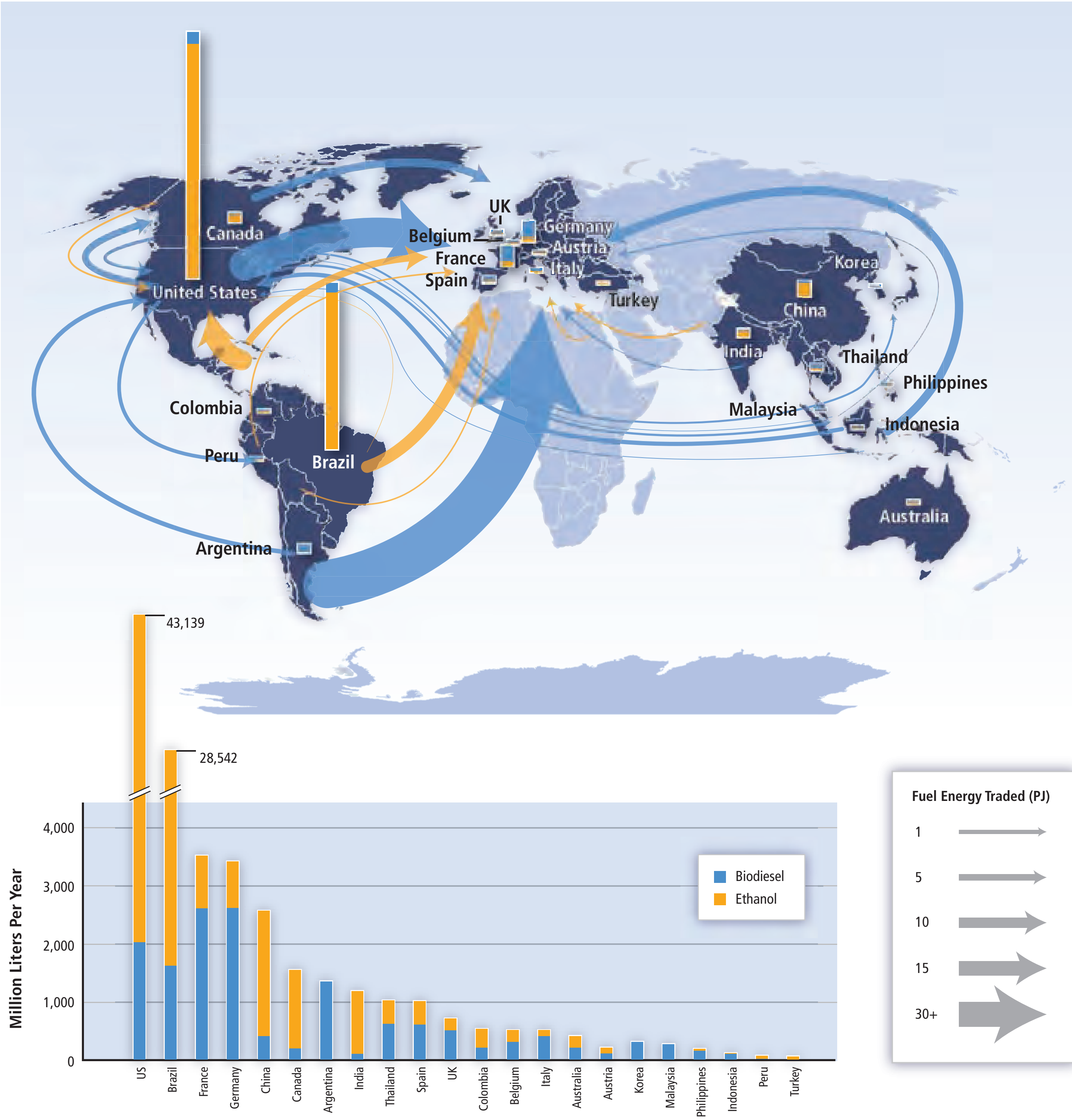


Figure 2.9 | Global biofuels production and main international trade, 2009. Biofuel volume sources: GAIN (2009a,b,[1] 2010a-j[2]); EIA (2010a); EurObserv'ER (2010); RFA (2010);[3] REN21 (2010).[4] Trade flows: Lamers et al. (2010).[5] The total intra-EU biodiesel and ethanol trade corresponds to 78 and 116 PJ, respectively (Lamers et al., 2011).

Notes: 1. Data for China and Indonesia. 2. Data for Argentina, Australia, Brazil, Canada, India, Korea, Malaysia, Peru, The Philippines, Thailand and Turkey. 3. www.ethanolrfa.org/pages/statistics. 4. See www.ren21.net/REN21Activities/ for updated information on biofuels volumes and targets for the various countries and other policy information and interactive tools (www.map.ren21.net). 5. For trade flows used in Figure 2.9 see www.chem.uu.nl/nws; for detailed data see Lamers et al. (2011).

bioenergy (e.g., ethanol, biodiesel, wood pellets) is growing rapidly. While practically no liquid biofuels or wood pellets were traded in 2000, the world net trade of liquid biofuels amounted to 120 to 130 PJ in 2009 (Figure 2.9), compared to about 75 PJ for wood pellets (Figure 2.8). Larger quantities of these products are expected to be traded internationally in the future, with Latin America and sub-Saharan Africa as potential net exporters and North America, Europe and Asia expected as net importers (Heinimö and Junginger, 2009). Trade can therefore become an important component of the sustained growth of the bioenergy sector. Figure 2.9 shows 2009 biofuels production in many countries along with the net global trade streams of bioethanol and biodiesel (see also Table 2.9). In 2008, around 9% of global biofuel production was traded internationally (Junginger et al., 2010). Production and trade of these three commodities are discussed in more detail below.

Global fuel *ethanol production* grew from around 0.375 EJ in 2000 to more than 1.6 EJ in 2009 (Lamers et al., 2011). The USA and Brazil, the two leading ethanol producers and consumers, accounted for about 85% of the world's production. In the EU, total consumption of ethanol for transport in 2009 was 94 PJ (3.6 Mt), with the largest users being France, Germany, Sweden and Spain (Lamers et al., 2011; EurObserv'ER, 2010). Data related to fuel *bioethanol trade* are imprecise on account of the various potential end uses of ethanol (i.e., fuel, industrial and beverage use) and also because of the lack of proper codes for biofuels in global trade statistics. As an estimate, a net amount of 40 to 51 PJ of fuel ethanol was traded in 2009 (Lamers et al., 2011).

World *biodiesel production* started below 20 PJ in 2000 and reached about 565 PJ in 2009 (Lamers et al., 2011). The EU produced 334 PJ (roughly two-thirds of the global production), with Germany, France, Spain and Italy being the top EU producers (EurObserv'ER, 2010). EU27 biodiesel production rates levelled off towards 2008 (FAPRI, 2009).[29] The intra-European biodiesel market has become more competitive, and the 2009 overcapacity has already led to the closure of (smaller, less vertically integrated, less efficient, remote, etc.) biodiesel plants in Germany, Austria and the UK. As shown in Figure 2.9, other main biodiesel producers include the USA, Argentina and Brazil. Biodiesel consumption in the EU amounted to about 403 PJ (8.5 Mt) (EurObserv'ER, 2010), with Germany and France consuming almost half of this amount. Net international *biodiesel trade* was below 1 PJ before 2005 but grew very fast from this small base to more than 80 PJ in 2009, as shown in Figure 2.9 (Lamers et al., 2011).

Production, consumption and trade of *wood pellets* have grown strongly within the last decade and are comparable to ethanol and biodiesel in terms of global trade volumes. As a rough estimate, in 2009, more than 13 Mt (230 PJ) of *wood pellets* were produced primarily in 30 European countries, the USA and Canada (Figure 2.8). Consumption was high in many EU countries and the USA. The largest EU consumers were Sweden (1.8 Mt or 32 PJ), Denmark, the Netherlands, Belgium, Germany and Italy (roughly 1 Mt or 18 PJ each). Main *wood pellet trade* routes lead from Canada and the USA to Europe (especially Sweden, the Netherlands and Belgium) and to the USA. In 2009, other minor trade flows were also reported, for example, from Australia, Argentina and South Africa to the EU. Canadian producers also started to export small quantities to Japan. Total imports of wood pellets by European countries in 2009 were estimated to be about 3.9 Mt (69 PJ), of which about half can be assumed to be intra-EU trade (Sikkema et al., 2010, 2011).

2.4.5 Overview of support policies for biomass and bioenergy[30]

Typical examples of support policies are shown in Table 2.11. For instance, *liquid biofuels* policies include the (former) Brazilian Proálcool programme, regulations in the form of mandates in many EU countries and the USA fiscal incentives such as tax exemptions, production tax credits and accelerated depreciation (WWI, 2007). The majority of successful policies for *heat* from biomass in recent decades have focused on more centralized applications for heat or CHP in district heating and industry (Bauen et al., 2009a). For these sectors, a combination of direct support schemes with indirect incentives has been successful in several countries, such as Sweden (Junginger, 2007). Both quota systems and FITs have been implemented in support of bioenergy *electricity* generation, though FITs have gradually become the more popular incentive. The effectiveness and efficiency of FITs and quota systems for promoting RE generation (including for bioenergy) has been thoroughly debated. A full discussion of these instruments can be found in Section 11.5.3. Next to FITs or quotas, almost all countries that have successfully stimulated bioenergy development have applied additional public finance relating to investment support and soft loans along with fiscal measures (GBEP, 2008). Additionally, grid access for renewable power is an important issue that needs to be addressed. Priority grid access for renewable sources is applied in most countries where bioenergy technologies have been successfully deployed (Sawin, 2004).

Support policies (see Table 2.11) have strongly contributed in past decades to the growth of bioenergy for electricity, heat and transport fuels. However, several reports also point out the costs and risks associated with support policies for biofuels. According to the WEO (IEA, 2010b), the annual global government support for biofuels in 2009, 2008 and 2007 was USD_{2009} 20 billion, 17.5 billion and 14 billion, respectively, with corresponding EU spending of USD_{2009} 7.9 billion, 8.0 billion and 6.3 billion and corresponding US spending of USD_{2009} 8.1 billion, 6.6 billion and 4.9 billion. The US spending was driven by energy security and fossil fuel import reduction goals. Concerns about food prices, GHG emissions and environmental impacts have also led to many countries rethinking biofuels blending targets. For example, Germany revised its blending target for 2009 downward from 6.25 to 5.25%.[31] Addressing these concerns led also to the incorporation of environmental and social

29 While most EU Member States (MS) increased their production volumes, the German biodiesel market shrunk both in supply and demand due to a change in the policy framework phasing out tax exemptions for neat biodiesel at the pump. At the same time biodiesel export to other EU MS became less and less feasible for German (and other) producers due to increasing shares of competitively priced biodiesel imports, mainly from the USA in the period from 2006 to 2008 and also from Argentina in the years 2008 and 2009 (Lamers et al., 2011).

30 Non-technology-specific policy issues are covered in Chapter 11 of this report.

31 Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit decision published on 22.10.2008 and available at www.bmu.de/pressearchiv/16_legislaturperiode/pm/42433.php.

sustainability criteria for biofuels in the EU Renewable Energy Directive. Although seemingly effective in supporting domestic farmers, the effectiveness of biofuel policies in reaching the climate change and secure energy supply objectives is coming under increasing scrutiny. It has been argued that these policies have been costly and have tended to introduce new distortions to already severely distorted and protected agricultural markets—at both domestic and global levels. This has not tended to favour an efficient international production pattern for biofuels and their feedstocks (FAO, 2008a; Bringezu et al., 2009). An overall biomass strategy would have to consider all types of use of food and non-food biomass (Bringezu et al., 2009).

The main drivers behind government support for the sector have been concerns over climate change and energy security as well as the desire to support the agricultural sector through increased demand for agricultural products (FAO, 2008a). According to the REN21 global interactive map (see note 4 to Figure 2.9) a total of 69 countries had one or several biomass support policies in place in 2009 (REN21, 2010; Section 11.2).

2.4.5.1 Intergovernmental platforms for exchange on bioenergy policies and standardization

Several multi-stakeholder initiatives exist in which policymakers can find advice, support and the possibility of exchanging experiences on policymaking for bioenergy. Examples of such international organizations and forums supporting the further development of sustainability criteria and methodological frameworks for assessing GHG mitigation benefits of bioenergy include the Global Bioenergy Partnership (GBEP from the G8+5),[32] the IEA Bioenergy Agreement,[33] the International Bioenergy Platform at the Food and Agriculture Organization (FAO),[34] the OECD Roundtable on Sustainable Development,[35] and standardization organizations such as the European Committee for Standardization[36] and the International Organization for Standardization[37] (ISO) that are actively working toward the development of sustainability standards.

32 The GBEP provides a forum to inform policy development frameworks, promote sustainable biomass and bioenergy development, facilitate investments in bioenergy, promote project development and implementation, and foster R&D and commercial bioenergy activities. Membership includes individual countries, multilateral organizations, and associations.

33 The IEA Bioenergy Agreement provides an umbrella organization and structure for a collective effort in the field of bioenergy including non-OECD countries interested in the topics from RD&D to policies. It brings together policy and decision makers and national experts from research, government and industry across the member countries.

34 See ftp.fao.org/docrep/fao/009/A0469E/A0469E00.pdf.

35 See www.oecd.org/dataoecd/14/3/46063741.pdf.

36 See www.cen.eu/cen/Sectors/TechnicalCommitteesWorkshops/CENTechnicalCommittees/Pages/default.aspx TC335 for solid biofuels standards, TC19 for liquid biofuels, and TC 383 for sustainability criteria for biofuels.

37 See www.iso.org/iso/standards_development/technical_committees/list_of_iso_technical_committees.htm TC 248 for sustainability criteria for biofuels, TC 238 for solid biofuels, TC255 for biogas, and TC 28/SC 7 for liquid biofuels.

2.4.5.2 Sustainability frameworks and standards

Governments are stressing the importance of ensuring sufficient climate change mitigation and avoiding unacceptable negative effects of bioenergy as they implement regulating instruments. For example, the Renewable Energy Directive (European Commission, 2009) provides mandatory sustainability requirements for liquid transport fuels.[38] Also, in the USA, the Renewable Fuel Standard—included in the 2007 Energy Independence and Security Act (EISA, 2007)—mandates minimum GHG reductions from renewable fuels, discourages use of food and fodder crops as feedstocks, permits use of cultivated land and estimates (indirect) LUC effects to set thresholds of GHG emission reductions for categories of fuels (EPA, 2010; see also Section 2.5). The California Low Carbon Fuel Standard set an absolute carbon intensity reduction standard and periodic evaluation of new information, for instance, on indirect land use impacts.[39] Other examples are the UK Renewable Transport Fuel Obligation, the German Biofuel Sustainability Ordinance, and the Cramer Report (The Netherlands). With the exception of Belgium, no mandatory sustainability criteria for solid biomass (e.g., wood pellets) have been implemented—the European Commission will review this at the end of 2011 (European Commission, 2010).

The development of impact assessment frameworks and sustainability criteria involves significant challenges in relation to methodology, process development and harmonization. As of a 2010 review, nearly 70 ongoing certification initiatives exist to safeguard the sustainability of agriculture and forestry products, including those used as feedstock for the production of bioenergy (van Dam et al., 2010). Within the EU, a number of initiatives started or have already set up certification schemes in order to guarantee a more sustainable cultivation of energy crops and production of energy carriers from modern biomass (e.g., ISCC[40]; REDCert[41] 2010 in Germany; or the NTA8080/8081 (NEN[42]) in the Netherlands). Many initiatives focus on the sustainability of liquid biofuels including primarily environmental principles, although some of them, such as the Council for Sustainable Biomass Production and the Better Sugarcane Initiative, the Roundtable for Sustainable Biofuels (RSB) and the Roundtable for Responsible Soy, include explicit socioeconomic impacts of bioenergy production. Principles such as those from the RSB have already led to a Biofuels Sustainability Scorecard used by the Inter-American Development Bank for the development of projects.

38 These requirements are: specific GHG emission reductions must be achieved, and the biofuels in question must not be produced from raw materials being derived from land of high value in terms of biological diversity or high carbon stocks.

39 The California Air Resources Board requires 10% absolute emissions reductions from fossil energy sources by 2020 and considers direct lifecycle emissions of the biofuels and also indirect LUC as required by legislation (CARB, 2009).

40 International Sustainability and Carbon Certification, Koeln, Germany, www.iscc-system.org/index_eng.html

41 REDcert Certification System, www.redcert.org

42 NTA 8080 - Sustainabley Produced Biomass. Dutch Normalization Institute (NEN), Delft, The Netherlands, www.sustainable-biomass.org/publicaties/3950

The proliferation of standards that has taken place over the past four years, and continues, shows that certification has the potential to influence local impacts related to the environmental and social effects of direct bioenergy production. Many of the bodies involved conclude that for an efficient certification system there is a need for further harmonization, availability of reliable data, and linking indicators at micro, meso and macro levels (see Figure 2.15). Considering the multiple spatial scales, certification should be combined with additional measurements and tools at regional, national and international levels.

The role of bioenergy production in iLUC is still uncertain; current initiatives have rarely captured impacts from iLUC in their standards, and the time scale becomes another important variable in assessing such changes (see Section 2.5.3). Addressing unwanted LUC requires overall sustainable agricultural production and good governance first of all, regardless of the end use of the product or of the feedstocks.

2.4.6 Main opportunities and barriers for the market penetration and international trade of bioenergy

2.4.6.1 Opportunities[43]

The prospects for biofuels for road transport depend on developments in competing low-carbon and oil-reducing technologies for road transport (e.g., electric vehicles). Biofuels may in the longer term be increasingly used within the aviation industry, for which high energy density carbon fuels are necessary (see Section 2.6.3), and also in marine shipping.

The development of international markets for bioenergy has become an essential driver to develop available biomass resources and market potential, which are currently underutilized in many world regions. This is true for both (available) residues as well as possibilities for dedicated biomass production (through energy crops or multifunctional systems such as agro-forestry). Export of biomass-derived commodities for the world's energy market can provide a stable and reliable income for rural communities in many (developing) countries, thus creating an important incentive and market access.[44]

Also on the demand side, large biomass users that rely on a stable supply of biomass can benefit from international bioenergy trade, as this enables (often very large) investments in infrastructure and conversion capacity.[45]

Introduction of incentives based on political decisions is a driving force and has triggered an expansion of bioenergy trade. For example, wood pellet imports in the Netherlands and Belgium have been driven respectively through a feed-in premium system and a Green Certificate system. However, the success of policies has varied, due partly to the nature of the design and implementation of the given policy but also to the fact that the institutions related to the incentives are different. For a full discussion of influencing factors outside of policies (e.g., institutions, network access), see Section 11.6.

Another driver is the utilization of established logistics for existing commodities. Taking again the example of wood pellet co-firing in large power plants, the existing infrastructure at ports and storage facilities used to supply coal and other dry bulk goods can (partially, and after adaptations) also be used for wood pellets, making cost-efficient transport and handling possible. Another form of integrated supply chain is bark, sawdust and other residues from imported roundwood, which is common in, for example, Northern Europe. Finally, the concept of regional biomass processing centres has been proposed to deal with supply side challenges and also to help address social sustainability concerns (Carolan et al., 2007).

2.4.6.2 Barriers

Major risks and barriers to deployment are found all along the bioenergy value chain and concern all final energy products (bioheat, biopower, and biofuel for transport).[46] On the supply side, there are challenges related to securing quantity, quality and price of biomass feedstock, irrespective of the origin of the feedstock (energy crops, wastes or residues). There are also technology challenges related to the varied physical properties and chemical composition of the biomass feedstock and challenges associated with the poor economics of current power and biofuel technologies at small scales. On the demand side, the main challenges are the stability and supportiveness of policy frameworks and investors' confidence in the sector and its technologies, in particular to overcome financing challenges associated with demonstrating the reliable operation of new technologies at commercial scale.[47] In the power and heat sectors, competition with other RE sources may also be an issue. Public acceptance and public perception are also critical factors in gaining support for energy crop production and bioenergy facilities.

Specifically for the bioenergy trade, Junginger et al. (2010) identified a number of (potential) barriers:

Tariffs. As of January 2007, import tariffs apply in many countries, especially for ethanol and biodiesel. Tariffs (expressed in local currency and year) are applied on bioethanol imports by both the EU (€ 0.192 per litre) and the USA (USD 0.1427 per litre and an additional 2.5%

43 This sub-section is largely based on Junginger et al. (2008).

44 Exports of ethanol from Brazil and wood pellets from Canada are examples where export opportunities (at least partially) were drivers to further develop the supply side.

45 Utilities in the Netherlands and Belgium import large amounts of wood pellets to co-fire with coal, as domestic biomass resources are very limited and of varying quality.

46 Most of the remainder of this paragraph is based on Bauen et al. (2009a).

47 Some governments have jointly financed first-of-a-kind commercial technological development with the private sector in the past five years, but the financial crisis is making it difficult to complete the private financing needed to continue to obtain government financing.

ad valorem subsidy). In general, the most-favoured nation tariffs range from roughly 6 to 50% on an ad valorem equivalent basis in the OECD, and up to 186% in the case of India (Steenblik, 2007). Biodiesel used to be subject to lower import tariffs than bioethanol, ranging from 0% in Switzerland to 6.5% in the EU and the USA (Steenblik, 2007). However, in July 2009, the European Commission confirmed a five-year temporary imposition of anti-dumping and anti-subsidy rights on American biodiesel imports, with fees standing between € 213 and 409 per tonne (local currency and year) (EurObserv'ER, 2010). These trade tariffs were a reaction to the so-called 'splash-and-dash' practice, in which biodiesel blended with a 'splash' of fossil diesel was eligible for a USD 1 per gallon subsidy (equivalent to USD 300/t) in 2008-2009; see Lamers et al. (2011) for detailed information on the various tariffs, trade regimes, and policies worldwide.

Technical standards describe in detail the physical and chemical properties of fuels. Regulations pertaining to the technical characteristics of liquid transport fuels (including biofuels) exist in all countries. These have been established in large part to ensure the safety of the fuels and to protect consumers from buying fuels that could damage their vehicles' engines. Regulations include maximum percentages of biofuels that can be blended with petroleum fuels and regulations pertaining to the technical characteristics of the biofuels themselves. In the case of biodiesel, the latter may depend on the vegetable oils used for the production, and thus regulations might be used to favour biodiesel from domestic feedstocks over biodiesel from imported feedstocks. Technical barriers for the bioethanol trade also exist. For example, the different demands for maximum water content have negative impacts on trade. However, in practice, most market actors have indicated that they see technical standards as an opportunity enabling international trade rather than as a barrier (Junginger et al., 2010).

Sustainability criteria and biomass and biofuels certification have been developed in increasing numbers in recent years as voluntary or mandatory systems (see Section 2.4.5.2); such criteria, so far, do not apply to conventional fossil fuels. Three major concerns in relation to the international bioenergy trade are:

1. Criteria, especially those related to environmental and social issues, could be too stringent or inappropriate to local environmental and technological conditions in producing developing countries (van Dam et al., 2010). The fear of many developing countries is that if the selected criteria are too strict or are based on the prevailing conditions in the countries setting up the certification schemes, only producers from those countries may be able to meet the criteria, and thus these criteria may act as trade barriers. As the criteria are extremely diverse, ranging from purely commercial aims to rainforest protection, there is a danger that a compromise could result in overly detailed rules that lead to compliance difficulties, or, on the other hand, in standards so general that they become meaningless. Implementing binding requirements is also limited by World Trade Organization rules.

2. With current developments by the European Commission, different European governments, several private sector initiatives, and initiatives of round tables and NGOs, there is a risk that in the short term a multitude of different and partially incompatible systems will arise, creating trade barriers (van Dam et al., 2010). If they are not developed globally or with clear rules for mutual recognition, such a multitude of systems could potentially become a major barrier for international bioenergy trade instead of promoting the use of sustainable biofuels production. A lack of transparency in the development of some methodologies, for example, in the EU legislation, is an issue. Also, the eventual existence of different demands for proving compliance with the criteria for locally produced biomass sources and imported ones is a potential barrier. Finally, lack of international systems may cause market distortions.

   Production of 'uncertified' biofuel feedstocks will continue and enter other markets in countries with lower standards or for non-biofuel applications that may not have the same standards. The existence of a 'two-tier' system would result in failure to achieve the safeguards envisaged (particularly for LUC and socioeconomic impacts).

3. Finally, note that to ensure that biomass commodities are being produced in a sustainable manner, some chain of custody (CoC) method must be used to track biomass and biofuels from production to end use. Generally, the three types of CoC methods are segregation (also known as track-and-trace), book-and-claim and mass-balance. While this is not necessarily a major barrier, it may cause additional cost and administrative burdens.

Logistics are a pivotal part of the system and essential to set up biomass fuel supply chains for large-scale biomass systems. Various studies have shown that long-distance international transport by ship is feasible in terms of energy use and transportation costs (e.g., Sikkema et al., 2010, 2011), but availability of suitable vessels and meteorological conditions (e.g., winter in Scandinavia and Russia) need to be considered. One logistical barrier is a general lack of technically mature technologies to densify biomass at low cost to facilitate transport, although technologies are being developed (Sections 2.3.2 and 2.6.2).

Sanitary and phytosanitary (SPS) measures may be faced by feedstocks for liquid biofuels or technical regulations applied at borders. SPS measures mainly affect feedstocks that, because of their biological origin, can carry pests or pathogens. One of the most common SPS measures is a limit on pesticide residues. Meeting pesticide residue limits is usually not difficult but on occasion has led to the rejection of imported shipments of crop products, especially from developing countries (Steenblik, 2007).

2.4.7 Synthesis

The review of developments in biomass use, markets and policy shows that bioenergy has seen rapid developments over the past years. The use of modern biomass for liquid and gaseous energy carriers is growing, in particular biofuels (with a 37% increase from 2006 to 2009). Projections from the IEA, among others, but also many national targets, count on biomass delivering a substantial increase in the share of RE. International trade in biomass and biofuels has also become much more important over recent years, with roughly 6% (reaching levels of up to 9% in 2008) of biofuels (ethanol and biodiesel only), and one-third of all pellet production for energy use, traded internationally in 2009. Pellets have proven to be an important facilitating factor in both increasing utilization of biomass in regions where supplies are constrained as well as mobilizing resources from areas where demand is lacking. Nevertheless, many barriers remain to developing well-working commodity trading of biomass and biofuels that at the same time meets sustainability criteria.

The policy context for bioenergy, and in particular biofuels, in many countries has changed rapidly and dramatically in recent years. The debate on food versus fuel competition and the growing concerns about other conflicts have resulted in a strong push for the development and implementation of sustainability criteria and frameworks as well as changes in temporization of targets for bioenergy and biofuels. Furthermore, the support for advanced biorefinery and second-generation biofuel options is driving bioenergy in more sustainable directions.

Persistent policy and stable policy support has been a key factor in building biomass production capacity and working markets, required infrastructure and conversion capacity that gets more competitive over time. These conditions have led to the success of the Brazilian programme to the point that ethanol production costs are lower than those of gasoline. Brazil achieved an energy portfolio mix that is substantially renewable and that minimized foreign oil imports. Sweden, Finland, and Denmark also have shown significant growth in renewable electricity and in management of integrated resources, which steadily resulted in innovations such as industrial symbiosis of collocated industries. The USA has been able to quickly ramp up production with the alignment of national and sub-national policies for power in the 1980s and for biofuels in the 1990s to present, as petroleum prices and instability in key producing countries increased; however, as oil prices decreased, policy support and bioenergy production decreased for biopower and is increasing again with environmental policies and sub-national targets.

Countries differ in their priorities, approaches, technology choices and support schemes for further development of bioenergy. Although this means increased complexity of the bioenergy market, this also reflects the many aspects that affect bioenergy deployment—agriculture and land use, energy policy and security, rural development and environmental policies. Priorities, stage of development and geographic access to the resources, and their availability and costs differ widely from country to country.

As policies surrounding bioenergy and biofuels become more holistic, using sustainability demands as a starting point is becoming an overall trend. This is true for the EU, the USA and China, but also for many developing countries such as Mozambique and Tanzania. This is a positive development but is by no means settled (see also Section 2.5). The 70 initiatives registered worldwide by 2009 to develop and implement sustainability frameworks and certification systems for bioenergy and biofuels, as well as agriculture and forestry, can lead to a fragmentation of efforts (van Dam et al., 2010). The needs for harmonization and for international and multilateral collaboration and dialogue are widely stressed at present.

2.5 Environmental and social impacts[48]

Recent studies have highlighted both positive and negative environmental and socioeconomic effects of bioenergy and the associated agriculture and forestry LUC (IPCC, 2000b; Millennium Ecosystem Assessment, 2005). Like conventional agriculture and forestry systems, bioenergy can exacerbate soil and vegetation degradation associated with overexploitation of forests, too intensive crop and forest residue removal, and water overuse (Koh and Ghazoul, 2008; Robertson et al., 2008). Diversion of crops or land into bioenergy production can influence food commodity prices and food security (Headey and Fan, 2008). With proper operational management, the positive effects can include enhanced biodiversity (C. Baum et al., 2009; Schulz et al., 2009), soil carbon increases and improved soil productivity (Tilman et al., 2006a; S. Baum et al., 2009), reduced shallow landslides and local flash floods, reduced wind and water erosion and reduced sediment volume and nutrients transported into river systems (Börjesson and Berndes, 2006). For forests, bioenergy can improve growth and productivity, improve site conditions for replanting and reduce wildfire risk (Dymond et al., 2010). However, forest residue harvesting can have negative impacts such as the loss of coarse woody debris that provides essential habitat for forest species.

Biofuels derived from purpose-grown agricultural feedstocks are water intensive (see Section 9.3.4.4 for comparisons of renewable and nonrenewable power sources; Berndes, 2002; King and Weber, 2008; Chiu et al., 2009; Dominguez-Faus et al., 2009; Gerbens-Leenes et al., 2009; Wu et al., 2009; Fingerman et al., 2010). Their influence on water resources and the wider hydrologic cycle depends on where, when and how the biofuel feedstock is produced. Among different bioenergy supply chains, across the spectrum of feedstocks, cultivation systems and conversion technologies, water demand varies greatly (Wu et al., 2009; Fingerman et al., 2010, De La Torre Ugarte, et al., 2010). While biofuel made from irrigated crops requires extraction of large volumes of water from lakes, rivers and aquifers, use of agricultural or forestry residues as bioenergy feedstocks does not generally require much additional land or water. Rain-fed feedstock production does not require water extraction from

48 A comprehensive assessment of social and environmental impacts of all RE sources covered in this report can be found in Chapter 9.

water bodies, but it can still reduce downstream water availability by redirecting precipitation from runoff and groundwater recharge to crop evapotranspiration. Using water for bioenergy has very different social and ecological consequences depending upon the state of the resource base from which that water was drawn.

Few universal conclusions about the socioeconomic and environmental implications of bioenergy can currently be drawn, given the multitude of rapidly evolving bioenergy sources, the complexities of physical, chemical and biological conversion processes, the multiple energy products, and the variability in environmental conditions. Thus, the positive and negative effects of bioenergy are a function of the socioeconomic and institutional context, the types of lands and feedstocks used, the scale of bioenergy programmes and production practices, the conversion processes, and the rate of implementation (e.g., Kartha et al., 2006; Firbank, 2008; E. Gallagher, 2008; OECD-FAO, 2008; Royal Society, 2008; UNEP, 2008b; Howarth et al., 2009; Pacca and Moreira, 2009; Purdon et al., 2009; Rowe et al., 2008).

Bioenergy system impact assessments (IAs) must be compared to the IAs of replaced systems.[49] The methodologies and underlying assumptions for assessing environmental (Sections 2.5.1 through 2.5.6) and socioeconomic (Section 2.5.7) effects (see Table 2.12 for examples of these impacts) differ greatly and therefore the conclusions reached by these studies are inconsistent (H. Kim et al., 2009). One particular challenge for socioeconomic IAs is that their boundaries are difficult to quantify and are a complex composite of numerous interrelated factors, many of which are poorly understood or unknown. Social processes have feedbacks that are difficult to clearly define with an acceptable level of confidence. Environmental IAs include many quantifiable impact categories but still lack data and are uncertain in many areas. The outcome of an environmental IA depends on methodological choices, which are not yet standardized or uniformly applied throughout the world.

2.5.1 Environmental effects

Studies of environmental effects, including those focused on energy balances and GHG emission balances, usually employ methodologies in line with the principles, framework, requirements and guidelines in the ISO 14040:2006 and 14044:2006 standards for Life Cycle Assessment (LCA) discussed in Section 9.3.4.1. An earlier specific method for assessing GHG balances of biomass and bioenergy systems was developed by Schlamadinger et al. (1997).

Key issues for bioenergy LCAs are system definition including spatial and dynamic boundaries, functional units, reference system, and the selection of methods for considering energy and material flows across system boundaries (Soimakallio et al., 2009a; Cherubini and Strømman, 2010). As part of cascading cycles, many processes create multiple products; for example, biomass is used to produce biomaterials while co-products and the biomaterial itself are used for energy after their useful life (Dornburg and Faaij, 2005). Such cascading results in significant data and methodological challenges because environmental effects can be distributed over several decades and in different geographical locations (Cherubini et al., 2009b).

Most of the assumptions and data used in LCA studies of existing bioenergy systems are related to first-generation biofuels and to conditions and practices in Europe or the USA, although studies are becoming available for Brazil, China and other countries (see examples in Tables 2.7, 2.13, and 2.15). Ongoing development of biomass production and conversion technologies makes many of these studies of commercial technologies outdated.[50] LCA studies of prospective bioenergy options involve projections of technology performance and have relatively greater uncertainties (see, e.g., Figure 9.9). The way that uncertainties

Table 2.12 | Environmental and socioeconomic impacts of bioenergy: example areas of concern with selected impact categories (synthesized from the literature review by van Dam et al., 2010).

Example areas of concern	Examples of impact categories
Global, regional, off-site environmental effects	GHGs; albedo; acidification; eutrophication; water availability and quality; regional air quality
Local/onsite environmental effects	Soil quality; local air quality; water availability and quality; biodiversity and habitat loss
Technology	Hazards; emissions; congestion; safety; genetically modified organisms/plants
Human rights and working conditions	Freedom of association; access to social security; job creation and average wages; freedom from discrimination; no child labour and minimum age of workers; freedom of labour (no forced labour); rights of indigenous people; acknowledgment of gender issues
Health and safety	Impacts on workers and users; safety conditions at work
Food security	Replacement of staple crops; safeguarding local food security
Land and property rights	Acknowledgment of customary and legal rights of land owners; proof of ownership; compensation systems available; agreements by consent
Participation and well-being of local communities	Cultural and religious values; contribution to local economy and activities; compensation for use of traditional knowledge; support to local education; local procurement of services and inputs; special measures to target vulnerable groups

49 A 'rebound effect' could be included, usually fossil fuels, but also other primary energy sources (Barker et al., 2009).

50 For instance, using a 2006 reference that analyzed an industrial system in 2002 will not represent the industry in 2010 because learning occurred in commercial technologies that exhibited a significant accumulation of production volume such as in the USA and in Brazil; an example of wide-spread adoption of a different technology in this industry is the USA where dry milling has become the major route to ethanol production (see Sections 2.3.4 and 2.7.2).

and parameter sensitivities are handled across the supply chain to fuel production significantly impacts the results (Sections 2.5.2 through 2.5.6). Studies combining several LCA models and/or Monte Carlo analysis provide bioenergy system uncertainties and levels of confidence for some bioenergy options (e.g., Soimakallio et al., 2009b; Hsu et al., 2010; Spatari and MacLean, 2010).

Most bioenergy system LCAs are designated as attributional to the defined process system boundaries. Consequential LCAs analyze bioenergy systems beyond these boundaries, in the context of the economic interactions, chains of cause and effect in bioenergy production and use, and effects of policies or other initiatives that increase bioenergy production and use. Consequential LCAs can investigate systemic responses to bioenergy expansion (e.g., how the food system changes if increasing volumes of cereals are used as biofuel feedstock or how petroleum markets respond if increased biofuels production results in reduced petroleum demand—see Section 2.5.3 and Figure 2.13). The outcome of *any* measure to reduce a certain use can be affected by a rebound effect—in the case of bioenergy, if increased production of solid, liquid and gaseous biofuels leads to lower demand for fossil fuels, this in turn could lead to lower fossil fuel prices and increased fossil fuel demand (Rajagopal et al., 2011; Stoft, 2010).[51] Similarly, when considering co-products, LCAs should ideally model displacement of alternative products as a dynamic result of market interactions. Consequential LCAs therefore require auxiliary tools such as economic equilibrium models.

2.5.2 Modern bioenergy: Climate change excluding land use change effects

The ranges of GHG emissions for bioenergy systems and their fossil alternatives per unit energy output are shown in Figure 2.10 for several uses (transport, power, heat) calculated based on LCA methodologies (land use-related net changes in carbon stocks and land management impacts

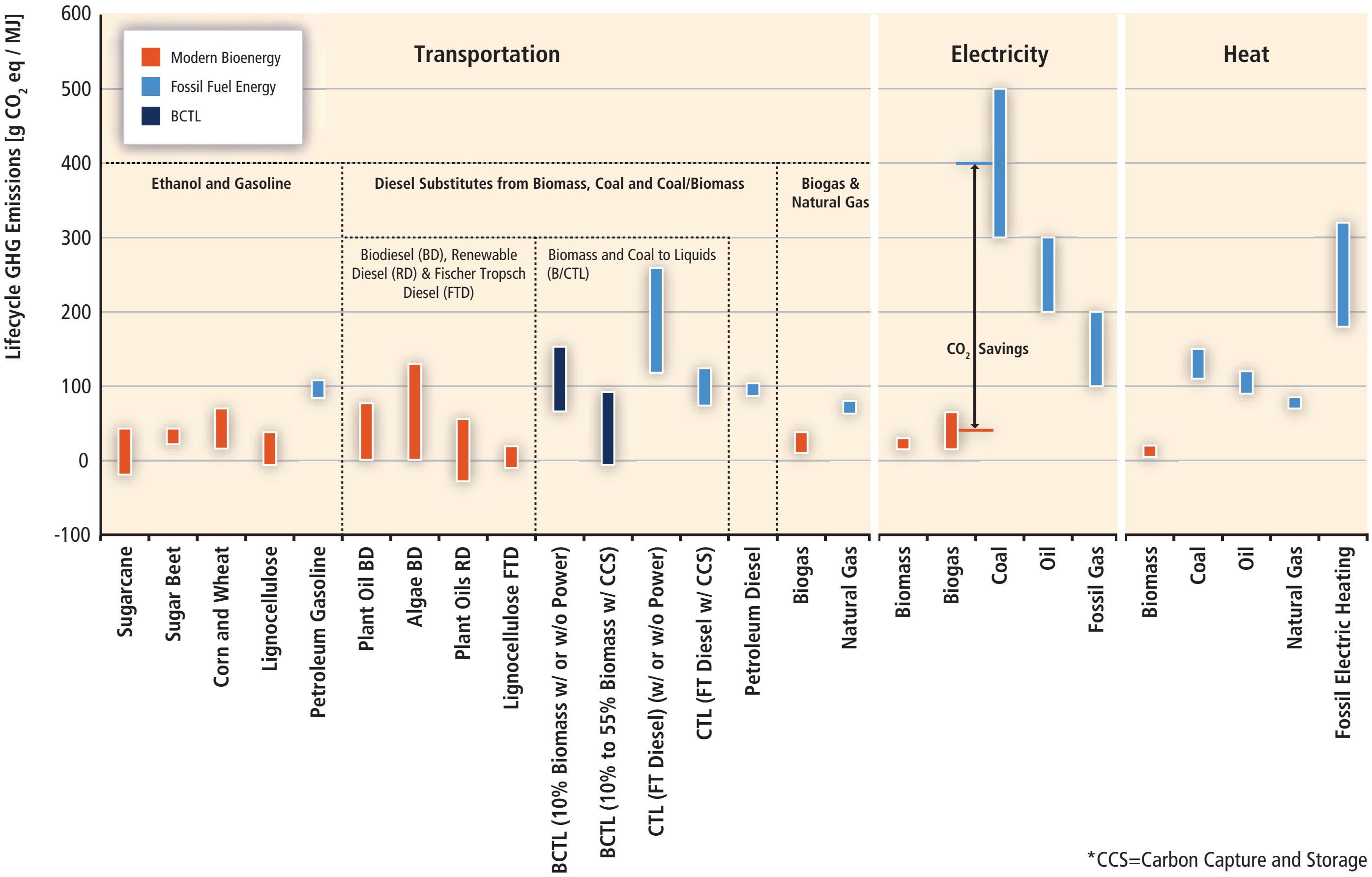


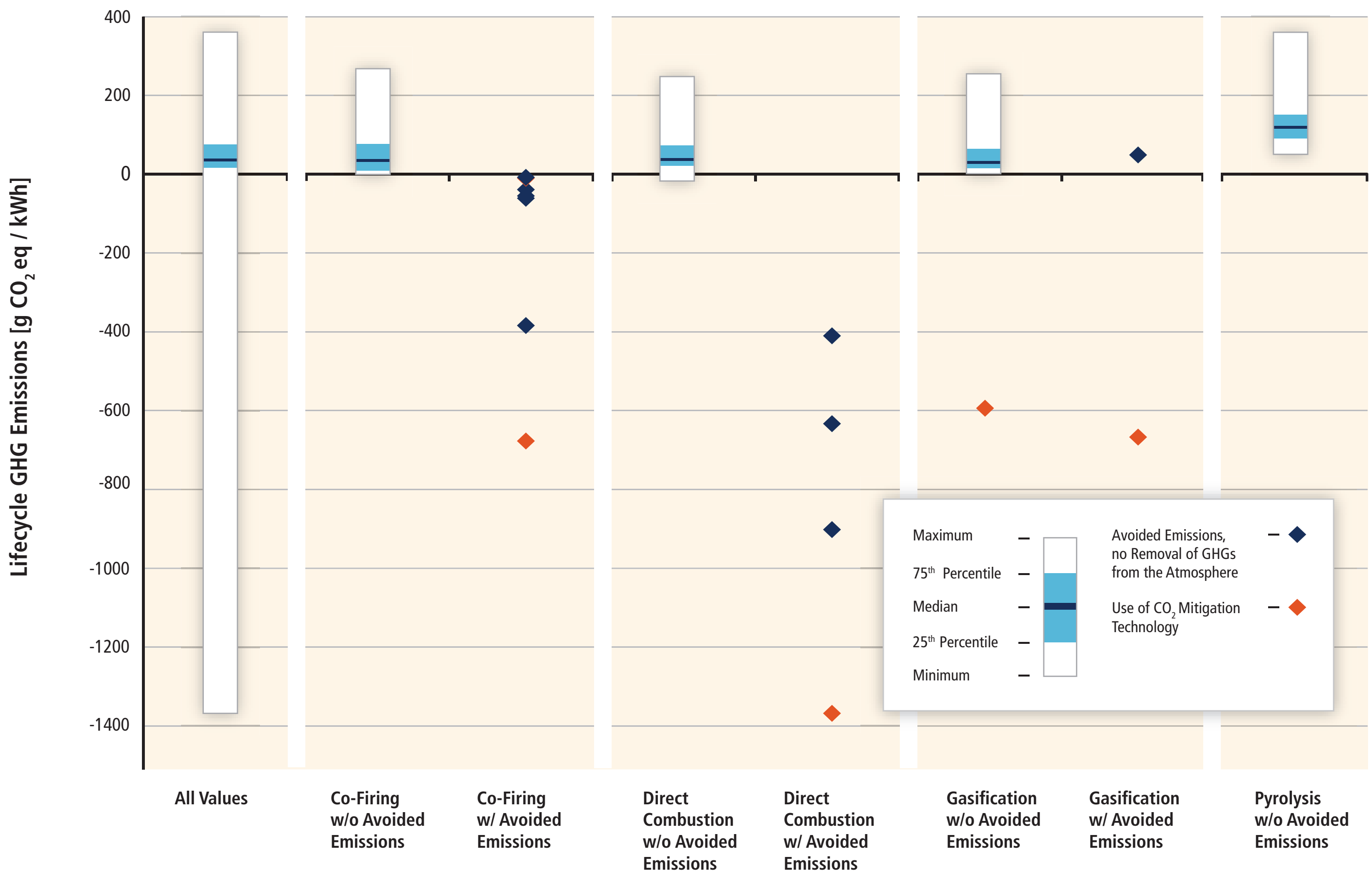
Figure 2.10 | Ranges of GHG emissions per unit energy output (MJ) from major modern bioenergy chains compared to conventional and selected advanced fossil fuel energy systems (land use-related net changes in carbon stocks and land management impacts are excluded). Commercial and developing (e.g., algae biofuels, Fischer-Tropsch) systems for biomass and fossil technologies are illustrated.

Data sources: Wu et al. (2005); Fleming et al. (2006); Hill et al. (2006, 2009); Beer and Grant (2007); Wang et al. (2007, 2010); Edwards et al. (2008); Kreutz et al. (2008); Macedo and Seabra (2008); Macedo et al. (2008); NETL (2008, 2009a,b); CARB (2009); Cherubini et al. (2009a); Huo et al. (2009); Kalnes et al. (2009); van Vliet et al. (2009); EPA (2010); Hoefnagels et al. (2010); Kaliyan et al. (2010); Larson et al. (2010); 25th to 75th percentile of all values from Figure 2.11.

51 The same rebound effect applies to other RE technologies displacing incumbent fossil technologies.

are excluded). Meta-analyses to quantify the influence of bioenergy systems on climate are complicated because of the multitude of existing and rapidly evolving bioenergy sources, the complexities of physical, chemical and biological conversion processes, and feedstock diversity and variability in site-specific environmental conditions—together with differences between studies in method interpretation, assumptions and data. Due to this, review studies report varying estimates of GHG emissions and a wide range of results have been reported for the same bioenergy options, even when temporal and spatial considerations are constant (see, e.g., S. Kim and Dale, 2002; Fava, 2005; Farrell et al., 2006; Fleming et al., 2006; Larson, 2006; von Blottnitz and Curran, 2007; Rowe et al., 2008; Börjesson, 2009; Cherubini et al., 2009a; Menichetti and Otto, 2009; Soimakallio et al., 2009b; Hoefnagels et al., 2010; Wang et al., 2010, 2011).

For electricity generated by various technologies, GHG emissions per kWh generated are detailed in Figure 2.11, based on published estimates from lifecycle GHG emissions (land use-related net changes in carbon stocks and land management impacts are excluded) of an extensive review of biopower LCAs.[52] Figure 2.11 shows that the majority of lifecycle GHG emission estimates cluster between about 16 and 74 g CO_2eq/kWh (4.4 and 21 g CO_2eq/MJ), with one estimate reaching



	All Values	Co-Firing w/o Avoided Emissions	Co-Firing w/ Avoided Emissions	Direct Combustion w/o Avoided Emissions	Direct Combustion w/ Avoided Emissions	Gasification w/o Avoided Emissions	Gasification w/ Avoided Emissions	Pyrolysis w/o Avoided Emissions
Estimates:	228	54	7	102	4	45	2	14
References:	53	19	4	26	3	20	1	3

Figure 2.11 | Lifecycle GHG emissions of biopower technologies per unit of electricity generation, including supply chain emissions (land use-related net changes in carbon stocks and land management impacts are excluded). Co-firing is shown for the biomass portion only (without GHG emissions and electricity output associated with coal). Included in the avoided GHG emissions category are only estimates in which the use of the feedstock itself (e.g. residues and wastes) leads to avoided emissions, for example, in the form of avoided methane emissions from landfills (most common in the literature).[1] Estimates that include avoided emissions from the production of co-products are not included in the avoided GHG emissions category. Individual data points were used instead of box plots for estimates with avoided emissions because of high variability. Red diamonds indicate that a carbon mitigation technology (CCS or carbonate formation by absorption) was considered. Along the bottom of the figure and aligned with each column are the number of estimates and the number of references (CCS estimates in parentheses) producing the distributions.

Note: 1. 'Negative estimates' within the terminology of lifecycle assessments presented in this report refer to avoided emissions. Unlike the case of bioenergy combined with CCS, avoided emissions do not remove GHGs from the atmosphere. Due to the inclusion of a non-CCS carbon sequestration technology and non-landfilling related reference cases of avoided emissions credits, estimates displayed here vary slightly from the aggregated values in Figure 9.8.

52 See Annex II for the complete list of references providing estimates for this figure and description of the literature review method.

360 g CO_2eq/kWh (100 g CO_2eq/MJ).[53] Again, variability is caused by differences in study methods, agricultural practice, technology performance and maturity of development (see Section 2.3.3). While the range and central tendency of each evaluated technology are similar to each other, the figure shows that depending on business-as-usual assumptions, avoided GHG emissions (here, mostly methane from landfills) from non-harvest wastes and residues can more than outweigh the GHG emissions associated with the biomass supply chains. Technologies with high conversion efficiency reach lower GHG emissions per kWh generated than less efficient technologies do. Though not displayed here, CHP and other integrated systems with many products could also be an effective way to minimize GHG emissions per unit of primary energy (e.g., in terms of primary energy), though the way co-products are considered in the quantification and allocation of GHG emissions can lead to different results. In the end, the economic value of outputs plays a decisive role, but climate policies that influence the cost of GHG emissions may alter the balance of products.

LCA aspects found to be especially important for GHG results are: (1) assumptions regarding GHG emissions from biomass production where LUC emissions (see Section 2.5.3) and nitrous oxide (N_2O) emissions are especially important; (2) methods used for considering co-products; (3) assumptions about conversion process design, process integration and the type of process fuel used in the conversion of biomass to solid or fluid fuels; (4) the performance of end-use technology, that is, vehicle technology or power/heat plant performance; and (5) the reference system.

N_2O emissions can have an important impact on the overall GHG balance of biofuels (Smeets et al., 2009; Soimakallio et al., 2009b). N_2O emissions vary considerably with environmental and management conditions, including soil water content, temperature, texture, carbon availability, and, most importantly, nitrogen fertilizer input (Bouwman et al., 2002; Stehfest and Bouwman, 2006). Emission factors are used to quantify N_2O emissions as a function of nitrogen fertilizer input. Crutzen et al. (2007) proposed that N_2O emissions from fresh anthropogenic nitrogen are considerably higher than results based on the IPCC's recommended tier 1 method and that N_2O emissions from biofuels consequently have been underestimated by a factor of two to three. IPCC tier 1 and Crutzen et al. (2007) estimates use different accounting approaches. About one-third of agricultural N_2O emissions are due to newly-fixed nitrogen fertilizer (A. Mosier et al., 1998) and two-thirds occur as nitrogen is recycled internally in animal production or by using plant residues as fertilizers. Recent modelling efforts by Davidson (2009) support the conclusion that emission factors based on Crutzen et al. (2007) overestimate the emissions. Using N_2O emissions factors from Crutzen et al. (2007) makes a specific bioenergy plantation responsible for all N_2O emissions taking place subsequently, even for the part of the applied nitrogen that is recirculated into other agriculture systems and substituted for other nitrogen input. See Bessou et al. (2010) for an overview of reactive nitrogen emissions impacts on LCAs.

Process fuel choice is critical and the use of coal especially can drastically reduce the climate benefit of bioenergy. Process integration and the use of biomass fuels or surplus heat from nearby energy/industrial plants can lower net GHG emissions from the biomass conversion process. For example, Wang et al. (2007) showed that GHG emissions for US corn ethanol can vary significantly—from a 3% increase if coal is the process fuel to a 52% reduction if wood chips are used or if improved dry milling processes are used (Wang et al., 2011). Similarly, the low fossil GHG emissions reported for Swedish cereal ethanol plants are explained by their use of biomass-based process energy (Börjesson, 2009). Sugarcane ethanol plants that use the fibrous by-product bagasse as process fuel can provide their own heat, steam and electricity and export surplus electricity to the grid (Macedo et al., 2008). Further improvements are possible as mechanical harvesting becomes established practice, because harvest residues can also be used for energy (Seabra et al., 2010).

However, the marginal benefit of using surplus heat or biomass for the conversion process depends on local economic circumstances and on alternative uses for the surplus heat and biomass (e.g., it could displace coal-based heat or power generation elsewhere). GHG reductions per unit weight of total biomass could be small when biomass is used both as a feedstock and as a process fuel for conversion to biofuels. This underscores the importance of using several indicators in bioenergy option evaluations (see also Section 9.3.4).

Practical uses of indicators to design and establish projects

As shown above, climate change effects can be evaluated based on indicators such as g CO_2eq per MJ (Figure 2.10) or per kWh (Figure 2.11), for which the reference system matters greatly (cf. bioenergy GHG emissions with those from coal and natural gas). Other indicators include mileage per hectare or per unit weight of biomass or per vehicle-km (see Section 8.3.1.3).[54] Limiting resources may define the extent to which land management and biomass-derived fuels can contribute to climate change mitigation, making the following indicators relevant in different contexts (Schlamadinger et al., 2005).

The *displacement factor* indicator describes the reduction in GHG emissions from the displaced energy system per unit of biomass used (e.g., tonne of carbon equivalent per tonne of carbon contained in the biomass that generated the reduction). This indicator does not discourage fossil inputs in the bioenergy chain if these inputs increase the displacement efficiency but it does not consider costs.

The indicator *relative GHG savings* describes the percentage emissions reduction with respect to the fossil alternative for a specific biomass

53 Note that the distributions in Figure 2.11 do not represent an assessment of likelihood; the figure simply reports the distribution of currently published literature estimates that passed screens for quality and relevance.

54 For example, the higher land use efficiency of electric vehicles using bioelectricity compared to ethanol cars reported by Campbell et al. (2009) is partly due to the assumed availability of advanced future drive trains for the bioelectricity option but not for the ethanol option.

use.[55] GHG savings favour biomass options with low GHG emissions. However, this indicator alone cannot distinguish between different biomass uses, such as transport fuel, heat, electricity or CHP, to determine which use reduces emissions more. It ignores the amount of biomass, land or money required, and it can be distorted as each use can have different reference systems.

The indicator *GHG savings per ha (or m² or km²) of land* favours biomass yield and conversion efficiency but ignores costs.[56] Intensified land use that increases the associated GHG emissions (e.g., due to higher fertilizer input) can still improve the indicator value if the amount of biomass produced increases sufficiently.

The indicator *GHG savings per monetary unit input* tends to favour the lowest cost, commercially available bioenergy options. Prioritization based on monetary indicators can lock in current technologies and delay (or preclude) future, more cost-effective or GHG reduction-efficient bioenergy options because their near-term costs are higher.

The usefulness of two indicators for considering local and regional bioenergy options is shown in Table 2.13. In the Finnish study, the use of logging residues in modern CHP plants receives a high ranking in relative GHG savings whether the displaced fossil source is coal or natural gas. However, the displacement factor indicator is only high when coal is displaced and is medium for natural gas displacement. The biodiesel from annual crops option receives the lowest ranking (<1) for both indicators, while the Fischer-Tropsch diesel, with or without electricity from wood residues, receives different rankings depending on indicator and plant configuration but is in all cases higher than crop-derived biodiesel. The standalone plant is the best option from the perspective of relative GHG savings. But if the displacement factor is used the integrated plant is preferable. From the plant owner's perspective, local monetary indicators enable assessment of additional costs of the integrated plant, the relative prices for biomass versus electricity, relative prices for fossil diesel versus CO_2 emissions, as well as existing policy support (and its duration). The differences between the two indicators highlight the need to consider the biomass system when planning bioenergy projects at specific locations. For example, in cases where the displacement factor is less than 1, using biomass to displace fossil fuels would increase net emissions (with respect to the global carbon sink baseline) at least within the next decades. The use of such biomass resources could be sustainable; but is not climate or emissions neutral during that period. Additional fossil carbon reductions may then be needed to achieve low GHG concentration stabilization levels.

For North American corn ethanol, technology improvements from 1995 to 2005 are reflected in both indicators. Implementation of improvements in plant efficiency with existing cogeneration systems brings

Table 2.13 | Two indicators of GHG performance facilitate ranking of new technologies using forest residues and comparison with current agricultural biofuel. Two indicators show improvement of technology performance with time for commercial ethanol systems and project the impact of technology improvements. Ranking: High >70; Low <30.

		Fossil energy reference	Displacement factor[1]	Relative GHG savings[2] (%)
Finnish modern CHP plant (from logging residues)		Coal	78	86[e]
		Natural gas	30	86[e]
Finnish Fischer-Tropsch diesel[3] as a stand-alone plant or integrated with a pulp and paper mill plant; with/without electricity	Standalone plant	Fossil diesel	39[a]	78[f]
	Integrated plant, minimize biomass		50[b]	55[g]
	Integrated plant, minimize electricity		50[c]	78[h]
Finnish biodiesel (rapeseed oil)		Fossil diesel	-9[d]	-15[i]
North American ethanol (corn) powered by natural gas (NG) dry mill		Fossil gasoline		
1995			18	26
2005			24	39
2015 with CHP[3]			31	55
2015 with CHP and CCS[3]			51	72
Brazilian ethanol (sugarcane)		Fossil gasoline/ electricity marginal NG		
2005–2006 (average 44 mills)			29	79
2020 CHP[3] (mechanical harvest)			36	120
2020 CHP and CCS[3]			51	160

Notes: 1. Tonne of carbon equivalent displaced per tonne of biomass carbon in the feedstock. 2. With respect to the fossil alternative and excluding LUC. 3. Projected performance

Uncertainty ranges: For displacement factors a. 35–46; b. 21–61; c. 45–57; d. -107–7. For relative GHG savings e. 60–94; f. 67–90; g. 31–86; h. 69–89; i. -150–5

References: Finland, Soimakallio et al. (2009b); North America, (S&T)2 Consultants (2009); and Brazil, Möllersten et al. (2003) and Macedo et al. (2008).

55 Relative GHG savings are used, for instance, in the EU Directive on Renewable Energy (European Commission, 2009).

56 See Bessou et al. (2010) for examples of LCA emissions as a function of area needed for a variety of feedstocks and biofuels in specific countries.

both indicators to medium range but improves the GHG reduction more than the displacement factor indicator. Application of developing CCS is projected to improve both indicators significantly and bring the GHG reduction indicator to high. In all Brazilian sugarcane ethanol cases, the GHG reduction indicator is high while the displacement factor is low to medium, which is expected because marginal natural gas, not coal, is the displaced fossil fuel and this is a site characteristic (EPE, 2010). The land use indicator differentiates the corn and sugarcane ethanol systems as producing 3,500 and 7,500 litres/ha, respectively. By 2020, biomass productivity increases and also CHP are projected to increase the land use indicator for corn and sugarcane ethanol systems to 4,500 and 12,000 litres/ha, respectively (Möllersten et al., 2003; Macedo et al., 2008; $(S\&T)^2$ Consultants, 2009). See also Wang et al. (2011) for more recent data confirming these trends.

2.5.3 Modern bioenergy: Climate change including land use change effects

Bioenergy is different from the other RE technologies in that it is a part of the terrestrial carbon cycle. The CO_2 emitted due to bioenergy use was earlier sequestered from the atmosphere and will be sequestered again if the bioenergy system is managed sustainably, although emissions and sequestration are not necessarily in temporal balance with each other (e.g., due to long rotation periods of forest stands). In addition to changes in atmospheric carbon, bioenergy use may cause changes in terrestrial carbon stocks. The significance of land use and LUC (e.g., Leemans et al., 1996) and forest rotation (Marland and Schlamadinger, 1997) was demonstrated in the 1990s when dLUC effects were also considered in LCA studies (e.g., Reinhardt, 1991; DeLuchi, 1993). DeLuchi (1993) also called for consideration of indirect effects and iLUC. These effects were first considered about 10 years later (Jungk and Reinhardt, 2000), but most LCA studies have not considered iLUC. LUC can affect GHG emissions in a number of ways, including when biomass is burned in the field during land clearing; when the land management practice changes so that the carbon stocks in soils and vegetation change and/or non-CO_2 emissions (N_2O, ammonium (NH_4^+)) change; and when LUC results in changes in rates of carbon sequestration, that is, CO_2 assimilation by the land increases or decreases relative to the case in which LUC is absent.

Schlamadinger et al. (2001) proposed that bioenergy can have direct/indirect, positive/negative effects on biospheric carbon stocks and that crediting under the CDM could stimulate development of systems that function as a positive carbon sink. Recently, negative effects have been re-emphasized, and studies have estimated LUC emissions associated with, primarily, biofuels for transport. Other bioenergy systems and impact categories (e.g., biodiversity, eutrophication; see Section 2.2.4) have received less attention (see Section 9.3.4). There has been little connection with earlier research in the area of land use, LUC and forestry that partly addressed similar concerns, for example, direct environmental and socioeconomic impacts and leakage (Watson, 2000b).

The quantification of the net GHG effects of dLUC occurring on the site used for bioenergy feedstock production requires definition of reference land use and carbon stock data for relevant land types. Carbon stock data can be uncertain but still appear to allow quantification of dLUC emissions with sufficient confidence for guiding policy (see, e.g., Gibbs et al., 2008).

The quantification of the GHG effects of iLUC is more uncertain. Existing methods for studying iLUC effects employ either (1) a deterministic approach where global LUC is allocated to specific biofuels/feedstocks grown on specified land types (Fritsche et al., 2010); or (2) economic equilibrium models integrating biophysical information and/or biophysical models (Edwards et al., 2010; EPA, 2010; Hertel et al., 2010a,b; Plevin et al., 2010). In the second approach, the amount (and approximate location) of additional land required to produce a specified amount of bioenergy is typically projected. This land is then distributed over land cover categories in line with historic LUC patterns, and iLUC emissions are calculated in the same way as dLUC emissions are. There are inherent uncertainties in this approach because models are calibrated against historic data and are best suited for studying existing production systems and land use regimes. Difficult aspects to model include innovation and paradigm shifts in land use including the presently little-used biomass and mixed production systems described in Sections 2.3 and 2.6. There are also studies that compare scenarios with and without increases in bioenergy to derive LUC associated with the bioenergy expansion (e.g., Fischer et al., 2009). Despite the uncertainties, important conclusions can be drawn from these studies.

Production and use of bioenergy influences climate change through:

- Emissions from the bioenergy chain including non-CO_2 GHG and fossil CO_2 emissions from auxiliary energy use in the biofuel chain.
- GHG emissions related to changes in biospheric carbon stocks often caused by associated LUC.
- Other non-GHG related climatic forcers including particulate and black carbon emissions from small-scale bioenergy use (Ramanathan and Carmichael, 2008), aerosol emissions associated with forests (Carslaw et al., 2010) and changes in surface albedo. Reduction in albedo due to the introduction of perennial green vegetative cover can counteract the climate change mitigation benefit of bioenergy in regions with seasonal snow cover or a seasonal dry period (e.g., savannas). Conversely, albedo increases associated with the conversion of forests to energy crops (e.g., annual crops and grasses) may reduce the net climate change effect from the deforestation (Schwaiger and Bird, 2010).
- Effects due to the bioenergy use, such as price effects on petroleum that impact consumption levels. The net effect is the difference between the influence of the bioenergy system and of the energy system (often fossil-based) that is displaced. Current fossil energy

chains and evolving non-conventional sources have land use impacts (Gorissen et al., 2010; Liska and Perrin, 2010; Yeh et al., 2010), but LUC has a tighter link to bioenergy because of its close association with agriculture and forestry.

- Other factors include the extent and timing of the reversion of cultivated land when the use for bioenergy production ends and how future climate change impacts relative to present impacts are treated (DeLucchi, 2010).

Mitigation efforts over the next two to three decades will influence prospects for achieving lower stabilization levels (van Vuuren et al., 2007; den Elzen et al., 2010). For instance, the dynamics of terrestrial carbon stocks in LUC and long-rotation forestry lead to GHG mitigation trade-offs between biomass extraction for energy use and the alternative to leave the biomass as a carbon store that could further sequester more carbon over time (Marland and Schlamadinger, 1997; Marland et al., 2007; Righelato and Spracklen, 2007). Observations indicate that old forests can be net carbon sinks (Luyssaert et al., 2008; Lewis et al., 2009) but fires, insect outbreaks and other natural disturbances can quickly convert a forest from a net sink to an emitter (Kurz et al., 2008a,b; Lindner et al., 2010).

Short- and long-term indicators

Indicators such as *carbon debt* (Fargione et al., 2008) and *ecosystem carbon payback time* (Gibbs et al., 2008) focus on upfront LUC emissions arising from the conversion of land to bioenergy production. The balance between short- and long-term emissions and the climate benefits of bioenergy projects are reflected in indicators that describe the dynamic effect of GHG emissions (see also Section 9.3.4), for example, *cumulative warming impacts* or *global warming potential* (Kirschbaum, 2003, 2006; Dornburg and Marland, 2008; Fearnside, 2008). These indicators have been used, to a limited extent, to describe bioenergy dynamic climate effects (Kendall et al., 2009; Kirkinen et al., 2009; Levasseur et al., 2010; O'Hare et al., 2009).

Figure 2.12 shows dLUC effects on GHG balances for liquid biofuels using the ecosystem carbon payback time indicator. The left diagram shows payback times with current yields and conversion efficiencies and the right diagram shows the effect of higher yields (set to equal the top 10% of area-weighted yields). The payback times in Figure 2.12 neglect the GHG emissions associated with production and distribution of the transport fuels. Because these emissions currently tend to be higher for biofuels than for gasoline and diesel, the payback times are underestimated. The payback times in Figure 2.12 are calculated assuming constant GHG savings from the gasoline/diesel displacement. Higher GHG savings, that is, reducing the payback times, would be achieved if the biofuels conversion efficiency improved, if more carbon intensive transport fuels were replaced, or if the produced biomass displaced carbon-intensive fossil options for heat/power (Figure 2.10). Further biomass yield increases would reduce payback times but may require higher agronomic inputs that lead to increased GHG emissions, notably N_2O. The payback times would increase if the feedstock production resulted in land degradation over time, impacting yield levels or requiring increased input to maintain yield levels.

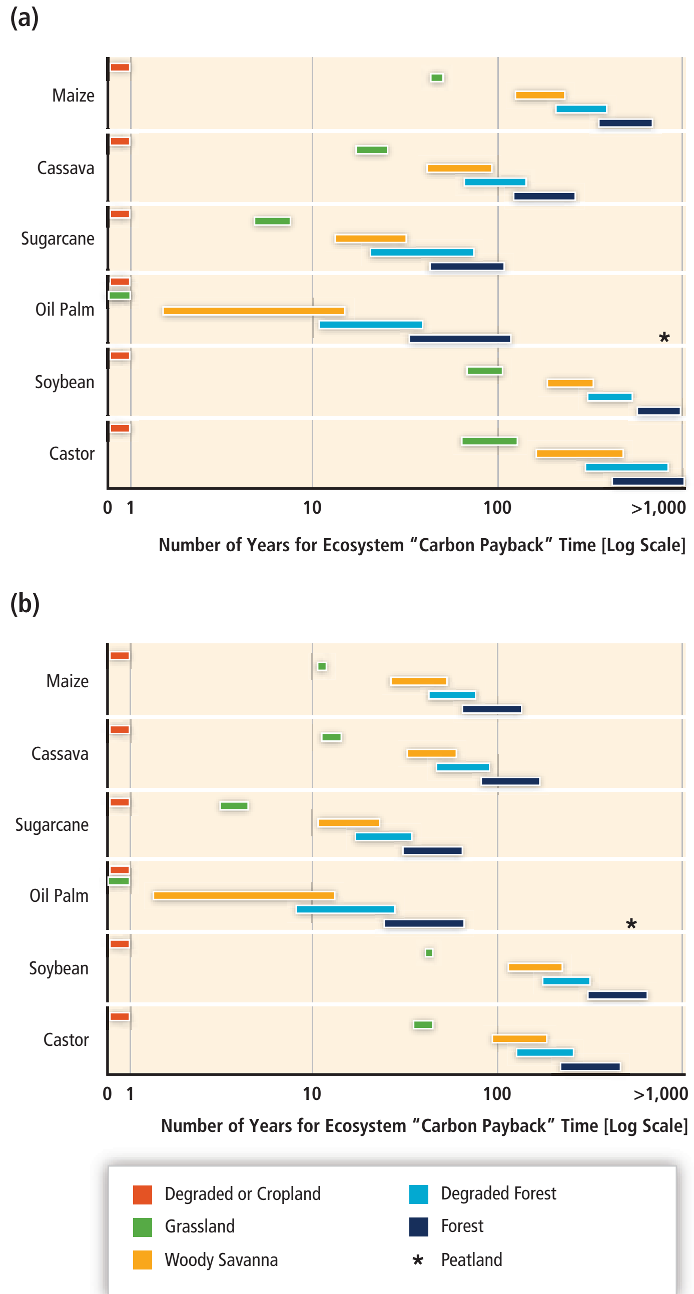


Figure 2.12 | The ecosystem carbon payback time for potential biofuel crop expansion pathways across the tropics comparing the year 2000 agricultural system shown in (a) with a future higher yield scenario (b) which was set to equal the top 10% of area-weighted yields. The asterisk represents oil palm crops grown in peatlands with payback times greater than 900 years in the year 2000 compared to 600 years for a 10% increase in crop productivity. Based on Gibbs et al. (2008) and reproduced with permission from IOP Publishing Ltd.

As shown, all biofuel options have significant payback times when dense forests are converted into bioenergy plantations. The starred points represent very long payback times for oil palm establishment on tropical peat swamp forests because drainage leads to peat oxidation and causes CO_2 emissions that occur over several decades and that can be several times higher than the displaced emissions of fossil diesel (Hooijer et al., 2006; Edwards et al., 2008, 2010). Under natural conditions, these tropical peat swamp forests have negligible CO_2 emissions and small methane emissions (Jauhiainen et al., 2008). Payback times are practically zero when degraded land or cropland is used, and they are relatively low for the most productive systems when grasslands and woody savannas are used (not considering the iLUC that can arise if these lands were originally used, for example, for grazing).

Targeting unused marginal and degraded lands for bioenergy production can thus mitigate dLUC emissions. For some options (e.g., perennial grasses, woody plants, mechanically harvested sugarcane), net gains of soil and aboveground carbon can be obtained (Tilman et al., 2006b; Liebig et al., 2008; Robertson et al., 2008; Anderson-Teixeira et al., 2009; Dondini et al., 2009; Hillier et al., 2009; Galdos et al., 2010). In this context, land application of biochar produced via pyrolysis could be an option to sequester carbon in a more stable form and improve the structure and fertility of soils (Laird et al., 2009; Woolf et al., 2010).

Bioenergy does not always result in LUC. Bioenergy feedstocks can be produced in combination with food and fibre, avoiding land use displacement and improving the productive use of land (Section 2.2). These possibilities may be available for bioenergy options that can use lignocellulosic biomass but also for some other options that use waste oil and oil seeds such as *Jatropha* (Section 2.3). The use of post-consumer organic waste and by-products from the agricultural and forest industries does not cause LUC if these biomass sources are wastes, that is, they were not utilized for alternative purposes. On the other hand, if not utilized for bioenergy, some biomass sources (e.g., harvest residues left in the forest) would retain organic carbon for a longer time than if used for energy. Such delayed GHG emissions can be considered a benefit in relation to near-term GHG mitigation, and this is an especially relevant factor in longer-term accounting for regions where biomass degradation is slow (e.g., boreal forests). However, as noted above, natural disturbances can convert forests from net sinks to net sources of GHGs, and dead wood left in forests can be lost in fires. In forest lands susceptible to periodic fires, good silviculture practices can lead to less frequent, lower intensity fires that accelerate forest growth rates and soil carbon storage. Using biomass removed in such practices for bioenergy can provide GHG and particulate emission reductions.

For different world regions, Edwards et al. (2010) describe the comparison of six equilibrium models to quantify LUC associated with a standard biofuel shock defined as a marginal increase in demand for first-generation ethanol or biodiesel from a base year.[57] All models showed significant LUC (dLUC and iLUC were not considered separable) with variations between models in terms of the extent of LUC and its distribution over regions and crops. A follow-on study by Hiederer et al. (2010) compared the ranges of LUC emissions shown in Figure 2.13 for common biofuel crops as a function of the 'biofuel shock' (0.2 to 1.5 EJ) for select studies. Figure 2.13 also shows the 2010 EPA model results with a relatively high resolution of land use distribution[58] for Brazil resulting in mid-range LUC emissions for sugarcane ethanol (5 to 10 g CO_2eq/MJ), similar to the European study (Al-Riffai et al., 2010) estimate of 12 g CO_2eq/MJ. The Brazilian study with measured LUC dynamics for common crops and native vegetation between 2005 and 2008 by Nassar et al. (2010) obtained 8 g CO_2eq/MJ for iLUC and dLUC, with the latter being nearly zero. Fischer et al. (2010) obtained 28 g CO_2eq/MJ using a deterministic methodology and assuming a high risk of deforestation. Model results from Figure 2.13 show all other crops as having higher LUC values than sugarcane ethanol. In the US maize ethanol case, Plevin et al. (2010) report a plausible range of 25 to 150 g CO_2eq/MJ based on uncertainty analysis of various model parameters and assumptions.

The utility of these models to study scenarios is illustrated with an analysis of the relative contributions of changes in yield and land area to increased crop output along with assumptions about trade-critical factors in model-based LUC estimates (D. Keeney and Hertel, 2009). Subsequent model improvements incorporate crop yields, by-product markets interactions, and trade and policy assumptions, and analyze past and project future usage with existing (2010) EU and US policies, finding LUC in other countries such as Latin America and Oceania to be primarily at the expense of pastureland followed by commercial forests (Hertel et al., 2010a,b).

Lywood et al. (2009b) report that the extent to which output change comes from increased crop yield or land area changes varies between crops and regions. They estimate that yield growth contributed 80 and 60% of the incremental output growth for EU cereals and US maize, respectively, between 1961 and 2007. Conversely, area expansion

57 Biofuel shock (Hertel et al., 2010a,b) is introduced in general equilibrium models by changing some economic parameters (e.g., subsidies to ethanol production) to reach predetermined volume levels (i.e., sum of government mandates for a certain year). The comparison of new and previously determined equilibrium enables estimates of land area changes impacted directly to meet mandates and those indirectly involved to compensate for that agricultural production no longer available, its co-products and its impact throughout the global economic chain. These studies have high uncertainties. Partial equilibrium models were also included in Edwards et al. (2010).

58 Based on the Nassar et al. (2009) Brazilian Land Use Model, which shows a lower share of LUC due to deforestation. More recently, Nassar et al. (2010) obtained elasticities for models from direct data (statistical and satellite-based) of land use substitution over time. The matrix elasticity results for major crops in various regions provide a deterministic estimate for the d+iLUC of sugarcane ethanol of about 8 g CO^2eq/MJ. Higher substitution coefficients are found for soy into native vegetation.

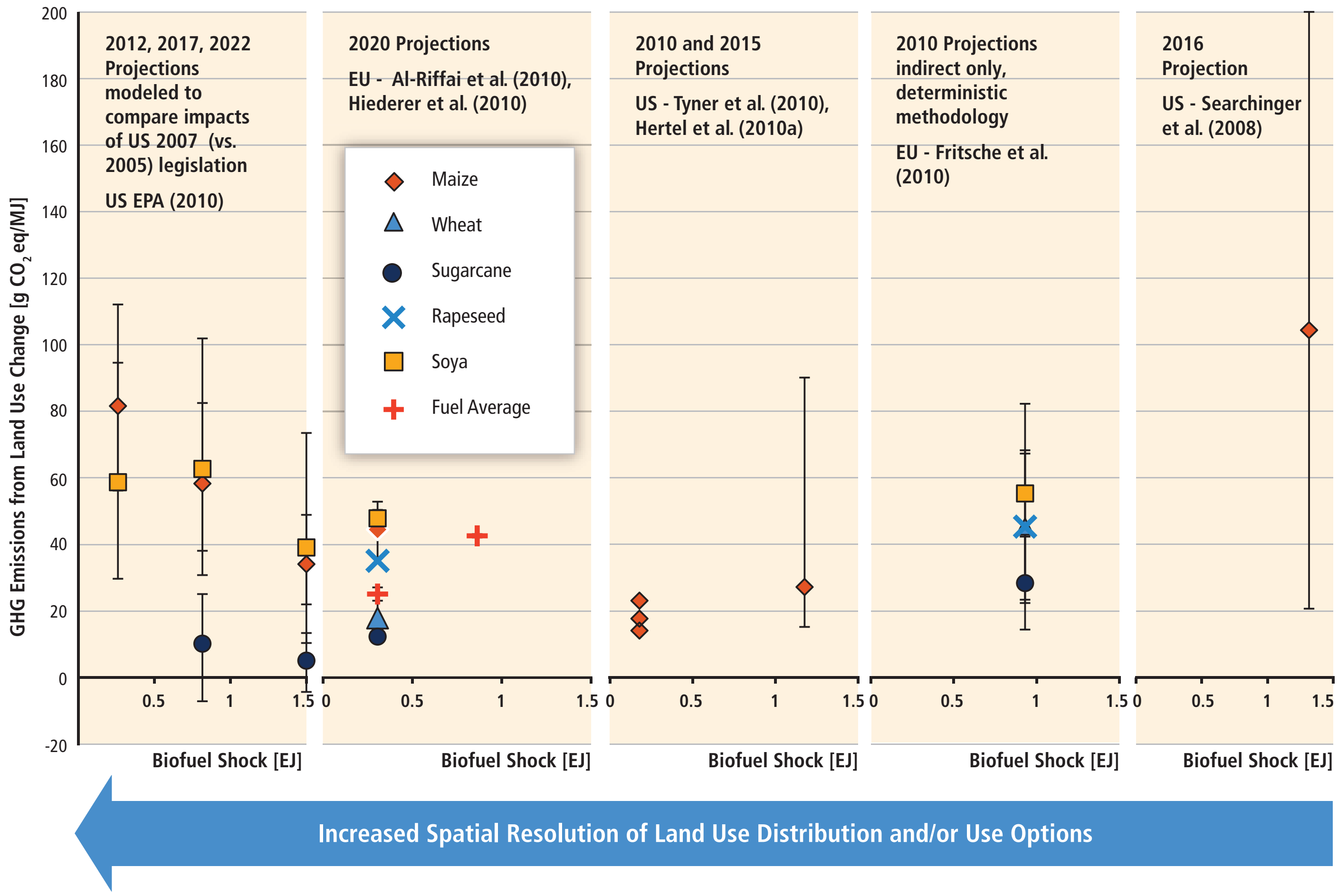


Figure 2.13 | Select model-based estimates of LUC emissions for major biofuel crops given a certain level of demand, a biofuel shock, expressed in EJ (30-year accounting framework). Mid-range values of multiple studies (g CO_2eq/MJ): 14 to 82 for US maize ethanol with high-resolution models and 100 for earlier models; 5 to 28 for sugarcane ethanol; 18 to 45 for European wheat ethanol; 40 to 63 for soy biodiesel (uncertain); and 35 to 45 for rapeseed biodiesel. Points for Tyner et al. (2010) and Hertel et al. (2010a) represent model improvements with the lowest value including feedstock yield and population increases (baseline 2006). Fritsche et al. (2010) value ranges derive from a deterministic methodology representing risk values of 25 and 75% of the theoretical worst case of LUC scenarios, such as high deforestation, to calculate iLUC.

contributed to more than 60% of output growth for EU rapeseed, Brazilian sugarcane, South American soy, and Southeast Asia oil palm. Studies report price-yield relationships; there is a weak basis for deriving these relationships (D. Keeney and Hertel, 2008) although rising oil prices and fuel tax exemptions show strong correlations for the USA and EU, respectively. Edwards et al. (2010) state that the marginal area requirement per additional unit output of a particular biofuel should increase due to decreasing productivity of additional land converted to biofuel feedstock production (also reflected in, e.g., R. Keeney and Hertel, 2005; Tabeau et al., 2006). Lywood et al. (2009b), however, state that in the case of EU cereals and US corn, there is no evidence that average yields decline as more land is used. The assumed or modelled displacement effect of process co-products used as feed can also have a strong influence on LUC values.

For European biofuels, if soy meal and cereals for feed are displaced, the net land area required to produce biofuel from EU cereal, rapeseed and sugar beet is much lower than the gross land requirement (e.g., only 6% for ethanol from feed wheat in northwestern Europe (Lywood et al., 2009a). Lywood et al. (2008) obtained large improvements in net GHG savings for European cereal ethanol and rapeseed biodiesel based on co-products displacing imported soy as animal feed, which reduces deforestation and other LUC for soy cultivation in Brazil. Conversely, increased corn cultivation at the cost of soy cultivation, in response to increasing ethanol demand in the USA, has been reported to increase soy cultivation in other countries such as Brazil (Laurance, 2007). Trade assumptions are critical and differ in the various models. In addition, marginal displacement effects of co-products may have a saturation level (McCoy, 2006; Edwards et al., 2010), although new uses may be developed, for example, to produce more biofuels (Yazdani and Gonzalez, 2007).

Bioenergy options that use lignocellulosic feedstocks are projected to have lower LUC values than those of first-generation biofuels (see, e.g., EPA, 2010; Hoefnagels et al., 2010; see Figure 9.9). As noted above, some of these feedstock sources can be used without causing LUC. Lower LUC values might be expected because of high biomass productivity, multiple products (e.g., animal feed) or avoided competition for prime cropland by using more marginal lands (Sections 2.2 and 2.3). The lower productivity of marginal lands, however, results in higher land requirements per given biomass output and presents particular challenges as discussed in Section 2.2. Also, as many lignocellulosic plants are grown under longer rotations, they should be less responsive to price increases because the average yield over a plantation lifetime can only be influenced through agronomic means (notably increased fertilizer input) and by variety selection at the time of replanting. Thus, output growth in response to increasing demand is more readily obtained by area expansion.

Depending on the atmospheric lifetime of specific GHGs, the trade-off between emitting more now and less in the future is not one-to-one in general. But the relationship for CO_2 is practically one-to-one, so that one additional (less) tonne CO_2 emitted today requires a future reduction (allows a future increase) by one tonne. This relationship is due to the close to irreversible climate effect of CO_2 emissions (Matthews and Caldeira, 2008; M. Allen et al., 2009; Matthews et al., 2009; Solomon et al., 2009).

Integrated energy-industry-land use/cover models can give insights into how an expanding bioenergy sector interacts with other sectors in society, influencing longer-term energy sector development, land use, management of biospheric carbon stocks, and global cumulative GHG emissions. In an example of early studies, Leemans et al. (1996) implemented in the IMAGE model (Integrated Model to Assess the Global Environment) the LESS (low CO_2-emitting energy supply system) scenario, which was developed for the IPCC Second Assessment Report (IPCC, 1996). This study showed that the required land use expansion to provide biomass feedstock can cause significant food-bioenergy competition and influence deforestation rates with significant consequences for environmental issues such as biodiversity, and that the outcome is sensitive to regional emissions and feedback in the carbon cycle. More recently, using linked economic and terrestrial biogeochemistry models, Melillo et al. (2009) found a similar level of cumulative CO_2 emissions associated with LUC from an expanded global cellulosic biofuels programme over the 21st century. The study concluded that iLUC was a larger source of carbon loss than dLUC; fertilizer N_2O emissions were a substantial source of global warming; and forest protection and best practices for nitrogen fertilizer use could dramatically reduce emissions associated with biofuels production.

Wise et al. (2009) also stressed the importance of limiting terrestrial carbon emissions and showed how the design of mitigation regimes can strongly influence the nature of bioenergy development and associated environmental consequences, including the net GHG savings from bioenergy. Including both fossil and LUC emissions in a carbon tax regime, instead of taxing only fossil emissions, was found to lower the cost of meeting environmental goals. However, this tax regime was also found to induce rising food crop and livestock prices and expansion of unmanaged ecosystems and forests. Improved crop productivity was proposed as a potentially important means for GHG emissions reduction, with the caution that non-CO_2 emissions (not modelled) need to be considered.

Biospheric carbon pricing as a sufficient mechanism to protect forests was proposed by Wise et al. (2009) and supported by Venter et al. (2009) and others. Persson and Azar (2010) acknowledge that pricing LUC carbon emissions could potentially make many of the current proximate causes of deforestation unprofitable (e.g., extensive cattle ranching, small-scale slash-and-burn agriculture and fuelwood use) but they question whether it will suffice to make deforestation for bioenergy production unprofitable because these bioenergy systems are highly productive according to the Wise et al. (2009) assumptions of generic feedstock productivity and biofuel conversion efficiency. A higher carbon price will increase not only the cost of forest clearing but also the revenues from certain bioenergy production systems. The upfront cost of land conversion may also be reduced if the bioenergy industry partners with the timber and pulp industries that seek access to timber revenues from clear felling forests as the first step in plantation development (Fitzherbert et al., 2008).

Three tentative conclusions are:

1. Additional, and stronger, protection measures may be needed to meet the objective of tropical forest preservation. A strict focus on the climate benefits of ecosystem preservation may put undue pressure on valuable ecosystems that have a relatively low carbon density. While this may have a small impact in terms of climate change mitigation, it may negatively impact other parts of the ecosystem, for example, biodiversity and water tables.

2. From a strict climate and cost efficiency perspective, in some places a certain level of upfront LUC emissions may be acceptable in converting forest to highly productive bioenergy plantations due to the climate benefits of subsequent continued biofuel production and fossil fuel displacement. The balance between bioenergy expansion benefits and LUC impacts on biodiversity, water and soil conservation is delicate. Climate change mitigation is just one of many rationales for ecosystem protection.

3. iLUC effects strongly (up to fully) depend on the rate of improvement in agricultural and livestock management and the rate of deployment of bioenergy production. Subsequently, implementation of bioenergy production and energy cropping schemes that follow effective sustainability frameworks and start from simultaneous improvements in agricultural management could mitigate conflicts and allow realization of positive outcomes, for example, in rural development, land amelioration and climate change mitigation including opportunities to combine adaptation measures.

2.5.4 Traditional biomass: Climate change effects

Traditional open fires and simple low-efficiency stoves have low combustion efficiency, producing large amounts of incomplete combustion products (CO, methane, particle matter, non-methane volatile organic compounds, and others) that have negative consequences for climate change and local air pollution (Smith et al., 2000; see also Box 9.4 in Section 9.3.4.2). When biomass is harvested renewably—for example, from standing trees or agricultural residues—CO_2 already emitted to the atmosphere is sequestered as biomass re-grows. Because the products of incomplete combustion also include important short-lived greenhouse pollutants and black carbon, even sustainable harvesting does not make such fuel cycles GHG neutral. Worldwide, it is estimated that household fuel combustion causes approximately 30% of the warming due to black carbon and CO emissions from human sources, about 15% of ozone-forming chemicals, and a few percent of methane and CO_2 emissions (Wilkinson et al., 2009).

Improved cookstoves (ICS) and other advanced biomass systems for cooking are cost-effective for achieving large benefits in energy use reduction and climate change mitigation. Fuel savings of 30 to 60% are reported (Berrueta et al., 2008; Jetter and Kariher, 2009). The savings in GHG emissions associated with these efficient stoves are difficult to derive because of the wide range of fuel types, stove designs, cooking practices and environmental conditions across the world. However, advanced biomass systems, such as small-scale gasifier stoves and biogas stoves, have had design improvements that increase combustion efficiency and dramatically reduce the production of short-lived GHGs by up to 90% relative to traditional stoves. Some of these new stoves even reach performance levels similar to liquid propane gas (Jetter and Kariher, 2009). Patsari improved stoves in rural Mexico save between 3 and 9 t CO_2eq/stove/yr relative to open fires, with renewable or non-renewable harvesting of biomass, respectively (M. Johnson et al., 2009).

Venkataraman et al. (2010) estimate that the dissemination of 160 million advanced ICS in India may result in the mitigation of 80 Mt CO_2eq/yr, or more than 4% of India's total estimated GHG emissions, plus a 30% reduction in India's human-caused black carbon emissions. Worldwide, with GHG mitigation per unit at 1 to 4 t CO_2eq/stove/yr compared to traditional open fires, the global mitigation potential of advanced ICS was estimated to be between 0.6 and 2.4 Gt CO_2eq/yr. This estimate does not consider the additional potential reduction in black carbon emissions. Actual figures depend on the renewability of the biomass fuel production, stove and fuel characteristics, and the actual adoption and sustained used of improved cookstoves. Reduction in fuelwood and charcoal use due to the adoption of advanced ICS may help reduce pressure on forest and agricultural areas and improve aboveground biomass stocks and soil and biodiversity conservation (Ravindranath et al., 2006; García-Frapolli et al., 2010).

2.5.5 Environmental impacts other than greenhouse gas emissions

2.5.5.1 Impacts on air quality and water resources

Air pollutant emissions from bioenergy production depend on technology, fuel properties, process conditions and installed emission reduction technologies. Compared to coal and oil stationary applications, sulphur dioxide (SO_2) and nitrous oxide (NO_x) emissions from bioenergy applications are mostly lower (see also Section 9.3.4.2). When biofuel replaces gasoline and diesel in the transport sector, SO_2 emissions are reduced, but changes in NO_x emissions depend on the substitution pattern and technology. The effects of replacing gasoline with ethanol and biodiesel also depend on engine features. Biodiesel can have higher NO_x emissions than petroleum diesel in traditional direct-injected diesel engines that are not equipped with NO_x control catalysts (e.g., Verhaeven et al., 2005; Yanowitz and McCormick, 2009).

Bioenergy production can have both positive and negative effects on water resources (see also Section 9.3.4.4). Bioenergy production generally consumes more water than gasoline production (Wu et al., 2009; Fingerman et al., 2010). However, this relationship and the water impacts of bioenergy production are highly dependent on location, the specific feedstock, production methods and the supply chain element.

Feedstock cultivation can lead to leaching and emission of nutrients that increase eutrophication of aquatic ecosystems (Millennium Ecosystem Assessment, 2005; SCBD, 2006; Spranger et al., 2008). Pesticide emissions to water bodies may also negatively impact aquatic life. Given that several types of energy crops are perennials grown in arable fields being used temporarily as a pasture for grazing animals or woody crops grown in multi-year rotations, the increasing bioenergy demand may drive land use towards systems with substantially higher water productivity. On the other hand, shifting demand to alternative—mainly lignocellulosic—bioenergy can decrease water competition. Perennial herbaceous crops and short-rotation woody crops generally require fewer agronomic inputs and have reduced impacts compared to annual crops, although large-scale production can require high levels of nutrient input (see Sections 2.2.4.2 and 2.3.1). Water impacts can also be mitigated by integrating lignocellulosic feedstocks in agricultural landscapes as vegetation filters to capture nutrients in passing water (Börjesson and Berndes, 2006). A prolonged growing season may redirect unproductive soil evaporation and runoff to plant transpiration (Berndes, 2008a,b). Crops that provide a continuous cover over the year can also conserve soil outside the growing season of annual crops by diminishing the erosion from precipitation and runoff (Berndes, 2008a,b). A number of bioenergy crops can be grown on a wide spectrum of land types that are not suitable for conventional food or feed crops. These marginal lands, pastures and grasslands could become available for feedstock production under sustainable management practices (if adverse downstream water impacts can be mitigated).

The subsequent processing of the feedstock into biofuels and electricity can increase chemical and thermal pollution loads from effluents and generate waste to aquatic systems (Martinelli and Filoso 2007, Simpson et al., 2008). These environmental impacts can be reduced if suitable equipment is installed (Wilkie et al., 2000; BNDES/CGEE, 2008).

Water demand for bioenergy can be reduced substantially through process changes and recycling (D. Keeney and Muller, 2006; BNDES/CGEE, 2008). Currently, most water is lost to the atmosphere through evapotranspiration during the production of cultivated feedstock (Berndes, 2002). Feedstock processing into fuels and electricity requires much less water (Aden et al., 2002; Berndes, 2002; D. Keeney and Muller, 2006; Phillips et al., 2007; NRC, 2008; Wang et al., 2010), but water needs to be extracted from lakes, rivers and other water bodies.

2.5.5.2 Biodiversity and habitat loss

Habitat loss is one of the major drivers of biodiversity decline globally and is projected to be the major driver of biodiversity loss and decline over the next 50 years (Sala et al., 2000; UNEP, 2008b; see Sections 9.3.4.5 and 9.3.4.6). Increased biomass output for bioenergy can directly impact wild biodiversity through conversion of natural ecosystems into bioenergy plantations or through changed forest management. Habitat and biodiversity loss may also occur indirectly, such as when productive land use displaced by energy crops is re-established by converting natural ecosystems into croplands or pastures elsewhere. Because biomass feedstocks can generally be produced most efficiently in tropical regions, there are strong economic incentives to replace tropical natural ecosystems—many of which host high biodiversity values (Doornbosch and Steenblik, 2008). However, forest clearing is mostly influenced by local social, economic, technological, biophysical, political and demographic forces (Kline and Dale, 2008).

Increasing demand for oilseed has put pressure on areas designated for conservation in some OECD member countries (Steenblik, 2007). Similarly, the rising demand for palm oil has contributed to extensive deforestation in parts of Southeast Asia (UNEP, 2008a). The palm oil plantations support significantly fewer species than the forest they replaced (Fitzherbert et al., 2008).

To the extent that bioenergy systems are based on conventional food and feed crops, biodiversity impacts from pesticide and nutrient loading can be expected from bioenergy expansion. Bioenergy production can also impact agricultural biodiversity when large-scale monocultures, based on a narrow pool of genetic material, reduce the use of traditional varieties.

Depending on a variety of factors, bioenergy expansion can also lead to positive outcomes for biodiversity. Using bioenergy to replace fossil fuels can reduce climate change, which is expected to be a major driver of habitat loss. Establishment of perennial herbaceous plants or short-rotation woody crops in agricultural landscapes has been found to improve biodiversity (Lindenmayer and Nix, 1993; Semere and Slater, 2007; Royal Society, 2008). Bioenergy plantations that are cultivated as vegetation filters can improve biodiversity by reducing the nutrient load and eutrophication in water bodies (Foley et al., 2005; Börjesson and Berndes, 2006) and providing a varied landscape.

Bioenergy plantations can be located in the agricultural landscape to provide ecological corridors through which plants and animals can move between spatially separated natural and semi-natural ecosystems. Thus, bioenergy plantations can reduce the barrier effect of agricultural lands (Firbank, 2008). However, bioenergy plantations can contribute to habitat fragmentation, as has occurred with some oil palm plantations (Danielsen et al. 2009; Fitzherbert, 2008).

Properly located biomass plantations can also protect biodiversity by reducing the pressure on nearby natural forests. A study from Orissa, India, showed that introducing village biomass plantations increased biomass consumption (as a consequence of increased availability) while decreasing pressure on the surrounding natural forests (Köhlin and Ostwald, 2001; Francis et al., 2005).

When crops are grown on degraded or abandoned land, such as previously deforested areas or degraded crop- and grasslands, the production of feedstocks for biofuels could have positive impacts on biodiversity by restoring or conserving soils, habitats and ecosystem functions (Firbank, 2008). For instance, several experiments with selected trees and intensive management on severely degraded Indian wastelands (such as alkaline, sodic or salt-affected lands) showed increases in soil carbon, nitrogen and available phosphorous within eight years (Garg, 1998).

2.5.5.3 Impacts on soil resources

The considerable soil impacts of increased biofuel production include soil carbon oxidation, changed rates of soil erosion, and nutrient leaching. However, these effects are heavily dependent on agronomic techniques and the feedstock under consideration (UNEP, 2008a). Land preparation required for feedstock production, as well as nutrient demand, varies widely across feedstocks. For instance, wheat, rapeseed and corn require significant tillage compared to oil palm, sugarcane and switchgrass (FAO, 2008a; UNEP, 2008a). In sugarcane production, soil quality benefits greatly from recycled nutrients from sugar mill and distillery wastes (IEA, 2006).

Using agricultural residues without proper management can lead to detrimental impacts on soil organic matter through increased erosion. However, this impact depends heavily on management, yield, soil type and location. In some areas, the impact of residue removal may be minimal.

Certain cultivation practices, including conservation tillage and crop rotations, can mitigate adverse impacts and in some cases improve environmental benefits of biofuel production. For example, *Jatropha* can stabilize soils and store moisture while it grows (Dufey, 2006). Other potential benefits of planting feedstocks on degraded or marginal lands include reduced nutrient leaching, increased soil productivity and increased carbon content (Berndes, 2002). If lignocellulosic energy crop plantations, which require low-intensity management and few fossil energy inputs relative to current biofuel systems, are established on abandoned agricultural or degraded land, soil carbon and soil quality could increase over time. This beneficial effect would be especially significant with perennial species.

2.5.6 Environmental health and safety implications

2.5.6.1 Feedstock issues

Currently, many crops used in fuel ethanol manufacturing are also traditional feed sources (e.g., maize, soy, canola and wheat). However, considerable efforts are focused on new crops that either enhance fuel ethanol production (e.g., high-starch corn) or that are not traditional food or feed crops (e.g., switchgrass). If the resultant distillers' grains from these new crops are used as livestock feed or could inadvertently end up in livestock feeds, pre-market assessment of their acceptability in feed prior to their use in fuel ethanol production will be necessary (Hemakanthi and Heller, 2010).

Concerns about cross-pollination, hybridization, pest resistance and disruption of ecosystem functions (FAO, 2004; FAO, 2008; IAASTD, 2009) have limited the use of genetically engineered (GE) crops in some regions. Transgene movement leading to weediness or invasiveness of the crop itself or of its wild or weedy relatives is a major reason (Warwick et al., 2009). Clarity, predictability and established risk assessment processes are literature recommendations to decrease GE crop use concerns (Warwick et al., 2009).[59] The first assessment (NRC, 2010) of the impact of GE crops in use in the USA since 1996 found that benefits to the farmer included increased worker safety from pesticide handling; indicated that water quality improves with GE crops; and acknowledged that more work needs to be done, particularly to install infrastructure to measure water quality impacts, develop weed management practices, and address the needs of farmers whose markets depend on the absence of GE traits.

Several grasses and woody species that are candidates for biofuel production have traits commonly found in invasive species (Howard and Ziller, 2008). These traits include rapid growth, high water-use efficiency and long canopy duration (Clifton-Brown et al., 2000). There are fears that if these crops are introduced, they could become invasive, displace indigenous species and decrease biodiversity. For example, *Jatropha curcas* is considered weedy in several countries, including India and many South American states (Low and Booth, 2007). Warnings have been raised about *Miscanthus* and switchgrass (*Panicum virgatum*). *Sorghum halepense* (Johnson grass), *Arundo donax* (giant reed) and *Phalaris arundinacea* (reed canary grass) are known to be invasive in the USA. A number of protocols have evolved that allow for a systematic assessment and evaluation of the inherent risk associated with species introduction (McWhorter, 1971; Randall, 1996; Molofsky et al., 1999; Dudley, 2000; Forman, 2003; Raghu et al., 2006). DiTomaso et al. (2010) address policies to keep these agro-ecosystems in check while developing desirable biofuels crops, such as preventive actions prior to and during cultivation of biofuel plants.

2.5.6.2 Biofuels production issues

Globally, most biofuels are produced with conventional production technologies (see Section 2.3) that have been used in many industries for many years (Gunderson, 2008; Abbasi and Abbasi, 2010). Hazards associated with most of these technologies are well characterized, and it is possible to limit risks to very low levels by applying existing knowledge and standards (see, e.g., Astbury, 2008; Hollebone and Yang, 2009; Marlair et al., 2009; Williams et al., 2009) and their typology is under development (Rivière and Marlair, 2009, 2010).

The literature highlights environmental health and safety areas for further evaluation as new technologies (see Section 2.6) are developed (e.g., Madsen et al., 2004; Madsen, 2006; Vinnerås et al., 2006; Narayanan et al., 2007; Gunderson, 2008; McLeod et al., 2008; Hill et al., 2009; Martens and Böhm, 2009; Moral et al., 2009; Perry, 2009; Sumner and Layde, 2009). Key areas include:

- Health risk to workers using engineered microorganisms or their metabolites.
- Potential ecosystem effects from the release of engineered microorganisms.
- Impact to workers, biofuel consumers or the environment from pesticides and mycotoxins that accumulate in processing intermediates, residues or products (e.g., spent grains, spent oil seeds).
- Risks to workers from infectious agents that can contaminate feedstocks in production facilities.
- Exposure to toxic substances, particularly for workers at biomass thermochemical processing facilities that use routes not currently practised by the fossil fuels industry.
- Fugitive air emissions and site runoff impacts on public health, air quality, water quality and ecosystems.

59 Other concerns include: reduction in crop diversity, increases in herbicide use, herbicide resistance (increased weediness), loss of farmer's sovereignty over seed, ethical concerns over transgenes origin, lack of access to intellectual property rights held by the private sector, and loss of markets owing to moratoriums on genetically modifed organisms (GMOs) (IAASTD, 2009).

- Exposure to toxic substances, particularly if production facilities become as commonplace as landfill sites or natural gas-fired electricity generating stations.

- Cumulative environmental impacts from the siting of multiple biofuel/bioenergy production facilities in the same air- and/or watershed.

2.5.7 Socioeconomic aspects

The large-scale and global development of bioenergy will be associated with a complex set of socioeconomic issues and trade-offs, ranging from local issues (e.g., income and employment generation, improved health conditions, agrarian structure, land tenure, land use competition and strengthening of regional economies) to national issues (e.g., food security, a secure energy supply and balance of trade). Participation of local stakeholders, in particular small farmers and poor households, is essential to ensure socioeconomic benefits from bioenergy projects.

2.5.7.1 Socioeconomic impact studies and sustainability criteria for bioenergy systems

The complex nature of bioenergy, with many conversion routes and the multifaceted potential socioeconomic impacts, makes the overall impact analysis difficult to conduct. Also, many impacts are not easily quantifiable in monetary or numerical terms. To overcome these problems, semi-quantitative methods based on stakeholder involvement have been used to assess social criteria such as societal product benefit and social dialogue[60] (von Geibler et al., 2006).

Regarding economic impacts, the most commonly reported variables are private production costs over the value chain, assuming a fixed set of prices for basic commodities (e.g., for fossil fuels and fertilizers). The bioenergy costs are usually compared to alternatives already on the market (fossil-based) to judge the potential competitiveness. Bioenergy systems are mostly analyzed at a micro-economic level, although interactions with other sectors cannot be ignored because of the competition for land and other resources. Opportunity costs may be calculated from food commodity prices and gross margins to account for food-bioenergy interactions. Social impact indicators include consequences for local employment, although this impact is difficult to assess because of possible offsets between fossil and bioenergy chains. Impacts at a macro-economic level include the social costs incurred because of fiscal measures (e.g., tax exemptions) to support bioenergy chains (DeLucchi, 2005). Fossil energy's negative externalities also need to be assessed (Bickel and Friedrich, 2005).

Several sustainability frameworks and certification systems have been proposed to better document and integrate the socioeconomic impacts of bioenergy systems, particularly at the project level (Bauen et al., 2009b; WBGU, 2009; van Dam et al., 2010; see also Section 2.4). Specifically, criteria and indicators related to the development of liquid biofuels have been proposed for these issues: human rights, including gender issues; working and wage conditions, including health and safety issues; local food security; rural and social development, with special regard to poverty reduction; and land rights (Table 2.12). So far, while rural and local development are included, specific economic criteria for the cost-effectiveness of the projects, level of subsidies and other financial aspects have not been included in the sustainability frameworks. Most of the frameworks are still under development. The progress of certification systems was reviewed by van Dam et al. (2008, 2010). The FAO's Bioenergy and Food Security Criteria and Indicators project has compiled bioenergy sustainability initiatives (see also Sections 2.4.5.1 and 2.4.5.2).

2.5.7.2 Socioeconomic impacts of small-scale systems

The inefficient use of biomass in traditional devices such as open fires has significant socioeconomic impacts including drudgery for getting the fuel, the cost of satisfying cooking needs, and significant health impacts from the very high levels of indoor air pollution, especially for women and children (Masera and Navia, 1997; Pimentel et al., 2001; Biran et al., 2004; Bruce et al., 2006; Romieu et al., 2009). Indoor air pollutants include respirable particles, CO, oxides of nitrogen and sulphur, benzene, formaldehyde, 1, 3-butadiene, and polyaromatic compounds such as benzo(a)pyrene (Smith et al., 2000). Wood smoke exposure can increase respiratory symptoms and problems (Thorn et al., 2001; Mishra et al., 2004; Schei et al., 2004; Boman et al., 2006). Exposures of household members have been measured to be many times higher than World Health Organization guidelines and national standards (Smith et al., 2000; Bruce et al., 2006) (see also Sections 9.3.4.3 and 9.4.4). More than 200 studies over the past two decades have assessed levels of indoor air pollutants in households using solid fuels. The burden from related diseases was estimated at 1.6 million excess deaths per year, including 900,000 children under five, and a loss of 38.6 million DALY (Disability Adjusted Life Year) per year (Smith and Haigler, 2008). This burden is similar in magnitude to the burden of disease from malaria and tuberculosis (Ezzati et al., 2002).

Properly designed and implemented ICS projects, based on the new generation of biomass stoves, have led to significant health improvements (von Schirnding et al., 2001; Ezzati et al., 2004). ICS health benefits include a 70 to 90% reduction in indoor air pollution, a 50% reduction in human exposure, and reductions in respiratory and other illnesses (Armendáriz et al., 2008; Romieu et al., 2009). Substantial health benefits can accrue even with modest reductions in exposure to indoor air pollutants. For example, in Guatemala, a 50% reduction in exposure has been shown to produce a 40% improvement in childhood pneumonia cases. In India, the health benefits from the dissemination of advanced ICS have been estimated to be potentially equivalent to eliminating nearly half the entire cancer burden in 2020. These health benefits include 240,000 averted premature deaths from acute lower

60 Multi Criteria Analysis methods have been applied in the bioenergy field during the past 15 years (Buchholz et al., 2009).

respiratory infections in children younger than five years and more than 1.8 million averted premature adult deaths from ischemic heart disease and chronic obstructive pulmonary disease (Bruce et al., 2006; Wilkinson et al., 2009).

Figure 2.14 shows the cost effectiveness of treatment options for the eight major risk factors that account for 40% of the global disease burden (Glass, 2006). ICS are among the most cost-effective options in terms of the cost per avoided DALY. Overall, ICS and other small-scale biomass systems represent a very cost-effective intervention with benefits to cost ratios of 5.6:1, 20:1 and 13:1 found in Malawi, Uganda and Mexico, respectively (Frapolli et al., 2010).

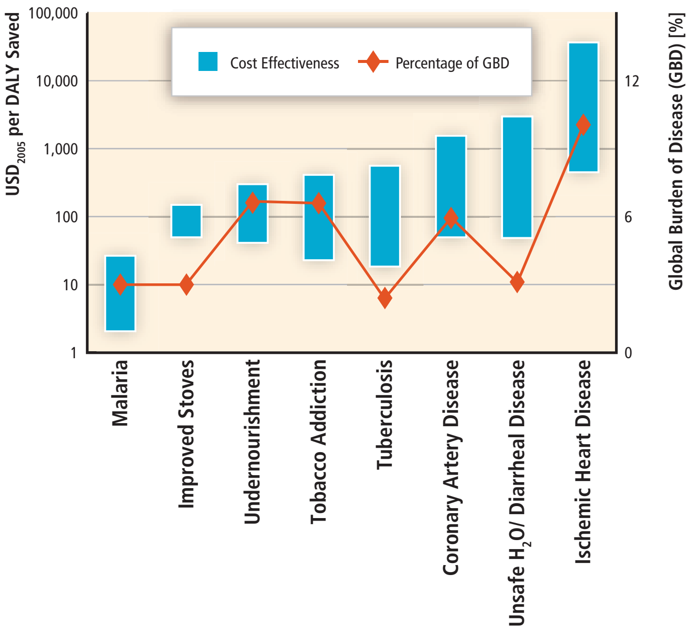


Figure 2.14 | Cost effectiveness of interventions expressed in dollars per disability adjusted life year (DALY) saved (Glass, 2006) on the left scale (logarithmic scale), and contributions to the global burden of disease (GBD) from eight major risk factors and diseases (in %, right scale). The figure shows that the dissemination of improved biomass stoves—depicted here as an intervention to reduce the health effects of indoor air pollution due to fuelwood use—compares well with the cost of interventions aimed at combating major health problems and diseases such as undernourishment, tuberculosis, heart diseases and others (Bailis et al., 2009 with permission from Elsevier B.V.).

Increased use of ICS frees up time for women to engage in income-generating activities. Reduced fuel collection times and savings in cooking time can also translate into increased time for education of rural children, especially girls (Karekezi and Majoro, 2002). ICS use fosters improvements in local living conditions, kitchens and homes, and quality of life (Masera et al., 2000). The manufacture and dissemination of ICS also represents an important source of income and employment for thousands of local small businesses around the world (Masera et al., 2005). Similar impacts were found for small-scale biogas plants, which have the added benefits of providing lighting for individual households and villages and increasing the quality of life. More efficient technologies than currently employed in small-scale industries (such as improved brick and charcoal kilns) are available that increase work productivity, quality of products and overall working conditions (FAO, 2006, 2010b).

2.5.7.3 Socioeconomic aspects of large-scale bioenergy systems

Large-scale bioenergy systems have sparked heated controversies around food security, income generation, rural development and land tenure. The controversy makes clear that there may be both advantages and disadvantages to the further development of large-scale bioenergy systems, depending on their characteristics, local conditions and the mode of implementation.

Impacts on job and income generation

Increased demand for agricultural and forestry waste materials (i.e., residues) can supplement farmers' and foresters' incomes, particularly if the wastes were previously burned or landfilled. Bioenergy can also generate jobs; in general, bioenergy generates more jobs per unit of energy delivered than other energy sources, largely due to feedstock production, especially in developing countries and rural areas (FAO, 2010b).

Wage income is a key contribution to the livelihoods of many poor rural dwellers (Ivanic and Martin, 2008). The benefits from bioenergy jobs depend on the relative labour intensity of the feedstock crop compared to the crop that was previously grown on the same land. For example, cultivation of perennial energy crops requires less labour than cereal crop cultivation, and this displacement effect should be taken into account (Thornley et al., 2009). While increased employment is an important potential benefit, highly labour-intensive operations might also reduce competitiveness (depending on the relative prices of labour and capital) (see Section 9.3.1.3).

The number of jobs created is very location-specific and varies considerably with plant size, the degree of feedstock production mechanization (Berndes and Hansson, 2007) and the contribution of imports to meeting demand (Nusser et al., 2007; Wydra, 2009). Estimates of the employment creation potential of bioenergy options differ substantially, but liquid biofuels based on traditional agricultural crops seem to provide the most employment, especially when the biofuel conversion plants are small (Berndes and Hansson, 2007). Even within liquid biofuel options, the use of different crops introduces wide differences. For ethanol, the number of direct and indirect jobs generated ranges from 45 (corn) to 2,200 (sugarcane) jobs/PJ of ethanol. For biodiesel, the number of direct and indirect jobs generated ranges from 100 (soybean) to 2,000 (oil palm) jobs/PJ of biodiesel (Dias de Moraes, 2007; Clayton et al., 2010). For electricity production, mid-scale power plants in developing countries using a low-mechanized system (25 MW) are estimated to generate approximately 400 jobs/plant or 250 jobs/PJ, of which 94% are in the production and harvesting of feedstocks. For instance, in a detailed UK study, 1.27 jobs/GWh were calculated for power generation from a 25 MW_e plant using dedicated crops (woody or *Miscanthus*). During the complete lifecycle, 4,000 to 6,000 person-year jobs are created, representing on a yearly basis 200 jobs/PJ (15, 73, and 12% at the electricity plant, feedstock production and delivery, and induced, respectively) (Thornley et al., 2008).

In Europe, if the EU25 scenario is followed, Berndes and Hansson (2007) estimate that biomass production for energy can create employment at a magnitude that is significant relative to total agricultural employment (up to 15% in selected countries) but small compared to the total industrial employment in a country. The latest analysis also shows some trade-offs—for instance, agricultural options for liquid biofuels create more employment, but forest-based options for electricity and heat production produce more climate benefits. In Brazil, the biofuel sector accounted for about one million jobs in rural areas in 2001, mostly for unskilled labour related to manual harvesting after field burning of sugarcane (Moreira, 2006). Indeed, mechanization, already ongoing in about 50% of the Center South production (responsible for 90% of the country's harvest), reduces demand for unskilled labour for manual harvest but produces an environmental benefit. Meanwhile, worker productivity continues to grow and part of the workforce is retrained for the skilled higher-paying jobs required for mechanized operations (Oliveira, 2009).

2.5.7.4 Risks to food security

Unless the feedstocks are grown on abandoned land or use residues that previously had no economic value, liquid biofuel production creates additional demand for food and agricultural commodities that places additional pressure on natural resources such as land and water and thus raises food commodity prices (Chakravorty et al., 2009; B. Wright, 2009). Lignocellulosic biofuels, because they can be grown more easily on land that is not suitable for food production, can reduce but not eliminate competition (Chakravorty et al., 2009). To the extent that domestic food markets are linked to international food markets, even countries that do not produce bioenergy may be affected by the higher prices.

Commodity prices are determined by a complex set of factors, of which biofuels is only one, and projections of future prices are highly uncertain. Nevertheless, several studies have examined the contribution of increased biofuels production to the surge in food prices that occurred in the mid-2000s. These studies use different analytical methods and report their results in different ways (for a comprehensive review of these studies, see DEFRA, 2009). For example, the OECD-FAO Agricultural Outlook (OECD-FAO, 2008) model found that if biofuel production were frozen at 2007 levels, coarse grains prices would be 12% lower and vegetable oil prices 15% lower in 2017 compared with a situation where biofuels production continues to increase as expected. Rosegrant et al. (2008) estimated that world maize prices would be 26% higher under a scenario of continued biofuel expansion according to the existing national development plans and more than 70% higher under a drastic biofuel expansion scenario where biofuel demand is double that under the first scenario (these scenarios are relative to a baseline of modest biofuel development where biofuel production remains constant at 2010 levels in most countries). IFPRI (2008) estimated that 30% of the weighted average increase in world cereal prices was attributable to biofuels between 2000 and 2007. Elobeid and Hart (2007) compared two modelled scenarios, with and without biofuel utilization barriers, and found that removing utilization barriers doubled the projected increases in corn and food basket prices. These studies generally agree that increased biofuels production played some role in increased food prices, but there is no consensus about the size of this contribution (FAO, 2008a; Mitchell, 2008; DEFRA, 2009; Baffes and Haniotis, 2010). Other factors include the weak US dollar, increased energy costs, increased agricultural production costs, speculation on commodities, and adverse weather conditions (Headey and Fan, 2008; Mitchell, 2008; DEFRA, 2009; Baffes and Haniotis, 2010). The eventual impact of biofuels on prices will depend, among other factors, on the specific technology used, the strength of government mandates for biofuel use, the design of trade policies that favour inefficient methods of biofuel production, and oil prices.

The impact of higher prices on the welfare of the poor depends on whether the poor are net sellers of food (benefit from higher prices) or net buyers of food (harmed by higher prices). On balance, the evidence indicates that higher prices will adversely affect poverty and food security in developing countries, even after taking into account the benefits of higher prices for farmers (Ivanic and Martin, 2008; Zezza et al., 2008). A major FAO study on the socioeconomic impacts of the expansion of liquid biofuels (FAO, 2008a) indicates that poor urban consumers and poor net food buyers in rural areas are particularly at risk. Rosegrant et al. (2008) estimated that the number of malnourished children would double under the two scenarios mentioned above.

A significant increase in the cultivation of crops for bioenergy indicates a close coupling of the markets for energy and food (Schmidhuber, 2008), and an analysis by the World Bank (2009) confirmed a strong association between food and energy prices when oil prices are above USD_{2005} 45 per barrel. Thus, if energy prices increase, there may be spillovers into food markets that increase food insecurity.

Meeting the food demands of the world's growing population will require a 70% increase in global food production by 2050 (Bruinsma, 2009). At the same time, FAO (2008b) estimates that the increase in arable land between 2005 and 2050 will be just 5% (Alexandratos et al., 2009). This limited increase indicates that economically exploitable arable land is scarce. Because biomass production is land-intensive, there could be significant competition between food and fuel for the use of agricultural land (Chakravorty et al., 2009). Increased biofuels production could also reduce water availability for food production, as more water is diverted to production of biofuel feedstocks (Chakravorty et al., 2009; Hoekstra et al., 2010).

2.5.7.5 Impacts on rural and social development

Growing demand for biofuels and the resulting rise in agricultural commodity prices can present an opportunity for promoting agricultural growth and rural development in developing countries (Schmidhuber, 2008). The development potential critically depends on whether the bioenergy market is economically sustainable without government subsidies. If long-term subsidies are required, fewer government funds will be available for the wide range of other public goods that are essential for economic and social development, such as agricultural research, rural roads, and education. Even short-term subsidies need to be considered very carefully, as once subsidies are implemented they can be difficult to remove. Latin American experience shows that governments that use agricultural budgets for investment in public goods experience faster growth and alleviate poverty and environmental degradation more rapidly than those that apply them for subsidies (López and Galinato, 2007).

Bioenergy may reduce dependence on fossil fuel imports and increase energy supply security. In many cases these benefits are not likely to be large, although the contribution could be substantial for countries with large amounts of arable land per person (FAO, 2008a). Recent analyses of the use of indigenous resources implies that much of the expenditure on energy is retained locally and recirculated within the local or regional economy, but there are trade-offs to consider. For example, the increased use of biomass for electricity production and the corresponding increase in demand for some types of biomass (e.g., pellets) could cause a temporary lack of biomass supply during periods of high demand. Households are particularly vulnerable to this market distortion.

The biofuels production technologies and institutions will also be an important determinant of rural development outcomes. In some instances, private investors will look to establish biofuel plantations to ensure security of supply. If plantations are established on non-productive land without harming the environment, there should be benefits to the economy. It is essential not to overlook the uses of land that are important to the poor. Governments may need to establish clear criteria for determining whether land is marginal or productive, and these criteria must protect vulnerable communities and female farmers who may have less secure land rights (FAO, 2008a). Research in Mozambique shows that, compared with a more capital-intensive plantation approach, an out-grower approach to producing biofuels helps to reduce poverty due to the greater use of unskilled labour and accrual of land rents to smallholders (Arndt et al., 2010).

Increased investment in rural areas will be crucial for making biofuels a positive development force. If governments rely exclusively on short-term farm-level supply side economic response, the negative effects of higher food prices will predominate. If higher prices motivate greater public and private investment in agriculture (e.g., rural roads and education, R&D), there is tremendous potential for sparking medium- and long-term rural development (De La Torre Ugarte and Hellwinckel, 2010). As one example, proposed biofuel investments in Mozambique could increase annual economic growth by 0.6% and reduce the incidence of poverty by about 6% over a 12-year period between 2003 and 2015 (Arndt et al., 2010).

2.5.7.6 Trade-offs between social and environmental aspects

Some important trade-offs between environmental and social criteria exist and need to be considered in future bioenergy developments. In the case of sugarcane, the environmental sustainability criteria promoted by certification frameworks (such as the Roundtable for Sustainable Biofuels) favour mechanical harvesting due to the avoided emissions from sugarcane field burning required in manual systems. Several other organizations are concerned about the large number of workers that will be displaced by these new systems. Also, the mechanized model tends to favour further concentration of land ownership, potentially excluding small- and medium-scale farmers and reducing employment opportunities for rural workers (Huertas et al., 2010).

Strategies for addressing such concerns can include providing support for small- and medium-size stakeholders that lack the capacity to meet the certification system requirements and/or developing alternative income possibilities for the seasonal workers that presently earn a substantial part of their annual income by cutting sugarcane (Huertas et al., 2010). Retraining workers from manual to skilled labour, such as truck driving, is already taking place in Center South Brazil (Oliveira, 2009).

2.5.8 Synthesis

As a component of the much larger agriculture and forestry systems of the world, traditional and modern biomass affects social and environmental issues ranging from health and poverty to biodiversity and water quality. Land and water resources need to be properly managed in concert with each specific region's economic development situation and suitable types of bioenergy. Bioenergy has the opportunity to contribute positively to climate change mitigation, secure energy supply and diversity goals, and economic development in developed and developing countries alike. However, the effects of bioenergy on environmental sustainability may also be negative depending upon local conditions, how criteria are defined, and how actual projects are designed and implemented, among many other factors.

- Climate change and biomass production can be influenced by interactions and feedbacks among land and water use, energy and climate at scales that range from micro through macro (see Figure 2.15). Social and environmental trade-offs may be present but can be minimized to a large extent with appropriate project design and implementation.

- Although crops grown as biofuels feedstocks currently use less than 1% of the world's agricultural land, the expansion of large-scale bioenergy systems raises several important socioeconomic issues including food security, income generation, rural development, land tenure and water scarcity in specific regions.

- Estimates of LUC effects require value judgments about the temporal scale of analysis, the land use under the assumed 'no action' scenario, the expected uses in the longer term, and the allocation of impacts among different uses over time. Regardless, a system that ensures consistent and accurate inventory of and reporting on carbon stocks is considered an important first step towards LUC carbon accounting.

- Emissions of pollutants, like SO_2 and NO_x, are generally lower for bioenergy than for coal, gasoline and diesel, though the NO_x results for biodiesel are more variable. Thus, bioenergy can reduce negative impacts on air quality. Bioenergy impacts on water resources can be positive or negative, depending on the particular feedstock, supply chain element and processing methodologies. Bioenergy systems similar to conventional food and feed crop systems can contribute to loss of habitat and biodiversity, but bioenergy plantations can be designed to provide filters for nutrient loss, to function as ecological corridors, to reduce pressure on natural forests and to restore degraded or abandoned land. Genetically engineered and potentially invasive bioenergy crops have raised concerns. More research and protocols are needed to monitor and evaluate the introduction of new or modified species.

- Advanced ICS for traditional biomass use can provide large and cost-effective mitigation of GHG emissions (GHG mitigation potential of 0.6 to 2.4 Gt CO_2eq/yr) with substantial co-benefits in health and living conditions, particularly for the poorest 2.7 billion people in the world. Efficient technologies for cooking are cost-effective and comparable to major health interventions such as those for tobacco addiction, undernourishment or tuberculosis.

- Biofuel production has contributed to increases in food prices, but additional factors affect food prices, including weather conditions, changes in food demand and increasing energy costs. Even considering the benefit of increased prices to poor farmers, increased food prices have adversely affected poverty, food security and malnourishment of children. On the other hand, biofuels can also

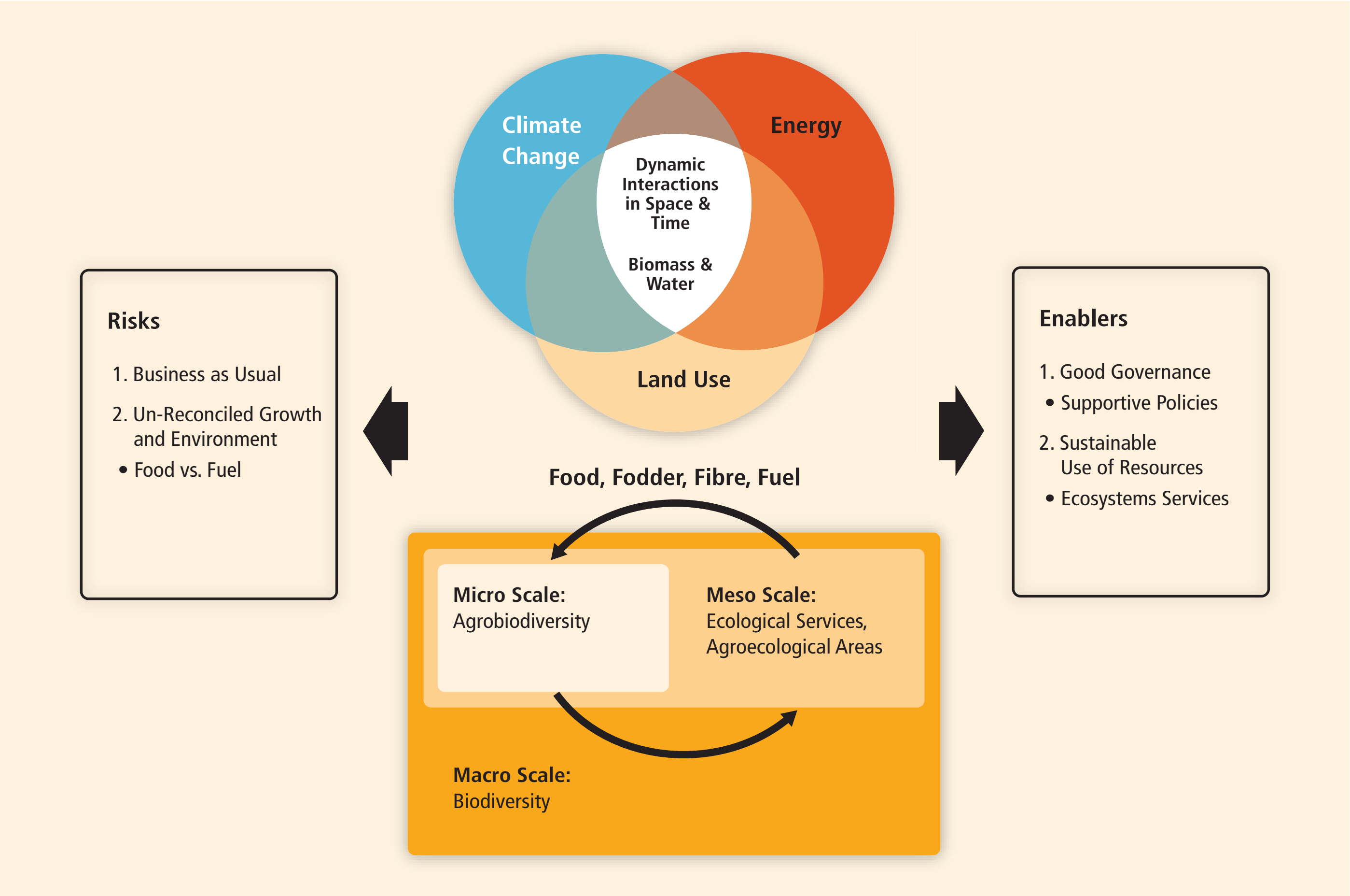


Figure 2.15 | Bioenergy's complex, dynamic interactions among society, energy and the environment include climate change feedbacks, biomass production and land use with direct and indirect impacts at various spatial and temporal scales on all resource uses for food, fodder, fibre and energy (Dale et al., 2011). Biomass resources need to be produced in sustainable ways as their impacts can be felt from micro to macro scales (van Dam et al., 2010). Risks are maintenance of business-as-usual approaches with uncoordinated production of food and fuel. Opportunities are many and include good governance and sustainability frameworks that generate effective policies that also lead to sustainable ecosystem services.

provide opportunities for developing countries to make progress in rural development and agricultural growth, especially when this growth is economically sustainable. Proper design, implementation, monitoring and adherence to sustainability frameworks may help minimize negative socioeconomic impacts and maximize benefits, particularly for local people.

- These social and environmental impacts should be compared with those of the energy systems they replace. Many lifecycle assessments that characterize the amount of RE provided relative to fossil energy used in biofuel production and compare that with the reference system show GHG emission savings for biofuels. These studies can be expanded to use multiple indicators and more comprehensively analyze the whole chain from feedstock to final energy use.

2.6 Prospects for technology improvement and innovation[61]

This section provides a literature overview of the sets of developing technologies, their performance characteristics and projections of cost performance for biomass feedstocks, logistics and supply chains, and conversion routes to a variety of biofuels alone or in combination with heat and power or with other bio-based products. Advanced power routes are also discussed. As illustrated in Figure 2.2 and Table 2.5, many such advanced biomass energy chains are commercial or in development at various stages ranging from small-scale R&D through near commercialization for each component of the chain, including some examples of integrated systems. Linkages are made with the various applications, with the suppliers of feedstocks, which can be residues from urban or rural areas, and with the existing and developing biomass conversion industry to products. The integration of biomass energy and related products into the electricity, natural gas, heating (residential and district, commercial and public services), industrial and fossil liquid fuels systems for transport is discussed more thoroughly in Chapter 8. The structure of this section parallels that of Section 2.3, following the bioenergy supply chain from feedstocks (Section 2.6.1) to logistics (Section 2.6.2) to end products (e.g., various advanced secondary energy carriers in gaseous or liquid states) made by various conversion technologies (Section 2.6.3).

2.6.1 Improvements in feedstocks

2.6.1.1 Yield gains

Increasing land productivity, whether for food or energy purposes, is a crucial prerequisite for realizing large-scale future deployment of biomass for energy because it would make more land available for growing biomass and reduce the associated demand for land. Much of the increase in agricultural productivity over the past 50 years came about through plant breeding and improved agricultural management practices including irrigation, fertilizer and pesticide use. The adoption of these techniques in the developing world is most advanced in Asia, where productivity grew strongly during the past 50 years, and also in Brazil, with sugarcane. Considerable potential exists for extending the same kind of gains to other regions, particularly sub-Saharan Africa, Latin America, Eastern Europe and Central Asia, where adoption of these techniques has been slower (Evenson and Gollin, 2003; FAO, 2008a). A recent long-term forecast by the FAO expects global agricultural production to rise by 1.5% per year for the next three decades, still significantly faster than projected population growth (World Bank, 2009). For the major food staple crops, maximum attainable yields may increase by more than 30% by switching from rain-fed to irrigated and optimal rainwater use production (Rost et al., 2009), while moving from intermediate- to high-input technology may result in 50% increases in tropical regions and 40% increases in subtropical and temperate regions. The yield increase when moving from low- to intermediate-input levels can reach 100% for wheat, 50% for rice and 60% for maize (Table 2.14), due to better pest control and adequate nutrient supply. However, important environmental trade-offs may be involved with agricultural intensification, and avenues for more sustainable management practices may need exploration and adoption (IAASTD, 2009).

Biotechnologies or conventional plant breeding could improve biomass production by focusing on traits relevant to energy production such as biomass per hectare, increased oil or fermentable sugar yields, or other characteristics that facilitate their conversion to energy end-products (e.g., Sannigrahi et al., 2010). Also, considerable genetic improvement is still possible for drought-tolerant plants (Nelson et al., 2007; Castiglioni et al., 2008; FAO, 2008b).

The projected increases in productivity reflect present knowledge and technology (Duvick and Cassman, 1999; Fischer and Schrattenholzer, 2001) and vary across the regions of the world (FAO, 2008a). In developed countries where cropping systems are already highly input-intensive, productivity increases will be more limited. Also, projections do not always account for the strong environmental limitations in many regions, such as water or temperature (Nelson et al., 2007; Castiglioni et al., 2008; FAO, 2008b).

Doubling the current yields of perennial grasses appears achievable through genetic manipulation such as marker-assisted breeding (Turhollow, 1994; Eaton et al., 2008; Tobias et al., 2008; Okada et al., 2010). Shifts to sustainable farming practices and large improvements in crop and residue yield could increase the outputs of residues from arable crops (Paustian et al., 2006).

Future feedstock production cost projections are scant because of their connections with food markets (which are, as all commodities, volatile and uncertain) and because many candidate feedstock types are still in the R&D phase. Cost figures for growing these feedstock species in commercial farms are not well understood yet but will likely reduce over time

61 Section 10.5 offers a complementary perspective on drivers and trends of technological progress across RE technologies.

Table 2.14 | Prospects for yield improvements by 2030 relative to 2007 to 2009 data from Table 2.4.

Feedstock type	Regions	Yield trend (%/yr)	Potential yield increase by 2030 (%)	Improvement routes	Ref.
DEDICATED CROPS					
Wheat	Temperate	0.7	20-50	New energy-oriented varieties	1,10
	Subtropics		30-100	Higher input rates, irrigation	
Maize	N America	0.7	20-35	New varieties, GMOs, higher plantation density, reduced tillage Higher input rates, irrigation	
	Subtropics		20-60		
	Tropics		50		
Soybean	USA	0.7	15-35	Breeding	2,3,10
	Brazil	1.0	20-60		
Oil palm	World	1.0	30	Breeding, mechanization	3
Sugarcane	Brazil	1.5	20-40	Breeding, GMOs, irrigation inputs	2,3,8,10
SR Willow	Temperate	—	50	Breeding, GMOs	3
SR Poplar	Temperate	—	45		
Miscanthus	World	—	100	Breeding for minimal input, improved management	
Switchgrass	Temperate	—	100	Genetic manipulation	
Planted forest	Europe Canada	1.3	20 20	Species choice, breeding, fertilization, shorter rotations, increased rooting depth	4,9 11
PRIMARY RESIDUES					
Cereal straw	World	—	15	Improved collection equipment, breeding for higher residue-to-grain ratios (soybean)	5,6
Soybean straw	N America	—	50		
Forest residues	Europe	1.0	25	Ash recycling, cutting increases, increased roundwood, productivity	4,7

Abbreviations: SR = short rotation; GMO = genetically modified organism.

References: 1. Fischer and Schrattenholzer (2001); 2. Bauen et al. (2009a); 3. WWI (2006); 4. Nabuurs et al. (2002); 5. Paustian et al. (2006); 6. Perlack et al. (2005); 7. EEA (2007); 8. Matsuoka et al. (2009); 9. Loustau et al. (2005); 10. Jaggard et al. (2010). 11. APEC (2003).

as farmers descend the learning curves, as past experience has shown in Brazil (van den Wall Bake et al., 2009).

Under temperate conditions, the expenses for the farm- or forest-gate supply of lignocellulosic biomass from perennial grasses or short-rotation coppice are expected to fall to less than USD_{2005} 2.5/GJ by 2020 (WWI, 2006) from a USD_{2005} 3 to 16/GJ range today (Table 2.6, without land rental cost). However, these are marginal costs, which do not account for the competition for land with other sectors and markets that would increase unit costs as the demand for biomass increases. This is reflected in supply curves (see Section 2.2 and Figure 2.5(b)). Recent studies in Northern Europe that include such land-related costs thus report somewhat higher projections, in a USD_{2005} 2 to 7.5/GJ range for herbaceous grasses and USD_{2005} 1.5 to 6/GJ range for woody biomass (Ericsson et al., 2009; de Wit and Faaij, 2010). For perennial species, the transaction costs required to secure a supply of energy feedstock from farmers may increase the production costs by 15% (Ericsson et al., 2009). Delivered prices for herbaceous crops are shown in Figure 2.5(d) for the USA and about 8 EJ could be delivered at USD_{2005} 5/GJ to the conversion facility.

In recent decades, forest productivity has increased more than 1% per year in temperate and boreal regions due to higher CO_2 concentrations and nitrogen deposition or fertilization rates (Table 2.14). This trend is projected to continue until 2030 when productivity might plateau due to increased stand ages and increased respiration rates in response to warmer temperatures (Nabuurs et al., 2002). However, yield trends vary across climatic zones at a finer scale. Water limitations in Mediterranean/semi-arid environments lead to zero or even negative variations in biomass yield increments by 2030 (Loustau et al., 2005). This may be counteracted by adaptive measures such as choosing species more tolerant to water stress or using appropriate thinning regimes (Loustau et al., 2005). Where water is non-limiting, productivity may be maximized by more intensive silvicultural practices, including shorter rotations, optimum row spacing, fertilization and improved breeding stock (Loustau et al., 2005; Feng et al., 2006). Increased roundwood extraction would also generate extra logging residues and carbon sequestration in forest soils as a co-benefit, outweighing several-fold the GHG emissions generated by management practices (Markewitz, 2006).

2.6.1.2 Aquatic biomass

Aquatic phototrophic organisms dominate the world's oceans, producing 350 to 500 billion tonnes of biomass annually and include 'algae', both microalgae (such as *Chlorella* and *Spirulina*) and macroalgae (i.e., seaweeds) and cyanobacteria (also called 'blue-green algae') (Garrison, 2008). Oleaginous microalgae such as *Schizochytrium* and *Nannochloropsis* can accumulate neutral lipids, analogous to seed oil triacylglycerides, at greater than 50% of their dry cell weight (Chisti, 2007). Weyer et al. (2009) reported yields of 40 x 10^3 to 50 x 10^3 litres/ha/yr (0.04 to 0.05 litres/m^2/yr) in unrefined algal oil from biomass grown in the Equator region and containing 50% oil. Assuming a neutral lipid yield ranging from 30 to 50%, algae productivity can be several-fold higher than palm oil productivity at 4.7 x 10^3 litres/ha/yr (0.0047 litres/m^2/yr). Photosynthetic cyanobacteria used to produce nutraceuticals at commercial scales (J. Lee, 1997; Colla et al., 2007) could also directly produce fuels such as H_2 (Hu et al., 2008; Sections 3.3.5 and 3.7.5).

Macroalgae do not accumulate lipids like microalgae do. Instead, they synthesize polysaccharides from which various fuels could be made (see Figure 2.6). Uncultivated macroalgae can have polysaccharide yields higher than those of terrestrial plants (per unit area) (Zemke-White and Ohno, 1999; Ross et al., 2009) and can live in marine environments. Halophiles, another group of phototrophic organisms, live in environments with high salt concentration.

Microalgae can photoproduce chemicals, fuels or materials in non-agricultural land such as brackish waters and highly saline soils. Hundreds of microalgae species, out of hundreds of thousands of species, have been tested or used for industrial purposes. Understanding the genetic potential, lipid productivity, growth rates and control, and use of genetic engineering allows broader use of land and decreases the LUC impacts of biofuels production (Hu et al., 2008). Microalgae can be cultivated in open ponds and closed photobioreactors (PBRs) (Sheehan et al., 1998a; van Iersel et al., 2009) but scale-up can involve logistical challenges, can require high cost to produce the biomass, and requires water consumption minimization (Borowitzka et al., 1999; Molina Grima et al., 2003). Production costs using low- to high-productivity scenarios currently range approximately from USD_{2005} 30 to 80/GJ for open ponds and from USD_{2005} 50 to 140/GJ for PBR (EPA, 2010).

Macroalgae are typically grown in offshore cultivation systems (Ross et al., 2009; van Iersel et al., 2009) that require shallow waters for light penetration (Towle and Pearse, 1973). The impact of biofuel production on competing uses (fisheries, leisure) and on marine ecosystems needs assessment. Using aquatic biomass harvested from algal blooms may provide multiple benefits (Wilkie and Evans, 2010).

The bioenergy potential from aquatic plants is usually excluded from resource potential determinations because of insufficient data available for such an assessment. However, the potential may be substantial compared to conventional energy crops, considering the high yield potential of cultivated microalgae production (up to 150 dry t/ha/yr, 0.015 t/m^2/yr) (Kheshgi et al., 2000; Smeets et al., 2007). With the large number of diverse algal species in the world, upper range productivity potentials of up to several hundred EJ for microalgae and up to several thousand EJ for macroalgae (Sheehan et al., 1998a; van Iersel et al., 2009) have been reported. Figure 2.10 shows very approximate ranges for GHG reductions relative to the fossil fuel replaced. Comparable or increased emission reductions relative to crop biodiesel could be achieved with successful RD&D and commercialization (EPA, 2010).

Some key conclusions from current efforts (US DOE, 2009; IEA Bioenergy, 2010; Darzins et al., 2010) are the following: (1) Microalgae can offer productivity levels above those possible with terrestrial plants. (2) There are currently several significant barriers to widespread deployment and many information gaps and opportunities for improvement and breakthroughs. (3) Various systems suited to different types of algal organisms, climatic conditions, and products are still being considered. (4) Basic information related to genomics, industrial design and performance is still needed. (5) Cost estimates for algal biofuels production vary widely, but the best estimates are promising at this early stage of technology development. (6) The cost of processing algae solely for fuel production is still too high. Producing a range of products for the food, fodder and fuel markets offers opportunities for economical operation of algal biorefineries. (7) Lifecycle assessments are needed to guide future developments of sustainable fuel production systems.

2.6.2 Improvements in biomass logistics and supply chains

Optimization of supply chains includes achieving economies of scale in transport, in pretreatment and in conversion technologies. Relevant factors include spatial distribution and seasonal supply patterns of the biomass resources, transportation, storage, handling and pretreatment costs, and economies of scale benefiting from large centralized plants (Dornburg and Faaij, 2001; Nagatomi et al., 2008). Smart utilization of a combination of biomass resources over time can help conversion plants gain economies of scale through year-round supplies of biomass and thus efficiently utilize the investment cost (Junginger et al., 2001; McKeough et al., 2005; Nishi et al., 2005; Ileleji et al., 2010; Kang et al., 2010) and technology transfer (Asikainen et al., 2010).

Over time the lower-cost biomass residue resources are increasingly depleted and more expensive (e.g., cultivated) biomass needs to cover the growing demand for bioenergy. Part of this growing demand may be met by learning and optimization, but, for example, future heat generation from pellets in the UK may be more costly (2020) than it is today due to a shift from local to imported feedstocks (E4tech, 2010). Similar effects are found in scenarios for large-scale deployment of biofuels in Europe (Londo et al., 2010).

Learning and optimization in the past one to two decades in Europe (Scandinavia and the Baltic in particular), North America, Brazil and also in various developing countries have shown steady progress in market development and cost reduction of biomass supplies (Section 2.7.2; Junginger et al., 2006). Well-working international biomass markets and substantial investments in logistics capacity are key prerequisites to achieve this (see also Section 2.4).

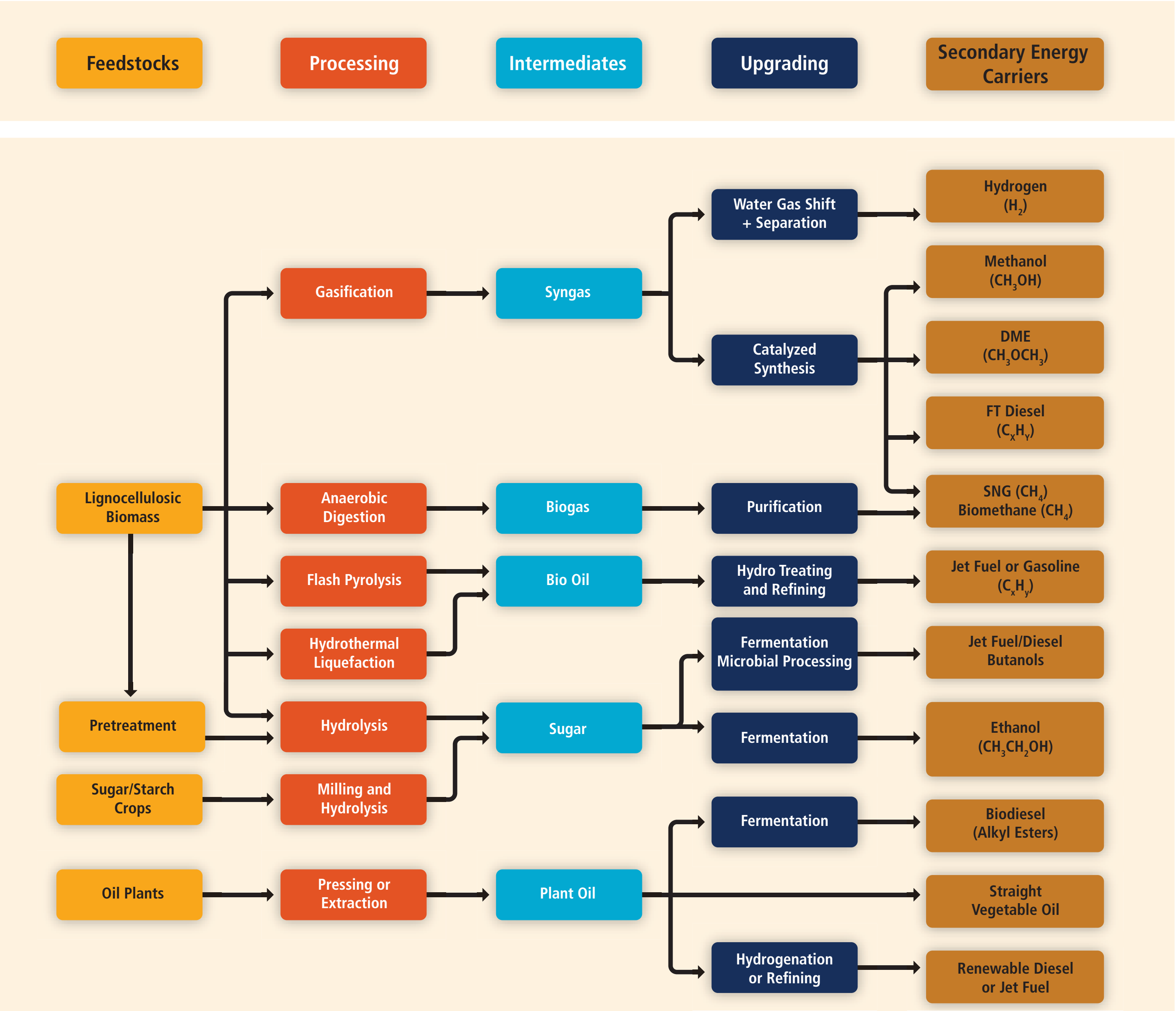


Figure 2.16 | Overview of lignocellulosic biomass, sugar/starch crops and oil plants (feedstocks) and the processing routes to key intermediates, which can be upgraded through various routes to secondary energy carriers, such as liquid and gaseous biofuels. Fuel product examples are (1) oxygenated biofuels to blend with current gasoline and diesel fuels or to use in pure form, such as ethanol, butanols, methanol, liquid ethers, biodiesel, and gaseous DME (dimethyl ether); (2) hydrocarbon biofuels such as Fischer Tropsch (FT) liquids, renewable diesel and some microbial fuels (which are compatible with the current infrastructure of liquid fuels because their chemical composition is similar to that of gasoline, diesel, and jet fuels (see Table 2.15.C)), or the simplest hydrocarbon methane for natural gas replacement (SNG) from gasification or biomethane from anaerobic digestion; and (3) H_2 for future transportation (adapted from Hamelinck and Faaij, 2006 and reproduced with permission from Elsevier B.V.).

Notes: Microbial fuels include hydrocarbons derived from isoprene, the component of natural rubber; a variety of non-fermentative alcohols with three to six carbon atoms including butanols (four carbons); and fatty acids which can be processed as plant oils to hydrocarbons (Rude and Schirmer, 2009).[1] For sugar and starch crops the sugar box indicates six-carbon sugars, while for lignocellulosic biomass this box is more complex and has mixtures of six- and five-carbon sugars, with proportions dependent on the feedstock type. Hardwoods and agricultural residues contain xylan and other polymers of five-carbon sugars in addition to cellulose that yield glucose, a six-carbon sugar.

1. Not shown are the aquatic plants (see Section 2.6.1.2) that can utilize the same types of processing shown for their vegetable oil and carbohydrate fractions.

Pretreatment technologies

Torrefied wood is manufactured by heating wood in a process similar to charcoal production. At temperatures up to 160°C, wood loses water, but it keeps its physical and mechanical properties and typically maintains 70% of its initial weight and 90% of the original energy content (D. Bradley et al., 2009). Torrefied wood only absorbs 1 to 6% moisture (Uslu et al., 2008). Torrefaction can produce uniform quality feedstock, which eliminates inefficient and expensive methods designed to handle feedstock variations and thus makes conversion more efficient (Badger, 2000) and more predictable.

Pyrolysis processes convert solid biomass to liquid bio-oil, a complex mixture of oxidized hydrocarbons. Although this liquid product is toxic and needs stabilization for longer-term storage, bio-oil is relatively easy to transport. Pyrolysis oil production is more expensive and less efficient per unit of energy delivered compared to torrefaction of wood pellets. Section 2.3.4 discusses the cost data for multiple countries based on Bain (2007); McKeough et al. (2005) arrive at similar figures of USD_{2005} 6.2 to 7.0/GJ. The process allows for separation of a solid fraction (biochar) that contains the bulk of the nutrients of the biomass. With proper handling, such biochars could be used to improve soil quality and productivity, recycle nutrients and possibly store carbon in the soil for long periods of time (Laird, 2008; Laird et al., 2009; Woolf et al., 2010).

2.6.3 Improvements in conversion technologies for secondary energy carriers from modern biomass

Different conversion technologies (or combinations) including mechanical, thermochemical, biochemical and chemical steps, as shown in Figure 2.2, are needed to transform the variety of potential feedstocks into a broader range of secondary energy carriers. In addition to electricity and heat as products, a variety of liquid and gaseous fuels or products can be made from biomass as illustrated in Figure 2.16, where key chemical intermediates that could make identical, similar or new products as energy carriers, chemicals and materials are highlighted (see Section 2.6.3.4 for further detail):

- **Sugars**, mixtures of five- and six-carbon sugars from lignocellulosic materials, are converted primarily through biochemical or chemical processes into liquid or gaseous fuels and a variety of chemical products.

- **Syngas** from thermochemical gasification processes, which can be converted in integrated gasification combined cycle (IGCC) systems to electricity, through a variety of thermal/catalytic processes to gaseous or liquid fuels, or through biological processes at low temperature to H_2 or polymers.

- **Oils** from pyrolysis or hydrothermal treatment, which can be upgraded into a variety of fuels and chemicals.

- **Lipids** from plant oils, seeds or microalgae, which can be converted into a wide variety of fuels, such as diesel or jet fuels, and chemicals.

- **Biogas** is a mixture of methane and CO_2 released from anaerobic degradation of organic materials with a lower heat content than its upgraded form, mostly methane, called biomethane. If upgraded, it can be added to natural gas grids or used for transport.

Table 2.15 contains process efficiency and projected improvements along with cost information expressed in USD_{2005}/GJ for several bioenergy systems and chains, in various stages of development, from various studies from multiple sources. Part A details processes for alcohols; Part B summarizes microalgal fuels; Part C details hydrocarbon fuels; and Part D includes gaseous fuels and electricity from IGCC. Financial assumptions are provided at the end of the table; some groups of references use the same assumptions but not all. First-of-a-kind plants are more expensive as there are technical uncertainties in the chemical, biochemical, thermochemical or mechanical component steps in a route, as shown by Kazi et al. (2010) and Swanson et al. (2010) compared to Bauen et al. (2009a) or Foust et al. (2009). Such combination of steps is often significantly more complex than a similar petroleum industry process because of the characteristics of solid biomass. Scaling up is conducted after initial bench-scale experimentation and encouraging initial techno-economic evaluation. As experience in operating the process and correcting design or operating parameters is gained, cost evaluations are conducted and the plant is operated until costs decrease at a slower pace. At this point, the technical and economic risks of the plant have decreased and the production costs have reached so-called nth plant status. The uncertainties in these studies are variable and higher for the least-developed concepts (Bauen et al., 2009a).

An overview of advanced pilot, demonstration and commercial-scale bioenergy projects in 33 countries is provided by Bacovsky et al. (2010a,b), including the site at Kalundborg, Denmark, where a wheat straw ethanol is made in the pilot plant and sold to a gasoline distributor in 2010.[62] The number of actual projects moving to pilot and demonstration scale is probably larger. The reference contains descriptions of most of the development projects listed in Table 2.15. See also the IEA (Renewable Energy Division, 2010) report on global sustainable second-generation technologies and future perspectives in the context of the transport sector and the recently published technology roadmap for biofuels (IEA, 2011).

This section focuses on bioenergy products to avoid repetition of technology descriptions provided in Section 2.3—for instance, a thermochemical technology such as gasification can produce multiple fuels and electricity. Similarly, a variety of end products can be made from sugars.

An initial meta-analysis of advanced conversion routes (Hamelinck and Faaij, 2006) for methanol, H_2, Fischer-Tropsch liquids and biochemical ethanol produced from lignocellulosic biomass under comparable financial assumptions suggests that these systems compare favourably with starch-based biofuels and offer more competitive fuel prices and opportunities in the longer term because of their inherently lower feedstock costs and because of the variety of sources of lignocellulosic biomass, including agricultural residues from cereal crop production, and forest residues. The feedstock cost range used in this meta-analysis is in line with costs highlighted in Section 2.6.1.1 and the low range of the supply curves shown in Figure 2.5. In the EU study, Northern Europe projected production costs are in the USD_{2005} 2 to 7.5/GJ range for herbaceous grasses and USD_{2005} 1.5 to 6/GJ for woody biomass (land-related costs included). For perennial species, transaction costs may need to increase by 15% to secure a supply of energy feedstock from farmers. This additional cost (e.g., transport to the conversion plant and payment to secure the feedstock) is already built into the prices of the US supply

62 An interactive website with this information is maintained by the IEA Bioenergy Task 39: biofuels.abc-energy.at/demoplants.

Table 2.15 | Summary of developing technologies costs projected for 2030 biofuel production and their 2010 industrial development level. Using today's performance for a pioneer plant built in the near term increases costs, and the majority of the references assumes that technology learning will occur upon development, referred to as nth plant costs. Costs expressed in USD_{2005}.

A: Fuels – Alcohols by Biochemical and Gasification Processes

Process	Feedstock	Efficiency and process economics. Eff. = Energy product/biomass energy Component costs in USD_{2005}/GJ	% GHG reduction from fossil reference	Potential technical advances and challenges	Production cost by 2030 (USD_{2005}/GJ)	Industrial development (see Bacovsky et al., 2010a,b)
Consolidated bioprocessing (CBP)	Lignocellulosic	Eff. ~49% for wood and 42% for straw (ethanol) + 5% power.[19]	Scenarios analyzed[30]	Lignin engineering cellulose access.[7] Develop CBP organisms.[44]	15.5[19] future	Demonstration and pilots. Reduce enzyme and pretreatment costs. Several pilots in many countries. First commercial plants. Lignin residues co-firing.[32]
Separate hydrolysis/co-fermentation		Eff. ~39% (ethanol) + 10% power.[1]		Efficient 5-carbon sugar conversion.[2,3] R&D investment.[5] Advanced enzyme.[6]	25[1]–27[19] 28–35[48]	
Simultaneous saccharification/co- fermentation	Barley straw	Steam explosion, enzyme hydrolysis, ethanol fermentation.[9] High solids 15%.	N/A	System integration, high solids, decrease toxicity for fermentation.	30[9] (Finland) from pilot data	
Simultaneous saccharification and fermentation	Corn stover	Dilute acid hydrolysis, 260 million L/yr; FC: 6.6, CC*: 10.1, CR: 1.1 for ethanol.[24]	83–88 Depending on co-product credit method[25]	Pretreatment, process integration, enzyme costs.[24]	15.5 (US) nth plant, future[24]	
	Lignocellulosic Various Eff. 35% ethanol + 4% power.[1]	Generic; 90 million L/yr; FC:14; CC*:14. At 360 million L/yr; FC:14; CC*:10; CR:0.5.[45]		Meta-analysis conditions.[45]	28 (2015)[45] 23.5 (2022)[45]	
		Eff. kg/L ethanol (poplar, *Miscanthus*, switchgrass, corn stover, wheat: 3.7, 3.2, 2.6, 2.6, 2.4). Plant sizes 1,500 to 1,000 t/day. FC 50% of total.[10]		Process integration—capital costs per installed litre of product USD 0.9 to 1.3 for plants of 150 to 380 million litres/yr (2020 estimates). Project a 25% operating cost reduction by 2025 and a 40% operating cost reduction by 2035.[10]	18–22[10] (2020) breakeven USD 100/barrel; + CCS USD 95/barrel; USD 50/t CO_2	
	Bagasse	Standalone plant[35] 370 L/t dry (ethanol) + 0.56 kWh/L ethanol (elec.).	86 Advanced CHP: 120% (replace NG peak power).[36]	Mechanical harvest improvements sugarcane residues (occurring).[35,36]	6[35]–15[35] w/o and w FC	
Gasification/catalytic synthesis ethanol	Lignocellulosic	170 million L per year plant (varies in size).[18] By-product propanol/butanols.	90[38]	Improvements in catalyst development and syngas cleaning.	12[49]–15[18] 14.5[24]	RD&D, pilot.
Fermentation; product compatible with gasoline infrastructure to butanols, in particular biobutanol	Sugar/starch	Development of an integrated biobutanol production and removal systems using the solvent-producing bacteria *Clostridia* improved by genetic engineering.[29] Initial acetone, butanol, and ethanol (ABE) fermentation is costly.	5–31 Depending on co-product credit method.[29]	For high selectivity to biobutanol: (1) mutated strain of *Clostridium beijernekei* BA101, or protein engineering in *E. coli* to increase selectivity/lower cost to biobutanol.[15,16] (2) dual fermentation to butyric acid and reduction to butanols.	29.6 for ABE;[18] 25.2 for mutated *Clostridia*[17] or 21.6 for dual process[17]	Large and small venture companies in different routes, including yeast host. Hydrocarbon precursor.
Gasification to butanols	Lignocellulosic	Catalytic process for synthesis of predominantly butanols.	N/A	Estimated production costs include return on capital.[17]	13[17]	N/A
Gasification/synthesis to methanol for fuel and/or power	Lignocellulosic	Eff. 55% fuel only[19] Eff. 48% fuel and 12% power.[19]	90[27]	Methanol (and dimethyl ether) production possible in various configurations that co-produce power.	12–18 (fuel)[19] 7.1–9.5 (fuel and power)[19]	Pilots, demos, and first commercial.

Continued next Page →

curves based on county-level data; the projected price of delivery to the conversion facility for forest and related residues is USD_{2005} 1 to 3/GJ up to about 1.5 EJ, and for woody and herbaceous plants and sorghum delivered to the conversion facility the projected price is USD_{2005} 2 to 4/GJ up to about 5 EJ (or more at higher price).

2.6.3.1 Liquid fuels

Alcohols. Estimated production costs for various fuel processes are assembled in Part A of Table 2.15, and they range from USD_{2005} 13 to 30/GJ.

B: Fuels – Algae

Process	Feedstock	Efficiency and process economics Eff. = Energy product/biomass energy Component costs in USD_{2005}/GJ	% GHG reduction from fossil reference	Potential technical advances and challenges	Production cost by 2030 (USD_{2005}/GJ)	Industrial development
Lipid production, extraction, and conversion of microalgae neutral lipids to biodiesel or renewable diesel. Remainder of algal mass digested or used in other process	Microalgae lipids; see Section 2.6.1.2	Assuming biomass production capacity of 10,000 t/yr, cost of production per kg is USD 0.47 and 0.60 for photobioreactors (PBR) and raceways, respectively.[23]	28–76 Scenarios for open pond and bioreactor[34]	Assuming[34] biomass contains 30% oil by weight, cost of biomass for providing a litre of oil would be USD 1 to 3 and USD 1.5 to 5 for algae of low productivity = 2.5 g/m²/day or high productivity = 10 g/m²/day in open ponds or photobiological reactors.	Preliminary Results 95 or more[23] 30–80[34] for open ponds 50–140[34] for PBR going from low to high productivity	Active R&D by companies small and large including pilots pursuing jet and diesel fuel substitutes.

C: Fuels – Hydrocarbons by Gasification, Pyrolysis, Hydrogenation and Isomerization of Vegetable Oils and Wastes

Process	Feedstock	Efficiency and process economics Eff. = Energy product/biomass energy Component costs in USD_{2005}/GJ	% GHG reduction from fossil reference	Potential technical advances and challenges	Production cost by 2030 (USD_{2005}/GJ)	Industrial development
Gasification to syndiesel followed by FT (Fischer-Tropsch) process. Known as biomass to liquids. With and without CCS. Process makes hydrocarbons fuels (number of carbon atoms) for gasoline (5–10); kerosene (jet fuel) (10–15); diesel (15–20); fuel oil (20–30)	Lignocellulosic	Eff. = 0.42 fuel only; 0.45 fuel + power.[19]	91[27] (EU)	CCS for CO_2 from processing.	14–20 (fuel only) 8–11 (fuel/power)[19] 15.2-18.6[43]	One first commercial plant (wood) under way. Many worldwide demonstration and pilot processes under way.
		80 million L/yr; FC:12, CC*17 (2015); 280 million L/yr; FC:12, CC*8 (2022).[45]		Meta-analysis conditions.[45]	20–29.5[45]	
		Eff. = 0.52 w/o CCS and 0.5 w/ CCS + 35 and 24 MW_e. 4000 t/day switchgrass. Plant cost ~ USD 650 Mi.[10]	90[26] (US)	Gas clean-up costs and scale/volume. Breakeven with barrel of crude oil of USD 122 (USD 113 with CCS and USD 50/t CO_2).[10]	25[10] (w/o CCS US) 30[10] (w/ CCS US) see[38] for cost breakdown (2020)	
		Eff. = 0.52 + 22 MW_e. Capital USD 500 million; wide range of densified feeds imported into EU for processing.[39]	Detailed Well-to-Wheel EU[39] US[14] scenarios	Breakeven with barrel of crude oil of USD 75. Mixture of 50% biomass and coal is climate neutral.	16–22.5[39]	
		Coal and biomass co-gasification.	See Fig. 2.10	Switchgrass and mixed prairie grasses.	29[38]	
Hydrogenation to renewable diesel	Plant oils, animal fat, waste	Technology well known. Cost of feedstock is the barrier.	63–130[26] Depending on the co-product treatment method	Feedstock costs drive this process. Process is standard in petrochemical operations.	17–18[34]	One large and few small commercial (see, e.g., footnote 68 in the main text); many demos.
Biomass pyrolysis[4] and catalytic upgrading to diesel/jet fuel; vegetable oils processed directly into a refinery [33]	Biomass/ wastes, plant oils, animal fat, waste oils	Developing pyrolysis[8,13] process (also from hydrothermal processing)[46] to a blendstock for a refinery,[33] for direct coupled firing in a boiler (e.g., with coal)[32] or a final product.		Catalyst development, process yield improvements with biomass.	14–24[47] for pyrolysis oils to refinery blendstocks	Demos and fuel product tests in USA, Brazil, EU. Test flights using biojet fuels from plant oils conducted.[33]

Continued next Page →

While some methanol, butanols and other alcohol production processes from biomass exist in various stages of technical development, the most predominant alcohol production pathways have ethanol as their finished product. Lignocellulosic ethanol technologies have many possible process chains (e.g., Sánchez and Cardona, 2008; Sims et al., 2010). Those with the highest sugar yields and with low environmental impact were considered more promising (Wooley et al., 1999) and involve chemical/biochemical, mechanical/chemical/biochemical, and biological/chemical/biochemical processing steps. Most of these chains involve a pretreatment step to overcome the recalcitrance of the plant cell wall, with separate and partial hydrolysis of the cellulose and hemicelluloses fibres to release the complex streams of five- and six-carbon sugars for fermentation. Simultaneous saccharification and fermentation (SSF), simultaneous saccharification and co-fermentation (SSCF) and consolidated bioprocessing

D: Gaseous Fuels, Power and Heat from Gasification

Process	Feedstock	Efficiency and process economics Eff. = product energy/biomass energy Component costs in USD_{2005}/GJ	% GHG reduction from fossil reference	Potential technical advances and challenges	Production cost by 2030 (USD_{2005}/GJ)	Industrial development
Gasification/syngas processing of H_2 to fuel and power	Lignocellulosic	Eff. 60% (fuel only). Needs 0.19 GJ of elect. per GJ H_2 for liquid estimated at USD 11–14/GJ (long term), wood USD 2.4/GJ, USD 568/kW_{th} capital.[19]	88[30]	Co-production H_2 and power (55% fuel efficiency, 5% power) in the longer term.[19] USD 426/kW_{th} capital.[19]	4–5[19] (longer) 6[20]–12[12] 5.5–7.7[41]	R&D stage.
Gasification/methanation to methane for fuel, heat and/or power	Lignocellulosic	Eff. ~60% (or higher for dry feed).[42] Combined fuel and power production possible.	98[27]	RD&D on gas clean up and methanation catalysts. For wet feedstocks wet gasification developing.[46]	10.6–11.5[42] wood USD 2.8/GJ	RD&D stage.
Anaerobic digestion, upgrading of gas, liquefaction	Organic wastes, sludges	Eff. ~20 to 30%; includes mixtures of animal and agriculture residues.		Improve technology robustness with new metagenomic tools, reduce costs.	15–16[21]	
Integrated gasification combined cycle for CHP	Lignocellulosic	District heating; power-to-heat ratio 0.8 to 1.2; power production efficiency 40 to 45%; total efficiency 85 to 90%. Investment USD 1,200/kW_{th}. Wood residues in Finland.[22]	96[31]	Gas cleaning, increased efficiency cycles, cost reductions. IGCC at 30 to 300 MW[45] with a capital cost of USD 1,150 to 2,300/kW_e, at 10% discount rate, 20 year plant life, and USD 3/GJ. Meta-analysis conditions.	8–11[11] 13–19[45] or US cents 4.5–6.9/kWh	Demos at 5 to 10 MW projected cost at USD 29–38/GJ or US cents 10–13.5/kWh.[45]

Notes: Abbreviations: *Conversion costs (CC) include investment costs and operating expenses; CR = Co-product Revenue; FC = feedstock cost; CC = conversion cost. All CC, CR, FC costs are given in USD_{2005}/GJ.

System Boundaries: Many references use a 10% discount rate, 20-yr plant life referred to as meta-analysis conditions. 17. Production costs include return on capital; 24.10% IRR (Internal Rate of Return), 39% tax rate, 20-yr plant life, Double-declining-balance depreciation method, 100% equity, nth plant, for the biochemical pathway costs are FC: 6, CC*: 10.6, CR: 1.1 and for thermochemical pathway costs are FC: 6.7, CC*: 10, CR: 2.5; 3012% IRR, 39% tax rate, 25-yr plant life, Modified Accelerated Cost Recovery System depreciation method (MACRS dep.), 65/35 equity/debt, 7% debt interest, nth plant, FC: 8.2, CC*: 16.9, CR: 2.6; 37. Pioneer (first-of-a-kind) plant example: 10% IRR, 39% tax rate, 20-yr plant life, MACRS dep., 100% equity, FC: 12.2–20.7, CC*: 27.3–38, CR: 0–6; 38. 7% discount rate, 39% tax rate, 20-yr plant life, MACRS dep., 45/55 equity/debt, 4.4% debt interest, nth plant, FC w/ CCS: 16, FC w/o CCS: 8.8, CC* w/ CCS: 14.7, CC* w/o CSS: 15.7, CR w/ CCS: 2, CR w/o CCS: 2.1; 39.10% discount rate, 10-yr plant life; 40. Pioneer plant example: 10% IRR, 39% tax rate, 20-yr plant life, MACRS dep, 100% equity, FC: 9.5, CC*: 24.5, CR: 1.1; 41.10% IRR, 15-yr plant life.

References: 1. Hamelinck et al. (2005a); 2. Jeffries (2006); 3. Jeffries et al. (2007); 4. Balat et al. (2009) and see IEA Bioenergy Pyrolosis Task (www.pyne.co.uk); 5. Sims et al. (2008); 6. Himmel et al. (2010); 7. Sannigrahi et al. (2010); 8. Bain (2007); 9. von Weyman (2007); 10. NRC (2009a); 11. IEA Bioenergy (2007); 12. Kinchin and Bain (2009); 13. McKeough et al 2005; 14. Wu et al. (2005); 15. Ezeji et al. (2007a); 16. Ezeji et al. (2007b); 17. Cascone (2008); 18. Tao and Aden (2009); 19. Hamelinck and Faaij (2006); 20. Hoogwijk (2004); 21. Sustainable Transport Solutions (2006); 22. Helynen et al. (2002); 23. Chisti (2007); 24. Foust et al. (2009); 25. Wang et al. (2010); 26. Kalnes et al. (2009); 27. Edwards et al. (2008); 28. Huo et al. (2009); 29. Wu et al. (2008); 30. Laser et al. (2009); 31. Daugherty (2001); 32. Cremers (2009) (see IEA co-firing database at www.ieabcc.nl/database/cofiring.php); 33. IATA (2009); 34. EPA (2010); 35. Seabra et al. (2010); 36. Macedo et al. (2008); 37. Kazi et al. (2010); 38. Larson et al. (2009); 39. van Vliet et al. (2009); 40. Swanson et al. (2010); 41. Hamelinck and Faaij (2002); 42. Mozaffarian et al. (2004); 43. Hamelinck et al. (2004); 44. van Zyl et al. (2007); 45. Bauen et al. (2009a); 46. Elliott (2008); 47. Holmgren et al. (2008); 48. Dutta et al. (2010); 49. Phillips et al. (2007).

(CBP), which combines all of the hydrolysis, fermentation and enzyme production steps into one, were defined as short-, medium- and longer-term approaches, respectively. For CBP, efficiencies and yields are expected to increase and costs to decrease by 35 and 66% relative to SSF and SSCF, respectively (Hamelinck et al., 2005a, and see Table 2.15).

Pretreatment is one of the key technical barriers causing high costs, and a multitude of possible options exist. So far, no 'best' technology has been identified (da Costa Sousa et al., 2009; Sims et al., 2010). Pretreatment overcomes the recalcitrance of the cell wall of woody, herbaceous or agricultural residues and makes carbohydrate polymers accessible to hydrolysis (e.g., by enzymes) and in some cases liberates a portion of the sugars for fermentation to ethanol (or butanols) and the lignin for process heat or electricity. Alternatively, multiple steps (including pretreatment) can be combined with other downstream conversion steps and material can be bioprocessed with multiple organisms simultaneously. To evaluate pretreatment options,[63] the use of common

63 The areas of biomass pretreatment and low-cost ethanol emerged as essential in 2009 with fourteen core papers establishing a biology/biochemistry/biomass chemical analysis concentration area (sciencewatch.com/dr/tt/2009/09-octtt-BIO/). Included were coordinated pretreatment research in multiple US and Canadian institutions, investigating common samples and analytical methodology and conducting periodic joint evaluation of technical and economic performance of these processes.

feedstocks and common analytical methodology (Wyman et al., 2005) is needed to differentiate between the performance of the many chains and combinations. For corn stover, among the evaluated options of ammonia fibre expansion (AFEX), dilute acid and hot water pretreatments, dilute acid pretreatment had the lowest cost and the hot water process cost was the highest by 25%. This ranking, however, does not hold for other feedstocks (Elander et al., 2009). On-site enzyme preparation increased the cost of the dilute acid pretreatment by 4.5% (Kazi et al., 2010). Apart from pretreatment, enzymes are another key variable cost and are the focus of major global efforts in RD&D and cost reduction (e.g., Himmel et al., 2010; Sims et al., 2010). Finally, all of the key individual conversion steps (e.g., pretreatment, enzymatic hydrolysis and fermentation) are highly interdependent. Therefore, process integration is another very important focus area, as many steps are either not yet optimized or have not been optimized in a fully integrated process.

The US National Academies analyzed liquid transport fuels from biomass (NRC, 2009a), and their cost analysis found the breakeven point for cellulosic ethanol with crude oil to be USD_{2005} 100/barrel (USD_{2005} 0.64/litre) in 2020, which translates to USD_{2005} 18 to 22/GJ. This projection is similar[64] to the USD_{2005} 23.5/GJ projected by Bauen et al. (2009a) for 2022. The National Research Council (NRC, 2009a) projects that by 2035, process improvements could reduce the plant-related costs by up to 40%, or to within USD_{2005} 12 to 15/GJ, in line with estimates for nth plant costs of USD_{2005} 15.5/GJ (Foust et al., 2009). Further cost reductions in some of the processing pathways may come from converting bagasse to ethanol, as the feedstock is already at the conversion facility, and the bagasse has the potential to produce an additional 30 to 40% yield of ethanol per unit land area in Brazil (Seabra et al., 2010). A similar strategy is currently being employed in the USA, where the coupling of crop residue collection and collocation of the second-generation (residue) and first-generation (corn) ethanol facilities are being pursued by two of the first commercial cellulosic ethanol plant developments by the U.S. Department of Energy.[65]

Several strains of microorganisms have been selected or genetically modified to increase the enzyme production efficiency (FAO, 2008b) for SSF (Himmel et al., 2010), for SSCF (e.g., Dutta et al., 2010) and for CPB (van Zyl et al., 2007; Himmel et al., 2010). Many of the current commercially available enzymes are produced in closed fermenters from genetically modified (GM) microorganisms. The final enzyme product does not contain GM microorganisms (Royal Society, 2008), which facilitates acceptance of the routes (FAO, 2008b).

64 See Table 2.15 for financial assumptions that are not identical; Bauen et al. (2009a) and Foust et al. (2009) are close.

65 Impact Assessment of first-of-a-kind commercial ethanol from corn stover and cobs collocated with grain ethanol facilities is provided by the Integrated Bioenergy Projects. U.S. DOE Golden Field Office web site: www.eere.energy.gov/golden/Reading_Room.aspx; www.eere.energy.gov/golden/PDFs/ReadingRoom/NEPA/Final_Range_Fuels_EA_10122007.pdf; www.eere.energy.gov/golden/PDFs/ReadingRoom/NEPA/POET_Project_LIBERTY_Final_EA.pdf; and www.biorefineryprojecteis-abengoa.com/Home_Page.html.

Microbial fuels. Industrial microorganisms[66] with imported genes to accelerate bioprocessing functions (Rude and Schirmer, 2009) can make hydrocarbon fuels, higher alcohols, lipids and chemicals from sugars. Researchers in synthetic biology have imported pathways, and more recently used artificial biology to design alternative biological paths into microorganisms, which may lead to increased efficiency of fuels and chemicals production (Keasling and Chou, 2008; S. Lee et al., 2008). Another route is to alter microorganisms' existing functions with metabolic engineering tools. Detailed production costs are not available in the literature but Regalbuto (2009) and E4tech (2009) summarize some data.[67] Additionally, some microalgae can metabolize sugars in the absence of light (heterotrophically) to make lipids (similar to plant oils) that are easily converted downstream to biodiesel and/or renewable diesel or jet fuel. With additional genetic engineering, the microorganisms can excrete lipids, leading to a decrease in production costs. Microbial biofuels and chemicals are under active development (Alper and Stephanopoulos, 2009; Rude and Schirmer, 2009).

Gasification-derived products (see Table 2.15.A and B)

Gasification of biomass to syngas (CO and H_2) followed by catalytic upgrading to either ethanol or butanols has estimated production costs (USD_{2005} 12 to 20/GJ) comparable to the biochemical chains discussed above. The lowest-cost liquid fuel is methanol (produced in combination with power) at USD_{2005} 7 to 10/GJ (USD_{2005} 12 to 18/GJ for fuel only). Further reduction in production costs of fuels derived from gasification will depend on significant development of IGCC (currently at the 5 to 10 MW_e demonstration phase) to obtain practical experience and reduce technical risks. Costs are projected to be USD_{2005} 13 to 19/GJ (US $cents_{2005}$ 4.6 to 6.9/kWh) for 30 to 300 MW_e plants (see Table 2.15; Bauen et al., 2009a). Although process reliability is still an issue for some designs, niche markets have begun to develop (Kirkels and Verbong, 2011).

Even though the cost bases are not entirely comparable, the recent estimates for Fischer-Tropsch (FT) syndiesel from Bauen et al. (2009a), van Vliet et al. (2009), the NRC (2009a) and Larson et al. (2009) are (in USD_{2005}/GJ), respectively: 20 to 29.5, 16 to 22, 25 to 30, and 28 (coal and biomass). The breakeven point would occur around USD_{2005} 80 to 120/barrel (USD_{2005} 0.51 to 0.74/litre). High efficiency gains are expected, especially in the case of polygeneration with FT fuels (Hamelinck and Faaij, 2006; Laser et al., 2009; Williams et al., 2009).

Process intensification is the combination of multiple unit operations conducted in a chemical plant into one thus reducing its footprint and

66 E.g., *Escherichia coli* and *Saccharomyces cerevisiae* have well-established genetic tools and industrial use.

67 Rude and Schimer (2009) report stoichiometric data, for example, per tonne of glucose the number of litres is 297 of farnesene (for diesel), and 384 of microbial biocrude oil (for jet fuel) compared with 648 of ethanol (for gasoline). Metabolic mass yields are 25 and 30% for farnesene and biocrude, respectively, compared to 51% for ethanol. The routes grow the intermediate cell mass that then starts producing biofuels or intermediates—these steps are usually aerobic and require air and agitation that reduce the overall energy efficiency.

capital costs and enabling plants to operate more cost effectively at smaller scale. Therefore chemical/thermal processing that previously could only be conducted at very large scale could now be downsized to match the supply of biomass cost effectively. Efficient heat and mass transfer in micro-channel reactors has been explored to compact reactors by 1-2 orders of magnitude in water-gas-shift, steam reforming and FT processes for conventional natural gas or coal gasification streams (Nehlsen et al., 2007) and significantly reduce capital costs (Schouten et al., 2002; Sharma, 2002; Tonkovich et al., 2004). Such intensification could lead to distributed biomass to liquids (BTL) production, as capital requirements would be significantly reduced (as they would be for coal to liquids (CTL) or gas to liquids (GTL) (Shah, 2007). Methanol/DME synthesis could be intensified as well. Additionally, combined biomass/coal gasification options could capture some of the economies of scale while taking advantage of biomass' favourable CO_2 mitigation potential.

Other intermediates: vegetable or pyrolysis/ hydrothermal processing oils

For **diesel substitution**, hydrogenation technologies are already commercially producing direct hydrocarbon diesel substitutes from hydrogenation of vegetable oils to renewable diesel in 2011.[68] Costs depend on the vegetable oil prices and subsidies (see Table 2.15.C and Section 2.3.4). Lignocellulosic residues from vegetable oil production could provide the energy for standalone hydrogenation. The downstream processing of the lipids/plant oils to finished fuels is often conducted in conjunction with a petroleum refinery, in which case jet fuel and other products can be made.

Fast **pyrolysis** processes or **hydrothermal liquefaction** processing of biomass make low-cost intermediate oil products (Bain, 2007; Barth and Kleinert, 2008; Section 2.7.1). Holmgren et al. (2008) estimated production costs for lignocellulose pyrolysis upgrading to a blendstock (component that can be blended with gasoline at a refinery) as USD_{2005} 14 to 24/GJ, from bench scale data.

Under mild conditions of **aqueous phase reforming** and in the presence of multifunctional supported metal catalysts, biomass-derived sugars and other oxygenated organics can be combined and chemically rearranged (with retention of carbon and hydrogenation) to make hydrocarbon fuels. These processes can also make hydrogen at moderate temperature and pressure (Cortright et al., 2002; Huber et al., 2004, 2005, 2006; Davda et al., 2005; Gurbuz et al., 2010). These developments have reached the pilot and demonstration phase (Regalbuto, 2009).

From carbon dioxide, water and light energy with photosynthetic algae (Table 2.15.B)

Microalgal lipids (microalgal oil) are at an early stage of R&D and currently have significant feedstock production and processing costs, ranging from USD_{2005} 30 to 140/GJ (EPA, 2010). Exploring the biodiversity of microbial organisms for their chemical composition and their innate microbial pathways can lead to use of highly saline lands, brackish waters or industrial waste waters, avoiding competition with land for food crops but the potential of microalgae is highly uncertain.

Prospects. In the near to medium term, the biofuel industry, encompassing first- and second-generation technologies that meet agreed-upon environmental and economic sustainability and policy goals, will grow at a steady rate. It is expected that the transition to an integrated first- and second-generation biofuel landscape will likely require another decade or two (Sims et al., 2008, 2010; NRC, 2009a; Darzins et al., 2010).

2.6.3.2 Gaseous fuels

Part D of Table 2.15 compares estimated production costs for the production of gaseous fuels from lignocellulosic biomass and various waste streams:

Anaerobic digestion. Production of methane from a variety of waste streams, alone or combined with agricultural residues, is being used throughout the world at various levels of performance. The estimated production costs depend strongly on the application: USD_{2005} 1 to 2/GJ for landfill gas, USD_{2005} 15 to 20/GJ for natural gas or transport applications, USD_{2005} 50 to 60/GJ for on-farm digesters/small engines and USD_{2005} 100 to 120/GJ for distributed electricity generation (see Tables 2.6 and 2.15). The reliability, predictability and cost of individual technologies and assembled systems could be decreased using advanced metagenomics tools[69] and microbial morphology and population structure (Cirne et al., 2007). Also, control and automation technologies and improved gas clean-up and upgrading and quality standards are needed to permit injection into natural gas lines, which could result in more widespread application. Avoided methane emissions provide a significant climate benefit with simultaneous generation of energy and other products.

Synthesis gas-derived methane (a substitute for natural gas), methanol-dimethyl ether (DME), and H_2 are gaseous products from biomass gasification that are projected to be produced in the USD_{2005} 5 to 18/GJ range. After suitable gas cleaning and tar removal, the syngas is converted in a catalytic synthesis reactor into other products by designing catalysts and types of reactors used (e.g., nickel/magnesium catalysts will lead to SNG, while copper/zinc oxide will preferentially make methanol and DME). Processes developed for use with multiple feedstocks in various proportions can decrease investment risks by ensuring continuous feedstock availability throughout the year and decreasing vulnerability to weather and climate. Methanol synthesis from natural gas (and coal) is practised commercially, and synthesis from biomass is being developed at demonstration and first commercial plants. H_2 production has the lowest potential costs, but more developed infrastructure

68 Renewable Diesel is currently produced by Neste Oil in Singapore from Malaysian palm oil and then shipped to Germany (see biofuelsdigest.com/bdigest/2011/03/11/neste-oil-opens-giant-renewable-diesel-plant-in-singapore/). The development of the process took about 10 years from proof of principle as described in www.climatechange.ca.gov/events/2006-06-27+28_symposium/presentations/CalHodge_handout_NESTE_OIL.PDF (nesteoil.com/).

69 See, for instance, www.jgi.doe.gov/sequencing/why/99203.html.

is needed for transportation applications (Kirkels and Verbong, 2011). DME is another product from gasification and upgrading (jointly produced with methanol). It can be made from wood residues and black liquor and is being pursued as a transportation fuel. Sweden considered scenarios for multiple bioenergy products, including a substantial replacement of diesel fuel and gasoline with DME and methanol (Gustavsson et al., 2007).

Microbial fuel cells using organic matter as a source of energy are being developed for direct generation of electricity. Electricity is generated through what may be called a microbiologically mediated oxidation reaction, which implies that overall conversion efficiencies are potentially higher for microbial fuel cells compared to other biofuel processes (Rabaey and Verstraete, 2005). Microbial fuel cells could be applied for the treatment of liquid waste streams and initial pilot winery wastewater treatment is described by Cusick et al. (2011).

2.6.3.3 Biomass with carbon capture and storage: long-term removal of greenhouse gases from the atmosphere

Bioenergy technologies coupled with CCS (Obersteiner et al., 2001; Möllersten et al., 2003; Yamashita and Barreto, 2004; IPCC, 2005; Rhodes and Keith, 2008; Pacca and Moreira, 2009) could substantially increase the role of biomass-based GHG mitigation if the geological technologies of CCS can be developed, demonstrated and verified to maintain the stored CO_2 over time. These technologies may become a cost-effective indirect mitigation, for instance, through offsets of emission sources that are expensive to mitigate directly (IPCC, 2005; Rhodes and Keith, 2008; Azar et al., 2010; Edenhofer et al., 2010; van Vuuren et al., 2010).

Corn ethanol manufacturers in the USA supply CO_2 for carbonated beverages, flash freezing meat and to enhance oil recovery in depleted fields, but due to the low commercial value of CO_2 markets and requirements for regional proximity, the majority of the ethanol plants vent it into the air. CO_2 capture from sugar fermentation to ethanol is thus possible (Möllersten et al., 2003) and may now be used for carbon sequestration. Demonstrations of these technologies are proceeding.[70] The impact of this technology was projected to reduce the lifecycle GHG emissions of a natural gas-fired ethanol plant from 39 to 70% relative to the fossil fuel ethanol replaced, while the energy balance is degraded by only 3.5% (see Table 2.13 for performance in different functional units) ((S&T)[2] Consultants, 2009).

Similarly, van Vliet et al. (2009) estimated that a net neutral climate change impact could be achieved by combining 50% BTL and 50% coal FTL fuels with CCS, if biomass gasification and CCS can be made to work at an industrial scale and the feedstock is obtained in a climate-neutral manner (see Figure 2.10). Perhaps additional removal could be achieved by using crops that increase soil carbon content (e.g., on degraded lands) as indicated by Larson et al. (2009).

2.6.3.4 Biorefineries

The concept of biorefining is analogous to petroleum refining in that a wide array of products including liquid fuels, chemicals and other products (Kamm et al., 2006) can be produced. Even today's first generation biorefineries are making a variety of products (see Table 2.7), many of which are associated with food and fodder production. For example, sugarcane ethanol biorefineries produce multiple energy products (EPE, 2008, 2010). Sustainable lignocellulosic biorefineries can also enhance the integration of energy and material flows (e.g., Cherubini and Strohman 2010). These biorefineries optimize the use of biomass and resources in general (including water and nutrients) while mitigating GHG emissions (Ragauskas et al., 2006). The World Economic Forum (King et al., 2010) projects that biorefinery revenue potentials with existing policies along the entire value chain could be significant and could reach about USD_{2005} 295 billion by 2020.[71]

2.6.3.5 Bio-based products

Bio-based products are defined as non-food products derived from biomass. The term is typically used for new non-food products and materials such as bio-based plastics, lubricants, surfactants, solvents and chemical building blocks. Plastics represent 73% of the total petrochemical product mix, followed by synthetic fibres, solvents, detergents and synthetic rubber (2007 data; Gielen et al., 2008). Bio-based products can therefore be expected to play a pivotal role in these product categories, in particular plastics and fibres.

The four principal ways of producing polymers and other organic chemicals from biomass are: (1) direct use of several naturally occurring polymers, usually modified with some thermal treatment, chemical transformation or blending; (2) thermochemical conversion (e.g., pyrolysis or gasification) followed by synthesis and further processing; (3) fermentation (for most bulk products) or enzymatic conversion (mainly for specialty and fine chemicals) of biomass-derived sugars or other intermediates; and (4) bioproduction of polymers or precursors in genetically modified field crops such as potatoes or *Miscanthus.*

Worldwide production of recently emerging bio-based plastics is expected to grow from less than 0.4 Mt in 2007 to 3.45 Mt in 2020 (Shen et al., 2009). Cost-effective bio-based products with properties superior to those in conventional materials, not just renewability, are

70 See sequestration.org/report.htm and www.netl.doe.gov/technologies/carbon_seq/database/index.html. In the USA, through the Midwest Geological Sequestration Consortium, a coal-fired wet-milled ethanol plant is planning over three years to inject 1 Mt of CO_2 into the Mount Simon sandstone saline formation in central Illinois at a depth of about 2 km in a verification phase test project including monitoring, verification and accounting, which is in the characterization phase (June 2010).

71 Approximate values (USD_{2005} billion by 2020) of business potential for the various parts of the value chain were estimated as: agricultural inputs (15), biomass production (89), biomass trading (30), biorefining inputs (10), biorefining fuels (80), biorefining chemicals and products (6), and biomass power and heat (65).

projected to penetrate the markets (King et al., 2010). For synthetic organic materials production, scenario studies indicate that at a productivity of 0.15 ha/t, an area of 75 million hectares globally could supply the equivalent of 15 to 30 EJ of value-added products (Patel et al., 2006).

Given the early stage of development, the GHG abatement costs differ substantially. The current abatement costs for polylactic acid are estimated at USD_{2005} 100 to 200/t of abated CO_2. Today's abatement costs for bio-based polyethylene, if produced from sugarcane-based ethanol, may be of the order of USD_{2005} 100/t CO_2 or lower. For all processes, technological progress in chemical and biochemical conversion and the combined production of bioenergy is likely to reduce abatement costs by USD_{2005} 50 to 100/t CO_2 in the medium term (Patel et al., 2006).

2.6.4 Synthesis

Lignocellulosic feedstocks offer significant promise because they (1) do not compete directly with food production; (2) can be bred specifically for energy purposes (or energy-specific products), enabling higher production per unit land area, and have a very large market for the products; (3) can be harvested as residues from crop production and other systems that increase land use efficiency; and (4) allow the integration of waste management operations with a variety of other industries offering prospects for industrial symbiosis at the local level.

Drivers and challenges for converting biomass to fuels, power, heat and multiple products are economic growth and development, environmental awareness, social needs, and energy and climate security. The estimated revenue potential along the entire value chain could be of the order of USD_{2005} 295 billion in 2020 with current policies (King et al., 2010).

Residues from crop harvests and from planted forests are projected to increase on average by about 20% by 2030 to 2050 in comparison to 2007 to 2009. Production costs of bioenergy from perennial grasses or short rotation coppice are expected to fall to under USD_{2005} 2.5/GJ by 2020 (WWI, 2006), from a range of USD_{2005} 3 to 16/GJ today. Supply curves projecting the costs and quantities available at specific sites are needed, and they should also consider competing uses as shown in examples in Figure 2.5. For example, EU and US lignocellulosic supply curves show more than 20 EJ at reasonable delivered costs by 2025 to 2030.

A new generation of aquatic feedstocks that use sunlight to produce algal lipids for diesel, jet fuels or higher-value products from CO_2 and water can provide strategies for lowering land use impacts because they enable use of lands with brackish waters or industrial waste water. Today's estimated production costs are very uncertain and range from USD_{2005} 30 to 140/GJ in open ponds and engineered reactors.

Many microbes could become microscopic factories to produce specific products, fuels or materials that decrease society's dependence on fossil energy sources.

Although significant technical progress has been made, the more complex processing required by lignocellulosic biomass and the integration of a number of new steps take time and support to bring development through the 'Valley of Death' in demonstration plants, first-of-a kind plants and early commercialization. Projected costs from a wide range of sources and process variables are very sensitive to feedstock cost and range from USD_{2005} 10 to 30/GJ. The US National Academies project a 40% reduction in operating costs for biochemical routes by 2035.

Cost projections for pilot integrated gasification combined cycle plants in many countries are USD_{2005} 13 to 19/GJ (US $cents_{2005}$ 4.6 to 6.9/kWh at USD_{2005} 3/GJ feedstock cost). In addition to providing power, syngas can be used to produce a wide range of fuels or can be used in a combined power and fuels approach. Estimated projected costs are in the range of USD_{2005} 12 to 25/GJ for methanol, ethanol, butanols and syndiesel. Biomass to liquids technology uses a commercial process already developed for fossil fuel feedstocks. Gaseous products (H_2, methane, SNG) have lower estimated production costs (USD_{2005} 6 to 12/GJ) and are in an early commercialization phase.

The production of biogas from a variety of waste streams and its upgrading to biomethane is already penetrating small markets for multiple applications, including transport in Sweden and heat and power in Nordic and European countries. A key factor is the combination of waste streams with agriculture residues. Improved upgrading and further cost reductions are still needed.

Pyrolysis oil/hydrothermal oils are low-cost transportable oils (see Sections 2.3.4 and 2.7.2) that could become a feedstock for upgrading either in standalone facilities or coupled to a petrochemical refinery. Pyrolysis oils have low estimated production costs of about USD_{2005} 7/GJ and provide options for electricity, heat and chemicals production. Pyrolysis-oil stabilization and subsequent upgrading still require cost reductions and are active areas of research.

Many bioenergy/biofuels routes enable CCS with significant opportunities for removal of GHGs from the atmosphere. As CCS technologies are further developed and verified, coupling concentrated CO_2 streams from fermentation or IGCC for electricity or biomass and coal to liquids through Fischer-Tropsch processes with CCS offer opportunities to achieve carbon-neutral fuels, and in some cases carbon-negative fuels, within the next 35 years. Achieving this goal will be facilitated by well-designed systems that span biomass selection, feedstock supply systems, conversion technologies to secondary energy carriers, and integration of these carriers into the existing energy systems of today and tomorrow.

2.7 Cost trends[72]

2.7.1 Determining factors

Determining the production costs of energy (or materials) from biomass is complex because of the regional variability in the costs of feedstock production and supply and the wide variety of deployed and possible biomass conversion technology combinations. Key factors that affect the costs of bioenergy production are:

- For crop production: the cost of land and labour, crop yields, prices of various inputs (such as fertilizer), water supply and the management system (e.g., mechanized versus manual harvesting) (Sections 2.3.1 and 2.6.1; see Wiskerke et al., 2010 for a local specific example).

- For delivering biomass to a conversion facility: spatial distribution of biomass resources, transport distance, mode of transport and the deployment (and timing) of pretreatment technologies in the chain. Supply chains range from onsite use (e.g., fuelwood or use of bagasse in the sugar industry, or biomass residues in other conversion facilities) all the way to international supply chains with shipped pellets or liquid fuels such as ethanol (Sections 2.3.2 and 2.6.2); see Dornburg and Faaij (2001) on regional transport for power; Hamelinck et al. (2005b) on international supply chains.

- For final conversion to energy carriers (or biomaterials): the scale of conversion, financing mechanisms, load factors, production and value of co-products and ultimate conversion costs (in the production facility). These key factors vary between technologies and locations. The type of energy carrier used in the conversion process influences the climate mitigation potential (Wang et al., 2011).

The analyses of Hoogwijk et al. (2009) provide a global and long-term outlook for potential biomass production costs (focused on perennial cropping systems) of different IPCC SRES scenarios (IPCC, 2000) discussed in Sections 2.8.4 and 2.8.5 (see Table 2.16 and Figure 2.17). Land rental/lease costs, although a smaller cost factor in most world regions, are dependent on intensity of land use in the underlying scenarios. Capital costs vary due to different levels of mechanization. Based on these analyses, a sizeable part (100 to 300 EJ) of the long-range technical potentials based on perennial cropping systems could cost around USD_{2005} 2.3/GJ. The cost range depends on the assumed scenario conditions, and is shown in Figure 10.23 (Hoogwijk et al., 2009; see also cost supply curves and potentials shown in Figure 2.5 for near-term production). More details on costs of both annual and perennial energy crop production are described in Sections 2.3.1 and 2.6.1.

Biomass supplies are, as with any commodity, subject to complex pricing mechanisms. Biomass supplies are strongly affected by fossil fuel prices (OECD-FAO, 2008; Schmidhuber, 2008; Tyner and Taheripour, 2008) and by agricultural commodity and forest product markets. In an ideal situation, demand and supply will balance and price levels will provide a good measure of actual production and supply costs (see also Section 2.5.3 for discussions on LUC). At present, market dynamics determine the costs of the most important biofuel feedstocks, such as corn, rapeseed, palm oil and sugarcane. For wood pellets, another important internationally traded feedstock for modern bioenergy production, prices have been strongly influenced by oil prices, because wood pellets partly replace heating oil, and by supportive measures to stimulate green electricity production, such as FITs for co-firing (Section 2.4; Junginger et al., 2008). In addition, prices of solid and liquid biofuels are determined by national settings, and specific policies and the market value of biomass residues for which there may be alternative applications is often determined by price mechanisms of other markets influenced by national policies (see Junginger et al., 2001 for a specific example for Thailand).

2.7.1.1 Recent levelized costs of electricity, heat and fuels for selected commercial systems

The factors discussed above make it clear that it is difficult to generate generic cost information for bioenergy that is valid worldwide. Nonetheless, this section provides estimates for the recent levelized cost of electricity (LCOE), heat (LCOH) and fuels (LCOF) typical of selected commercial bioenergy systems, some of which are described in more technological detail in Section 2.3.4.[73] The methodology for calculating levelized cost is described in Annex II. Data and assumptions used to produce these figures are provided in Annex III, with those assumptions derived in part from the literature summarized earlier.

The results of the LCOE, LCOH and LCOF calculations for a selected set of commercially available bioenergy options, and based on recent costs, are summarized in Figure 2.18 and discussed below.

To calculate the LCOE for electricity generation, a standardized range of feedstock cost of USD_{2005} 1.25 to 5/GJ was assumed (based on High Heating Value, HHV). To calculate the LCOE of CHP plants where both electricity and heat are produced, the heat was counted as a co-product with revenue that depended on the assumed quality and application of the heat. For large-scale CHP plants, where steam is generated for process heat, the co-product revenue was set at USD_{2005} 5/GJ. For small-scale CHP plants, on the other hand, the revenue was effectively set according to the cost of hot water, or USD_{2005} 13/GJ (applicable, e.g., in Nordic countries and Europe).

The LCOH for heating systems illustrated in the light blue bars of Figure 2.18 is less certain due to a more limited set of available literature. For

72 Discussion of costs in this section is largely limited to the perspective of private investors producing secondary energy carriers. Chapters 1 and 8 to 11 offer complementary perspectives on cost issues covering e.g. costs of integration, external costs and benefits, economy-wide costs and costs of policies.

73 The levelized cost of energy represents the cost of an energy generating system over its lifetime; it is calculated as the per-unit price at which energy must be generated from a specific source over its lifetime to break even. It usually includes all private costs that accrue upstream in the value chain, but does not include the downstream cost of delivery to the final customer the cost of integration or external environmental or other costs. Subsidies and tax credits are also not included.

Table 2.16 | Estimated regional technical potential of energy crops for 2050 (in EJ) on abandoned agricultural land and rest of land at various cut-off costs (in USD_{2005}/GJ biomass harvested, including local transport) for the two extreme SRES land use scenarios A1 and A2 (Hoogwijk et al., 2009; reproduced with permission from Elsevier B.V.).

Region	A1: high crop growth intensity and maximum international trade in 2050			A2: low crop growth intensity and minimum trade and low technology development in 2050		
cut-off cost	**<1.15 USD/GJ**	**<2.3 USD/GJ**	**<4.6 USD/GJ**	**<1.15 USD/GJ**	**<2.3 USD/GJ**	**<4.6 USD/GJ**
Canada	0	11.4	14.3	0.0	7.9	9.4
USA	0	17.8	34.0	0.0	6.9	18.7
C America	0	7.0	13.0	0.0	2.0	2.9
S America	0	11.7	73.5	0.0	5.3	14.8
N Africa	0	0.9	2.0	0.0	0.7	1.3
W Africa	6.6	26.4	28.5	7.9	14.6	15.5
E Africa	8.1	23.8	24.4	3.6	6.2	6.4
S Africa	0	12.5	16.6	0.1	0.3	0.7
W Europe	0	3.0	11.5	0.0	5.6	12.5
E Europe	0	6.8	8.9	0.0	6.2	6.3
Former USSR	0	78.6	84.9	0.8	41.9	46.6
Middle East	0	0.1	3.0	0.0	0.0	1.3
South Asia	0.1	12.1	15.3	0.6	8.2	9.8
East Asia	0	16.3	63.6	0.0	0.0	5.8
SE Asia	0	8.8	9.7	0.0	6.9	7.0
Oceania	0.7	33.4	35.2	1.6	16.6	18.0
Japan	0	0.0	0.1	0.0	0.0	0.0
Global	**15.5**	**271**	**438**	**14.6**	**129**	**177**

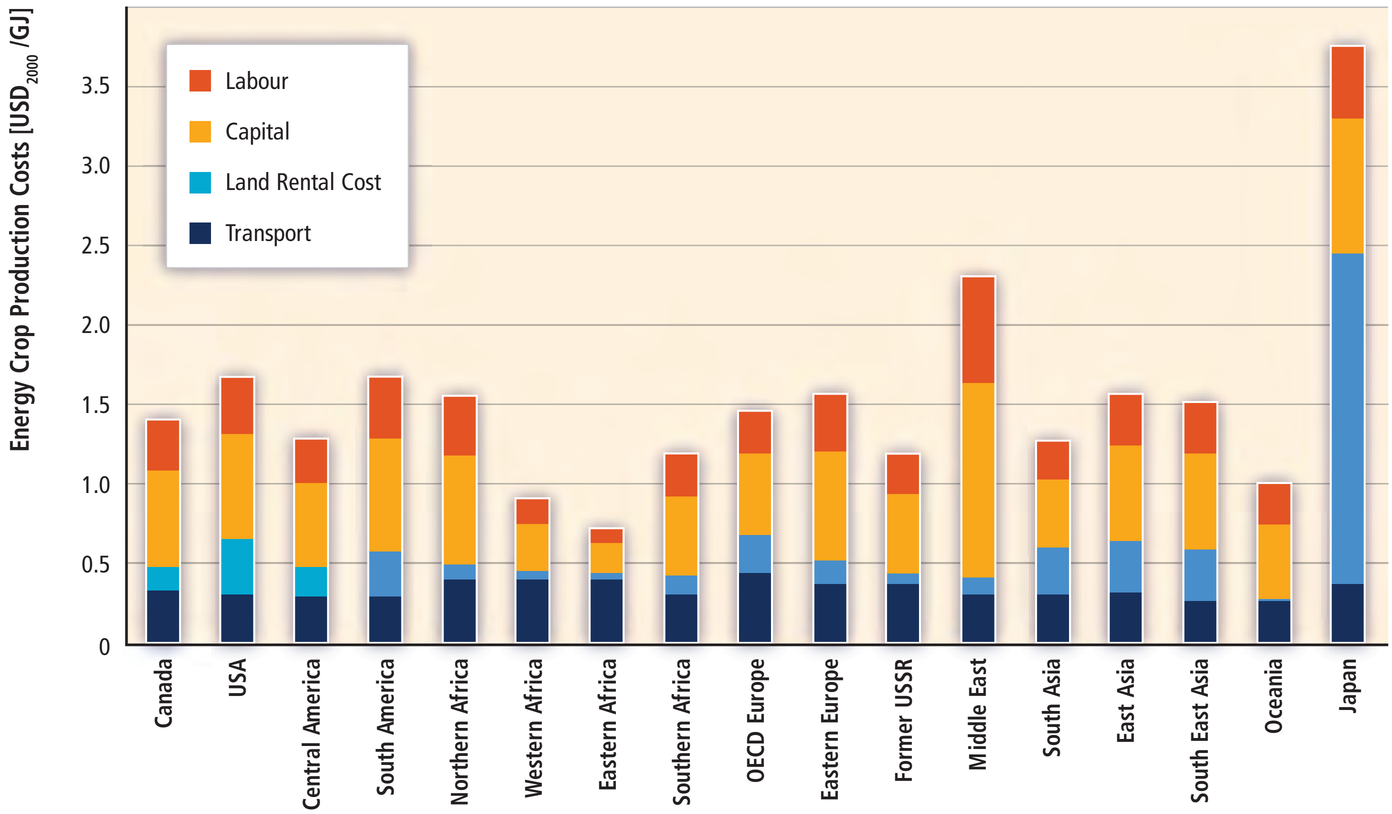


Figure 2.17 | Cost breakdown for energy crop production costs in the grid cells with the lowest production costs within each region for the SRES A1 scenario (IPCC, 2000) in 2050 (in USD_{2000} instead of USD_{2005})(Hoogwijk et al., 2009; reproduced with permission from Elsevier B.V.).

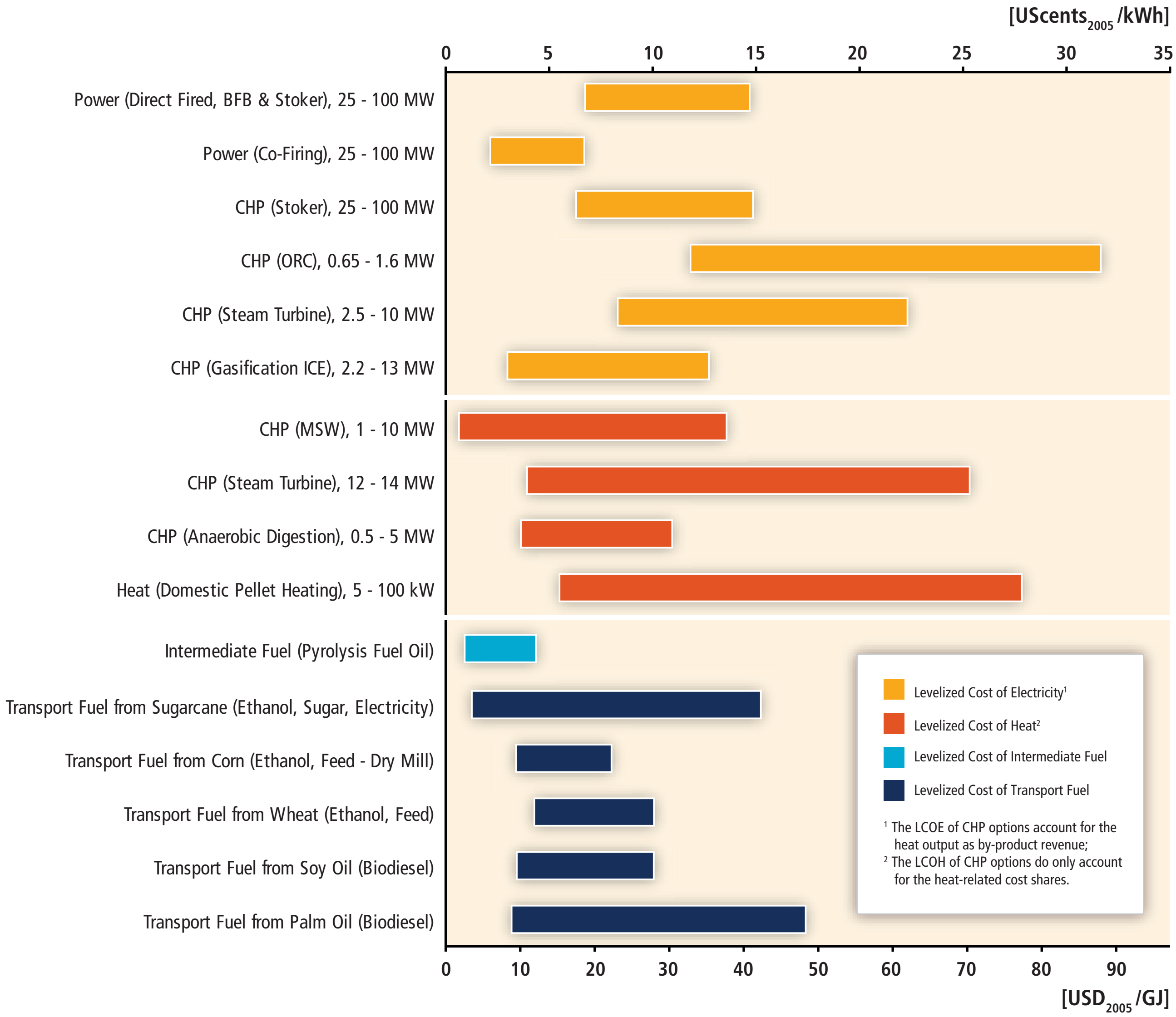


Figure 2.18 | Typical recent levelized cost of energy service from commercially available bioenergy systems at 7% discount rate. Feedstock cost ranges differ between technologies. For levelized cost at other discount rates (3 and 10%) see Annex III and Section 10.5. For biofuels, the range of LCOF represents production in a wide range of countries whereas LCOE and LCOH are given only for major user markets of the technologies for which data were available. The underlying cost and performance assumptions used in the calculations are summarized in Annex III. Calculations are based on HHV.

Abbreviations: BFB: Bubbling fluidized bed; ORC: Organic Rankine cycle; ICE: Internal combustion engine.

heating applications, investment cost assumptions came principally from literature from European and Nordic countries, which are major users of these applications (see Figure 2.8). Feedstock cost ranges came from the same literature and therefore may not be representative of other world regions: feedstock costs were assumed to be USD_{2005} 0 to 3.0/GJ for MSW and low-cost residues, USD_{2005} 2.5 to 3.7/GJ for anaerobic digestion, USD_{2005} 3.7 to 6.2/GJ for steam turbine and USD_{2005} 10 to 20/GJ for pellets. The LCOH figures presented here are therefore most representative of European systems.

LCOF estimates were derived from a techno-economic evaluation of the production of biofuels in multiple countries (Bain, 2007).[74] Underlying feedstock cost assumptions represent the maximum and minimum recent feedstock cost in the respective regions, and are provided in Annex III. All routes for biofuel production take into account sometimes multiple co-product revenues, which were subtracted from expenditures to calculate the LCOF. In the case of ethanol from sugarcane, for example,

74 The study was done in conjunction with a preliminary economic characterization of feedstock supply curves for the Americas, China and India (Kline et al., 2007) described in Section 2.2.3. The biomass market potential associated with these calculations (Alfstad, 2008) is shown in Figure 2.5(c) (45 EJ, 25 EJ and 8 EJ respectively for the high-growth, baseline and low-growth cases for these countries).

the revenue from sugar was set at USD_{2005} 4.3/GJ_{feed}, though this value varies with sugar market prices and can go up to about USD_{2005} 5.6/GJ_{feed}. For the LCOF calculations, however, average by-product revenues were assumed. Along with ethanol and sugar (and potentially other biomaterials in the future), the third co-product is electricity, revenues for which were also assumed to be deducted in calculating the LCOF. A similar approach was used for other biofuel pathways (see Annex III). This single example, however, illustrates the complexity of biofuel production cost assessments.

Finally, the levelized cost of pyrolysis oil as an intermediate fuel, a densified energy carrier, was also assessed, because pyrolysis oils are already used for heating and CHP applications and are also being investigated for stationary power and transport applications (see Sections 2.3.3.2, 2.6.2 and 2.6.3.1).

Figure 2.18 presents a broad range of values, driven by variations not only in feedstock costs but also investment costs, efficiencies, plant lifetimes and other factors. Feedstock costs, however, not only vary substantially by region but also represent a sizable fraction of the total levelized cost of many bioenergy applications. The effect of different feedstock cost levels on the LCOE of the electricity generation technologies considered here is shown more clearly in Figure 2.19, where variations are also shown for investment costs and capacity factors.[75] Similar effects are shown for the levelized cost of biofuels (LCOF) in Figure 2.20. (Though a figure is not shown for heating systems, a similar relationship would

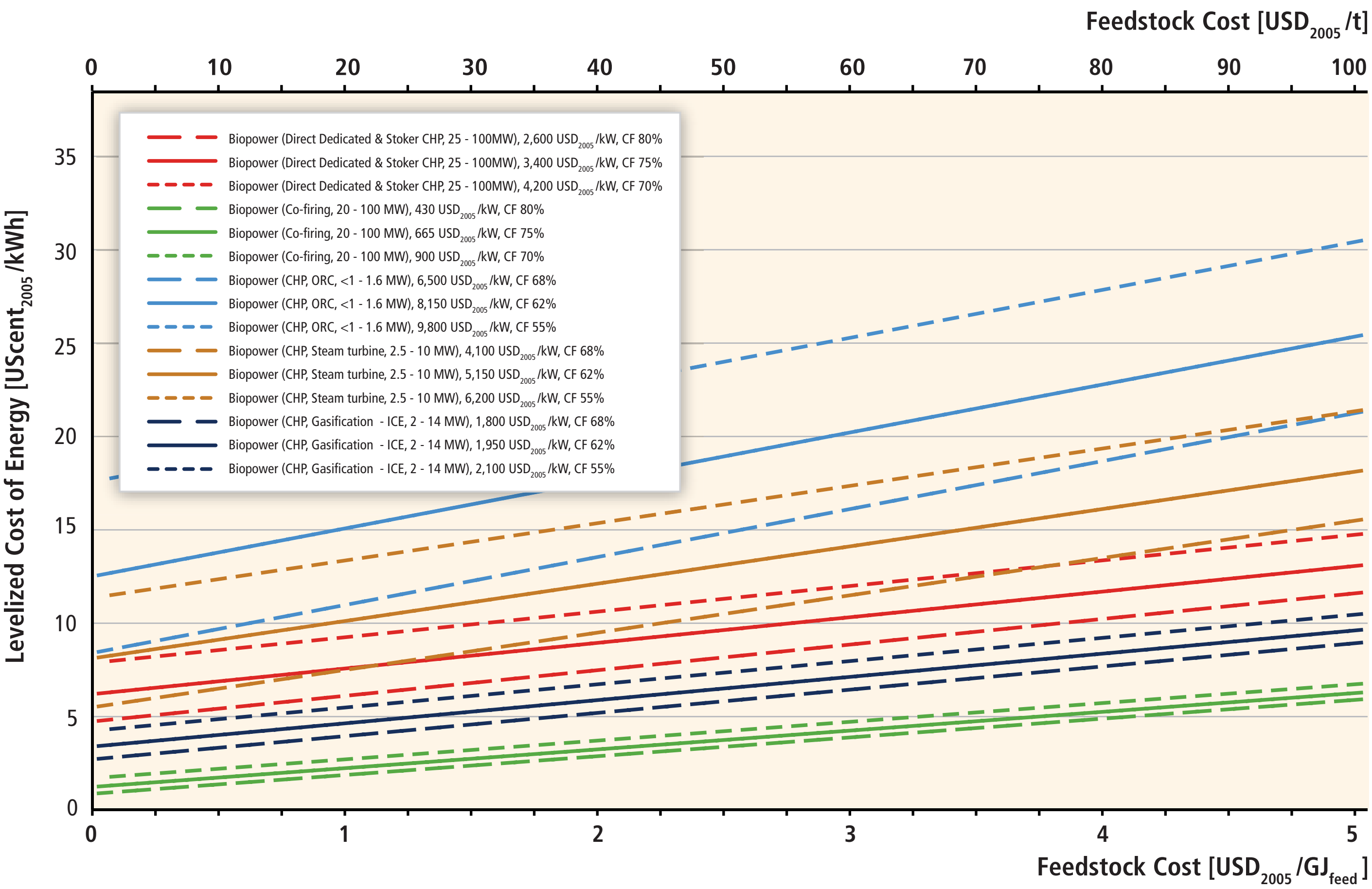


Figure 2.19 | Sensitivity of LCOE with respect to feedstock cost for a variety of investment costs and plant capacity factors (CF). LCOE is based on a 7% discount rate, the mid-value of the operations and maintenance (O&M) cost range, and the mid-value of the lifetime range (see Annex III). Calculations are based on HHV.

References: DeMeo and Galdo (1997); Bain et al. (2003); EIA (2009); Obernberger and Thek (2004); Sims (2007); McGowin (2008); Obernberger et al. (2008); EIA (2010b); Rauch (2010); Skjoldborg (2010); Bain (2011); OANDA (2011).

75 Note that large-scale power only and CHP technologies have been aggregated in Figure 2.18, while they are shown separately in Figure 2.19.

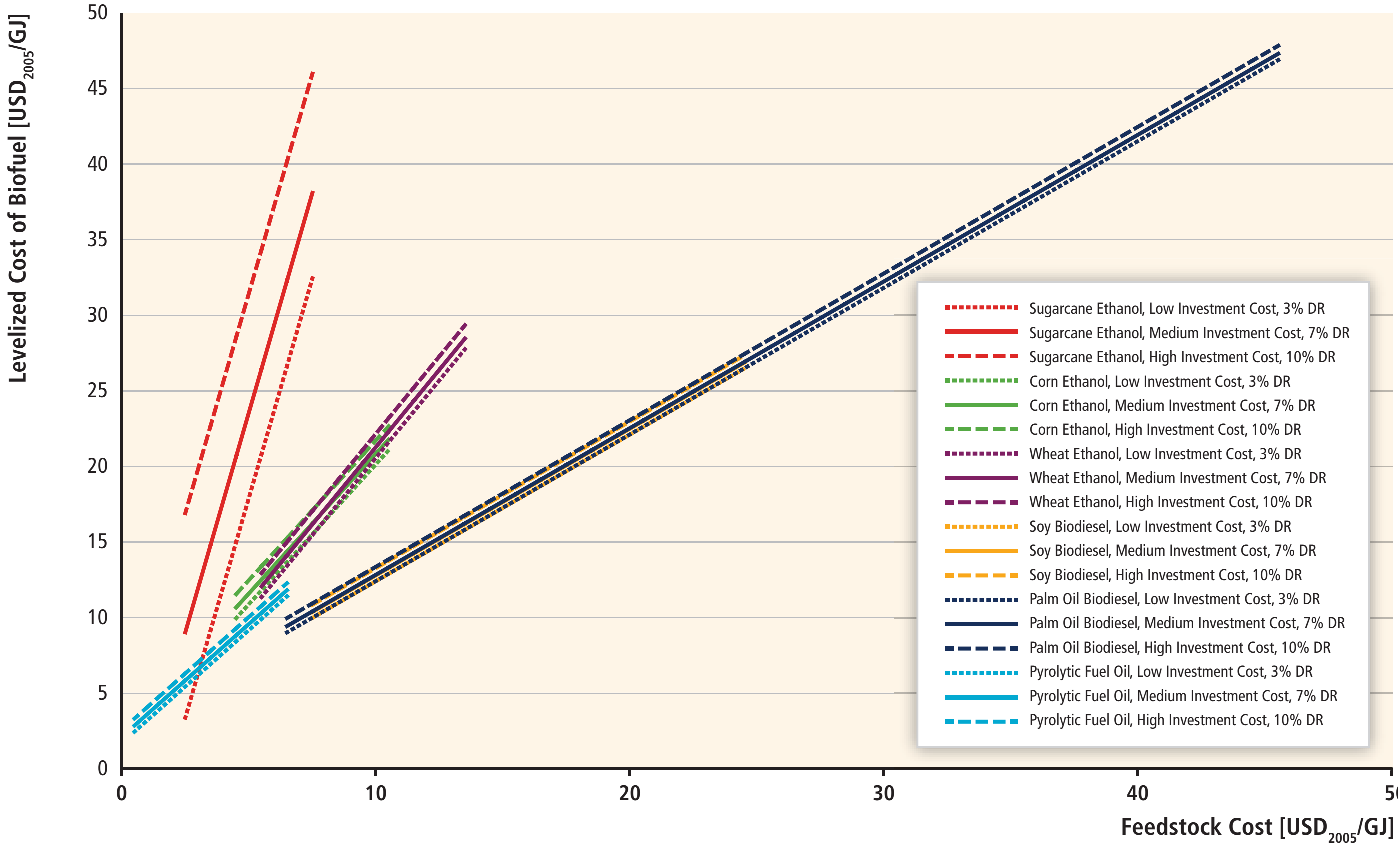


Figure 2.20 | Sensitivity of LCOF with respect to feedstock cost for different discount rates and the mid-values of other cost components from multiple countries (see Annex III). Calculations are based on HHV.

References: Delta-T Corporation (1997); Sheehan et al. (1998b); McAloon et al. (2000); Rosillo-Calle et al. (2000); McDonald and Schrattenholzer (2001); Ibsen et al. (2005); Jechura (2005); Bohlmann (2006); CBOT (2006); Haas et al. (2006); Oliverio (2006); Oliverio and Ribeiro (2006); Ringer et al. (2006); Shapouri and Salassi (2006); USDA (2006); Bain (2007); Kline et al. (2007); USDA (2007); Alfstad (2008); RFA (2011); University of Illinois (2011).

exist.) References used to generate the cost data are assembled in notes to the figures.

2.7.2 Technological learning in bioenergy systems

Cost trends and technological learning in bioenergy systems are not as well described as those for solar or wind energy technologies. Recent literature, however, gives more detailed insights into the learning curves of various bioenergy systems. Table 2.17 and Figure 2.21 summarize a number of analyses that have quantified learning, expressed by learning rates (LR) and learning (or experience) curves, for three commercial biomass systems:

1. Sugarcane-based ethanol production (van den Wall Bake et al., 2009),
2. Corn-based ethanol production (Hettinga et al., 2009),
3. Wood fuel chips and CHP in Scandinavia (Junginger et al., 2005 and a number of other sources).

The LR is the rate of a unit cost decline associated with each doubling of cumulative production (see Section 10.2.5 for a more detailed discussion). For example, a LR of 20% implies that after one doubling of cumulative production, unit costs decreased by 20% of the original costs. The definition of the 'unit' depends on the study variable.

Learning curve studies have accuracy limitations (Junginger et al., 2008; see also Section 10.5.3). Yet, there are a number of general factors that drive cost reductions that can be identified: For biomass feedstocks for ethanol production such as sugar crops (sugarcane) and starch crops (corn), increasing crop yields have been the driving force behind cost reductions.

- For sugarcane, cost reductions have come from R&D efforts to develop varieties with increased sucrose content and thus ethanol yield, increasing the number of harvests from the crop ratoon (from shoots) before replanting the field, increasingly efficient manual harvesting and the use of larger trucks for transportation. More recently, mechanical harvesting of sugarcane is replacing manual harvest, increasing the amount of residues for electricity production (van den Wall Bake et al., 2009; Seabra et al., 2010).

- For the production of corn, the highest cost decline occurred in costs for capital, land and fertilizer until 2005. Additional drivers behind cost reductions were increased plant sizes through cooperatives that

Table 2.17 | Experience curves for major components of bioenergy systems and final energy carriers expressed as reduction (%) in cost (or price) per doubling of cumulative production.

Learning system	LR (%)	Time frame	Region	N	R^2
Feedstock production					
Sugarcane (tonnes sugarcane)[1]	32±1	1975–2005	Brazil	2.9	0.81
Corn (tonnes corn)[2]	45±1.5	1975–2005	USA	1.6	0.87
Logistic chains					
Forest wood chips (Sweden)[3]	12–15	1975–2003	Sweden/Finland	9	0.87–0.93
Investment and O&M costs					
CHP plants[3]	19–25	1983–2002	Sweden	2.3	0.17–0.18
Biogas plants[4]	12	1984–1998		6	0.69
Ethanol production from sugarcane[1]	19±0.5	1975–2003	Brazil	4.6	0.80
Ethanol production from corn (only O&M costs)[2]	13±0.15	1983–2005	USA	6.4	0.88
Final energy carriers					
Ethanol from sugarcane[5]	7 29	1970–1985 1985–2002	Brazil	~6.1	n.a.
Ethanol from sugarcane[1]	20±0.5	1975–2003	Brazil	4.6	0.84
Ethanol from corn[2]	18±0.2	1983–2005	USA	7.2	0.96
Electricity from biomass CHP[4]	8–9	1990–2002	Sweden	~9	0.85–0.88
Electricity from biomass[6]	15	Unknown	OECD	n.a.	n.a.
Biogas[4]	0–15	1984–2001	Denmark	~10	0.97

Notes: Abbreviations: LR: Learning Rate, N: Number of doublings of cumulative production, R^2: Correlation coefficient of the statistical data.

References: 1. van den Wall Bake et al. (2009); 2. Hettinga et al. (2009); 3. Junginger et al. (2005); 4. Junginger et al. (2006); 5. Goldemberg et al. (2004); 6. IEA (2000).

enabled higher production volumes, efficient feedstock collection, decreased investment risk through government loans and the introduction of improved efficiency natural gas-fired ethanol plants, which are responsible for nearly 90% of ethanol production in the USA (Hettinga et al., 2009). Higher yields were achieved from corn hybrids genetically modified to have higher pest resistance and increased adoption of no-till practices that improved water quality (NRC, 2010). While it is difficult to quantify the effects of these factors, it seems clear that R&D efforts (realizing better plant varieties), technology improvements and learning by doing (e.g., more efficient harvesting) played important roles.

For ethanol production, industrial costs from both sugarcane and corn mainly decreased because of increasing scales of the ethanol plants.

- Cost breakdowns of the sugarcane production process showed reductions of around 60% within all sub processes from 1975 to 2005. Ethanol production costs (excluding feedstock costs) declined by a factor of three between 1975 and 2005 (in real terms, i.e., corrected for inflation). Investment and operation and maintenance costs declined mainly due to economies of scale. Other fixed costs, such as administrative costs and taxes, did not fall dramatically, but cost reductions can be ascribed to automated administration systems. Decreased costs can be primarily ascribed to increased scales and load factors (van den Wall Bake et al., 2009).

- For ethanol from corn, the conversion costs (without costs for corn) declined by 45% from USD_{2005} 240/ m^3 in the early 1980s to USD_{2005} 130/m^3 in 2005. Costs for energy, labour and enzymes contributed in particular to the overall decline in costs. Additional drivers behind these reductions are higher ethanol yields, the introduction of automation and control technologies that require less energy and labour and the up-scaling of average dry grind plants (Hettinga et al., 2009).

2.7.3 Future scenarios of cost reduction potentials

2.7.3.1 Future cost trends of commercial bioenergy systems

For the production of ethanol from sugarcane and corn, future production cost scenarios based on direct experience curve analysis were found in the literature:

For Brazilian sugarcane ethanol (van den Wall Bake et al., 2009), total production costs in 2005 were approximately USD_{2005} 340/m^3 (USD_{2005} 16/GJ). Based on the experience curves for the cost components shown in Figure 2.21 (feedstock and ethanol without feedstock costs), total ethanol production costs in 2020 are estimated between USD_{2005} 200 and 260/m^3 (USD_{2005} 9.2 to 12.2/GJ). These costs compare well with those in Table 2.7 for Brazil with a current production cost estimate of USD_{2005} 14.8/GJ and projected 2020 cost of USD_{2005} 9 to 10/GJ. Ethanol production costs without feedstocks are in a range of USD_{2005} 139 to 183/m^3 (USD_{2005} 6.5 to 8.6/GJ) in 2005 and could reach about USD_{2005}113/m^3 (USD_{2005} 6.6/GJ) by 2020, assuming a constant 82 m^3 hydrous ethanol per t of sugarcane.

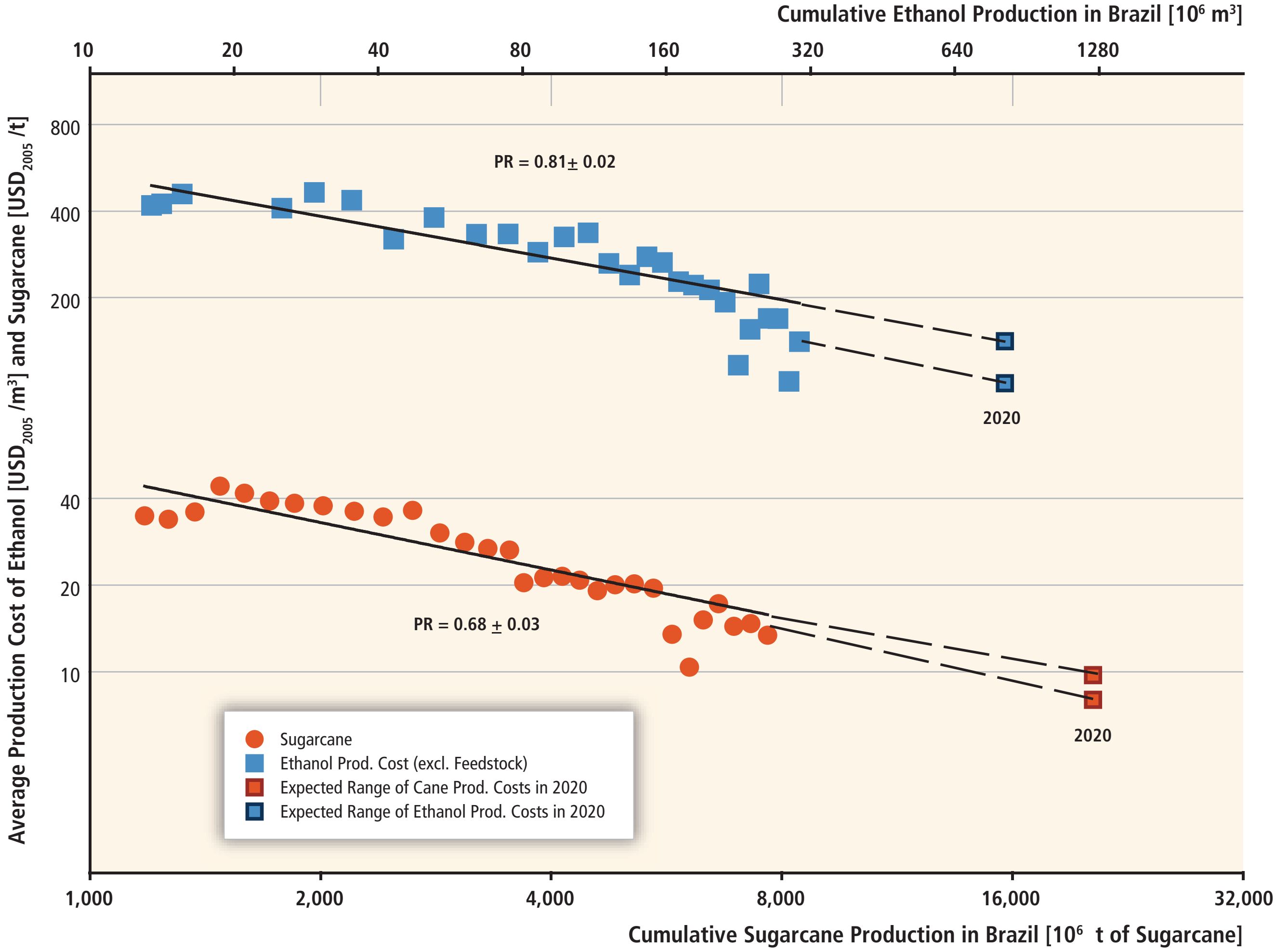


Figure 2.21 | Brazilian sugarcane and ethanol production cost learning curves for between 1975 and 2005 and extrapolated to 2020 (in USD_{2005}). Progress ratio (PR=1-LR) is obtained by best fit to data (van den Wall Bake et al., 2009; reproduced with permission from Elsevier B.V.).

For US ethanol from corn (Hettinga et al., 2009), costs of corn production and ethanol processing are estimated respectively as USD_{2005} 75/t and USD_{2005} 60 to 77/m³ by 2020. Overall ethanol production costs could decline from a current level of USD_{2005} 310/m³ to USD_{2005} 248/m³ (USD_{2005} 14.7 to 11.7/GJ) by 2020. This estimate excludes the investment costs and the effect of future corn prices. The EPA (2010) Regulatory Impact Analysis of the Renewable Fuel Standard 2 modelled the current corn ethanol industry in detail and projected a decrease in total production cost from USD_{2005} 17.5 to 16/GJ by 2022 by taking into account both feedstock and process improvements listed in Table 2.7 and the anticipated co-product revenue.

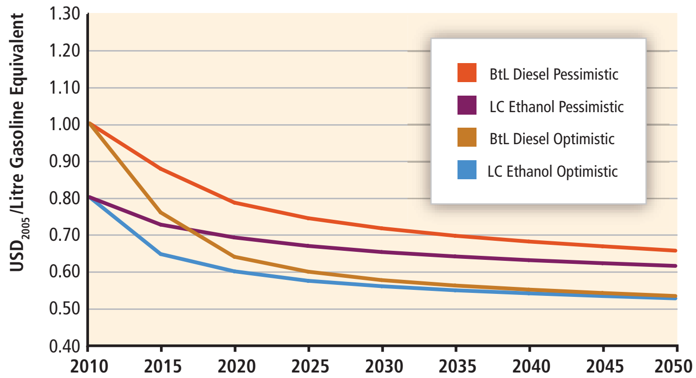
Confirming the trend and supporting the projections to 2020, Table 2.13 illustrates key indicators for environmental performance of a North American corn dry-grind natural gas-fired mill and the Brazilian sugarcane benchmark of 44 mills in terms of GHG emissions per carbon content of the biomass feedstock (displacement factor), emissions reductions relative to the reference fossil fuel in the production region (GHG savings), and a land use efficiency (volume of production per unit area) indicator. The commercial North American system's performance improved with time; for instance, using the relative GHG savings, which were 26% in 1995 and 39% in 2005, and the projected efficiency improvements through application of commercial CHP systems alone or in combination with CCS, would lead to 55 and 72% emissions savings by 2015, respectively. Similarly, the Brazilian sugarcane ethanol/electricity/sugar mill would go from 79 to 120 and 160% in relative GHG savings for the 2005-2006 baseline and the CHP and CCS scenarios, respectively.

In the Renewable Fuels for Europe project that focused on deployment of biofuels in Europe (de Wit et al., 2010; Londo et al., 2010), specific attention was paid to the effects of learning for lignocellulosic biofuels technologies on projections of future costs. The analyses showed two key points:

- Lignocellulosic biofuels have considerable potential for improvement in the areas of crop production, supply systems and the conversion technology. For conversion in particular, economies of scale are a very important element of the future cost reduction potential as specific capital costs can be reduced (partly due to improved conversion efficiency). Biomass resources may become somewhat more expensive due to a reduced share of (less costly) residues over time. It was estimated that lignocellulosic biofuel production cost could compete with gasoline and diesel from oil at USD_{2005} 60 to 70/barrel by 2030 (USD_{2005} 0.38 to 0.44/litre) (Hamelinck and Faaij, 2006).

- The penetration of lignocellulosic biofuel options depends considerably on the rate of learning. This rate is in turn dependent on increased market penetration (which allows for producing with larger production facilities), which makes the LR partly dependent on market support or mandates in earlier phases of market penetration.

The IEA Energy Technology Perspectives report (IEA, 2008a) and the WEO (IEA, 2009b) project a rapid increase in production of lignocellulosic biofuels, especially between 2020 and 2030, accounting for all incremental biomass increases after 2020. The biofuels analysis projects an almost complete phase-out of cereal- and corn-based ethanol production and edible oilseed-based biodiesel after 2030. The potential cost reductions from current demonstration projects to future commercial-scale facilities for production of specific lignocellulosic biofuels are shown in Figure 2.22. Such potential cost reductions are also quantified in Hamelinck and Faaij (2006) and van Vliet et al. (2009).



Note: BtL = Biomass-to-Liquids; LC = Lignocellulose

Figure 2.22 | Cost projections for lignocellulosic ethanol and BTL diesel (*Energy Technology Perspectives 2008*, © OECD/IEA, Figure 9.11, p. 335 in IEA (2008a); for additional future cost considerations see also Sims et al. (2008), IEA Renewable Energy Division (2010) and IEA (2011)).

Table 2.18 presents projected ranges of production costs for developing technologies such as integrated gasification combined cycle for the production of higher efficiency electricity and gasification-(syngas) derived fuels, including diesel, jet fuel, and H_2, methane, dimethyl ether and other oxygenated fuels through catalytic upgrading of the syngas. The sugar intermediates, lignocellulosic for instance, can be converted through biochemical routes to a variety of fuels with the properties of petroleum-based fuels. Similarly, pyrolysis oil-based hydrocarbon fuels are under development. Oilseed crop and tree seed oil development could also expand the range of fuel products with properties of petroleum fuels because they are readily upgraded to hydrocarbons. Finally, algae for biomass production are photosynthetic, using CO_2, water, and sunlight to biologically produce a variety of carbohydrates, lipids, plastics, chemicals or fuels like H_2, along with oxygen. In addition, heterotrophic microbes, such as certain algae are engineered to metabolize sugars and excrete lipids in the dark. Microorganisms or their consortia can consolidate various processing steps; genetically engineered yeasts or bacteria can make specific fuel products, including hydrocarbons and lipids, developed either with tools from synthetic biology or through metabolic engineering (see also IEA, 2011).

2.7.3.2 Future cost trends for pre-commercial bioenergy systems

A number of bioenergy systems are evolving, as shown in Figure 2.2 and discussed in Section 2.6. The key intermediates that enable generation of bioenergy from modern biomass include syngas, sugars, vegetable oils/lipids, thermochemical oils derived from biomass (pyrolysis or other thermal treatments), and biogas. These intermediates can produce higher efficiency electricity and heat, a wider range of liquid hydrocarbon fuels, alcohols (including some with higher energy density), ethers, and chemical products and polymers (bio-based materials) in the developing biorefineries that are discussed in Section 2.6. Initial R&D on producing hydrocarbon fuels is starting with sugar and starch crops and covering the range of gasoline, diesel and higher-energy content transport fuels such as jet fuels and chemicals. Both improved first-generation crops, perennial sugarcane-derived, in particular, and second-generation plants have the potential to provide a variety of energy products suited to specific geographic regions, and high-volume chemicals and materials traditionally derived from the petrochemical industry, maximizing the outputs of end products per unit of feedstock.

2.7.4 Synthesis

Despite the complexities of determining the economic performance and regional specificities of bioenergy systems, several key conclusions can be drawn from available experiences and literature:

- Several important bioenergy systems today can be deployed competitively, most notably sugarcane-based ethanol and heat and power generation from residues and waste.

- Although not all bioenergy options discussed in this chapter have been investigated in detail with respect to technological learning, several important bioenergy systems have reduced their cost and improved environmental performance over time. These systems still

Table 2.18 | Projected production cost ranges estimated for developing technologies (see Section 2.6.3).

Selected Bioenergy Technologies	Energy Sector (Electricity, Thermal, Transport)*	2020-2030 Projected Production Costs (USD_{2005}/GJ)
IGCC [1]	Electricity and/or transport	12.8–19.1 (4.6–6.9 cents/kWh)
Oil plant-based renewable diesel and jet fuel	Transport and electricity	15–30
Lignocellulose sugar-based biofuels[2]	Transport	6–30
Lignocellulose syngas-based biofuels[3]		12–25
Lignocellulose pyrolysis-based biofuels[4]		14–24 (fuel blend components)
Gaseous biofuels[5]	Thermal and transport	6–12
Aquatic plant-derived fuels, chemicals	Transport	30–140

Notes: 1. Feed cost USD_{2005} 3.1/GJ, IGCC (future) 30 to 300 MW, 20-yr life, 10% discount rate; 2. ethanol, butanols, microbial hydrocarbons from sugar or starch crops or lignocellulose sugars; 3. syndiesel, methanol and gasoline, etc.; syngas fermentation routes to ethanol; 4. biomass pyrolysis (or other thermal treatment) and catalytic upgrading to gasoline and diesel fuel blend components or to jet fuels; 5. synfuel to SNG, methane, dimethyl ether, or H_2 from biomass thermochemical and anaerobic digestion (larger scale). *Several applications could be coupled with CCS when these technologies, including CCS, are mature and thus could remove GHGs from the atmosphere.

require government subsidies that are put in place for economic development, poverty reduction, a secure and diverse energy supply, and other reasons.

- There is clear evidence that further improvements in power generation technologies, production of perennial cropping systems and development of supply systems can bring the costs of power (and heat) generation from biomass down to attractive cost levels in many regions. With the deployment of carbon taxes of up to USD_{2005} 50/t, biomass can, in many cases, also be competitive with coal-based power generation. Nevertheless, the competitive production of bio-electricity depends also on the performance of alternatives such as wind and solar energy, CCS coupled with coal, and nuclear energy (see Section 10.2.2.4 and Chapter 8).

- Bioenergy systems for ethanol and biopower production show technological learning and related cost reductions with LRs comparable to those of other RE technologies. This applies to cropping systems (following progress in agricultural management of annual crops), supply systems and logistics (as clearly observed in Scandinavia, as well as international logistics) and in conversion (ethanol production, power generation and biogas).

- With respect to lignocellulosic biofuels, recent analyses have indicated that the improvement potential is large enough to make them competitive with oil prices of USD_{2005} 60 to 70/barrel (USD 0.38 to 0.44/litre). Currently available scenario analyses indicate that if shorter-term R&D and market support are strong, technological progress could allow for commercialization around 2020 (depending on oil price developments and level of carbon pricing). Some scenarios also indicate that this would mean a major shift in the deployment of biomass for energy, because competitive production would decouple deployment from policy targets (mandates) and demand for biomass would move away from food crops to biomass residues, forest biomass and perennial cropping systems. The implications of such a (rapid) shift have not been studied.

- Data about the production of biomaterials and cost estimates for chemicals from biomass are rare in peer-reviewed literature. Future projections and LRs are even rarer, because successful bio-based products are just now entering the market place. Two examples are as partial components of otherwise fossil-derived products (e.g., poly(1,3)-propylene terephthalates based on 1,2-propanediol derived from sugar fermentation) or as fully new synthetic polymers such as polylactides based on lactic acid derived from sugar fermentation. This is also the case for biomass conversion coupled with CCS (see Section 2.6.3.3) concepts, which are not developed at present and for which cost trends are not available in literature. CO_2 from ethanol fermentation is commercially sold to carbonate beverages, flash freeze meats or enhance oil recovery, and demonstrations of CCS are ongoing (see Section 2.6.3.3). Nevertheless, recent scenario analyses indicate that advanced biomaterials (and cascaded use of biomass) as well as other biomass conversion coupled to CCS may become attractive medium-term mitigation options. It is therefore important to gain experience so that more detailed analyses on those options can be conducted in the future.

2.8 Potential Deployment[76]

2.8.1 Current deployment of bioenergy

Modern biomass use (for electricity and CHP for the power sector; modern residential, commercial, and public buildings heating; or transport fuels) already provides a significant contribution of about 11.3 EJ (see Table 2.1; IEA, 2010a,b) out of the 2008 TPES from biomass of 50.3 EJ. Between 60 and 70% of the total biomass supply is used in rural areas and relates to charcoal, wood, agricultural residues and manure used for cooking, lighting and space heating, generally by the poorer part of the population in developing countries. From 1990 to 2008, the

76 Complementary perspectives on potential deployment based on a comprehensive assessment of numerous model-based scenarios of the energy system are presented in Sections 10.2 and 10.3 of this report.

average annual growth rate of solid biomass use for bioenergy was 1.5%, while the average annual growth rate of modern liquid and gaseous biofuels use was 12.1 and 15.4%, respectively, during the same period (IEA, 2010c). As a result, biofuels' share of global road transport fuels was about 2% in 2008; and nearly 3% of global road transport fuels in 2009, as oil demand decreased for the first time since 1980 (IEA, 2010b). Government policies in various countries fostered the five-fold increase in global biofuels production from 2000 to 2008. Biomass and renewable waste power generation was 259 TWh (0.93 EJ) in 2007 and 267 TWh (0.96 EJ) in 2008, representing 1% of the world's electricity and a doubling since 1990 (from 131 TWh, 0.47 EJ) (Section 2.4.1). Modern bioenergy heating applications, including space and hot water heating systems such as for district heating, account for 3.4 EJ (see Table 2.1 and Section 2.4.1).

International trade in biomass and biofuels has also become much more important over the recent years, with roughly 6% (reaching levels of up to 9% in 2008) of biofuels (ethanol and biodiesel only) traded internationally and one-third of pellet production dedicated to energy use in 2009 (Figures 2.8 and 2.9; Junginger et al., 2010; Lamers et al., 2010; Sikkema et al., 2011). The latter has proven to be an important facilitating factor in both increased utilization of biomass in regions where supplies are constrained and mobilizing resources from areas where demand is lacking.

The policy context for bioenergy and particularly biofuels has changed rapidly and dramatically since the mid-2000s in many countries. The food versus fuel debate and growing concerns about other conflicts created a strong push for the development and implementation of sustainability criteria and frameworks and changes in temporization of targets for bioenergy and biofuels. Furthermore, the support for advanced biorefinery and second-generation biofuel options drives bioenergy in more sustainable directions.

Nations like Brazil, Sweden, Finland and the USA have shown that persistent and stable policy support is a key factor in building biomass production capacity and working markets, required competitive infrastructure and conversion capacity (see also Section 2.4) and results in considerable economic activity.

2.8.2 Near-term forecasts

Countries differ in their priorities, approaches, technology choices and support schemes for bioenergy development. Although on the one hand complex for the market, this is also a reflection of the many aspects that affect bioenergy deployment: agriculture and land use; forestry and industry development; energy policy and security; rural development; and environmental policies. Priorities, the stage of technology development, and access to, availability of and cost of resources differ widely from country to country and in different settings.

The near-term forecasts reflect that the policies already in place, as shown in Table 2.11, are driving current forecasts. For instance, the WEO (IEA, 2010b) projects that the bioenergy industry will continue the growth observed in the past five years and reach about 60 EJ by 2020 in the Current Policies scenario (which replaces the former Reference scenario), with slightly higher levels of up to 63 EJ in the more ambitious New Policies and 450-ppm CO_2 scenarios (Section 2.4.1). Considering the 2008 starting point at 50 EJ/yr, this represents a 10 to 13 EJ increase in bioenergy consumption over 10 years. Much of the increase happens in the transport sector, with biofuel consumption starting from 2.1 EJ in 2009 and increasing to 4.5 to 5.1 EJ in 2020 in the three presented scenarios. Most of this growth is therefore already expected due to existing policies, and additional growth relying on new policies is expected to only foster an additional 10% increase. The global primary biomass supply (efficiency of about 65% for first-generation biofuels) needed to deliver this amount of biofuels ranges between 7.4 and 8.4 EJ. The increase at the global level goes along with further regional diversification of biofuels adoption. While the currently dominant biofuels markets in Brazil, the USA and the EU are projected to roughly double consumption by 2020, many other regions with very little or no biofuels consumption currently are expected to adopt biofuel policies, resulting in significant growth, most notably in Asia. Electricity generation increases by 85% from 265 TWh/yr (0.96 EJ/yr) in 2008 to 493 TWh/yr (1.8 EJ/yr) in the Current Policies scenario, again with relatively modest additional growth (20%) in the more ambitious policy scenarios (up to 594 TWh/yr or 2.1 EJ/yr) (Table 2.10).

2.8.3 Long-term deployment in the context of carbon mitigation

The AR4 (IPCC, 2007d) demand projections for primary biomass for production of transportation fuel were largely based on WEO (IEA, 2006) global projections, with a relatively wide range of about 14 to 40 EJ of primary biomass, or 8 to 25 EJ of biofuels in 2030. However, higher estimates were also included, in the range of 45 to 85 EJ of demand for primary biomass for electricity generation in 2030 (equivalent to roughly 30 to 50 EJ of biofuel). Demand for biomass for heat and power was stated to be strongly influenced by (availability and introduction of) competing technologies such as CCS, nuclear power and non-biomass RE. The demand in 2030 for biomass was estimated in the AR4 to be around 28 to 43 EJ. These estimates focus on electricity generation. Heat was not explicitly modelled or estimated in the WEO (on which the AR4 was based); therefore it underestimates total demand for biomass. Also, potential future demand for biomass in industry (especially new uses such as biochemicals, but also expansion of charcoal use for iron and steel production) and the built environment (heating as well as increased use of biomass as building material) was highlighted as important, but no quantitative projections were included in potential demand for biomass at the medium or longer term.

A summary of the literature on the possible future contribution of RE supplies in meeting global energy needs under a range of GHG stabilization scenarios is provided in Chapter 10. Focussing specifically on bioenergy, Figure 2.23 presents modelling results for global primary energy supply from biomass (a) and global biofuels production in secondary energy terms (b). Between about 100 and 140 different long-term scenarios underlie Figure 2.23 (Section 10.2). These scenario results derive from a diversity of modelling teams and cover a wide range of assumptions about—among other variables—energy demand growth, the cost and availability of competing low-carbon technologies and the cost and availability of RE technologies (including bioenergy). A description of the literature from which the scenarios have been taken (Section 10.2.2) and how changes in some of these variables impact RE deployment outcomes are displayed in Figure 10.9.

in most scenarios, which means that modern use of biomass as liquid biofuels, biogas, and electricity and H_2 produced from biomass tends to increase even more strongly than suggested by the above primary energy numbers. This trend is also illustrated by the example of liquid biofuels production shown in the right panel of Figure 2.23(b). With increasingly ambitious GHG concentration stabilization levels, bioenergy supply increases, indicating that bioenergy could play a significant long-term role in reducing global GHG emissions. The median levels of biomass deployment for energy in the most stringent mitigation categories I and II (<440 ppm atmospheric CO_2 concentration by 2100) increase significantly compared to the baseline levels to 63, 85 and 155 EJ/yr by 2020, 2030 and 2050, respectively.

Despite these robust trends, there is by no means an agreement about

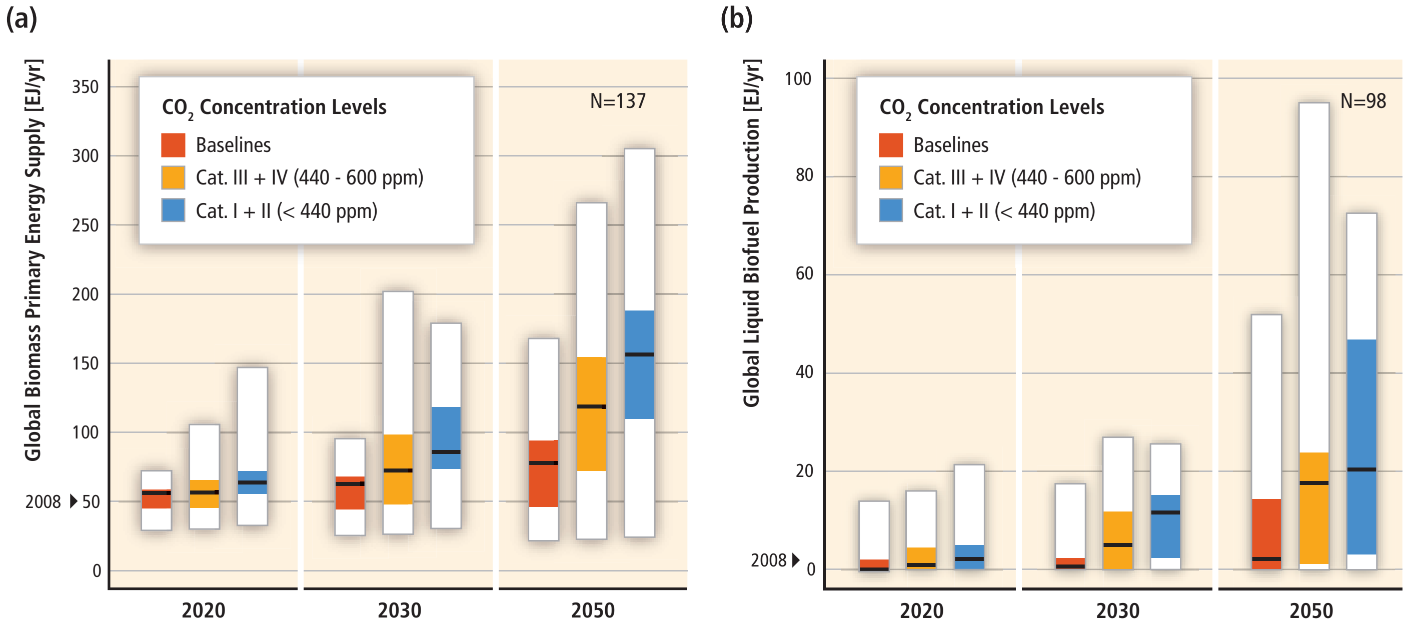
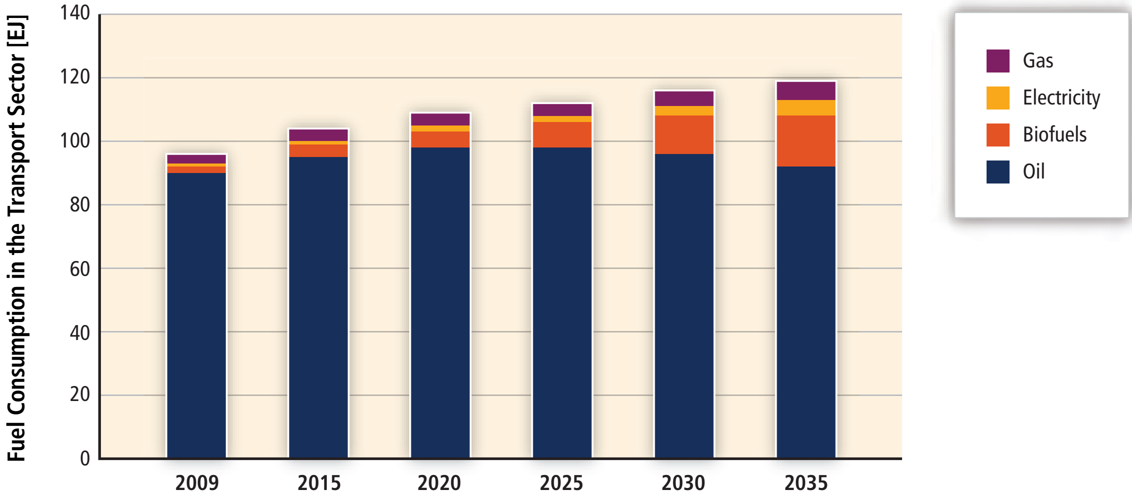


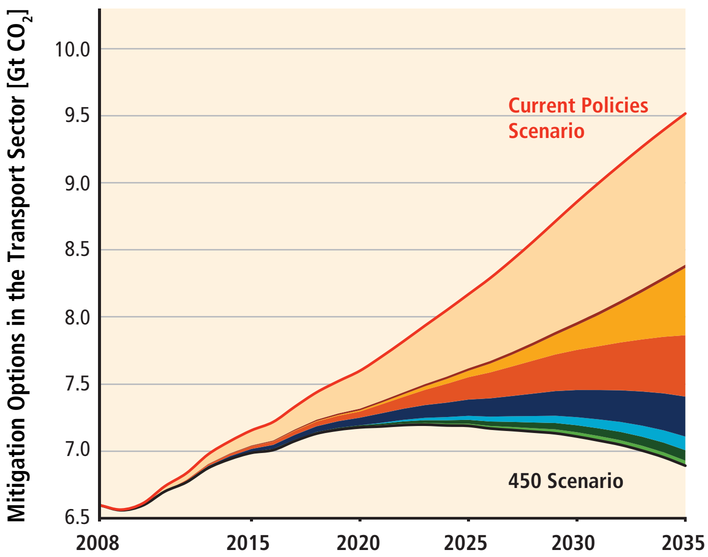
Figure 2.23 | (a) The global primary energy supply from biomass in long-term scenarios; (b) global biofuels production in long-term scenarios reported in secondary energy terms of the delivered product (median, 25th to 75th percentile range and full range of scenario results; colour coding is based on categories of atmospheric CO_2 concentration levels in 2100; the number of scenarios underlying the figure is indicated in the right upper corner) (adapted from Krey and Clarke, 2011). For comparison, the historic levels in 2008 are indicated by the small black arrows on the left axis.

In Figure 2.23, the results for biomass deployment for energy under these scenarios for 2020, 2030 and 2050 are presented for three GHG stabilization ranges based on the AR4: Categories I and II (<440 ppm CO_2), Categories III and IV (440-600 ppm CO_2) and Baselines (>600 ppm CO_2) all by 2100. Results are presented for the median scenario, the 25th to 75th percentile range among the scenarios, and the minimum and maximum scenario results. Figure 2.23(a) shows a clear increase in global primary energy supply from biomass over time in the baseline scenarios, that is, absent climate policies, reaching about 55, 62 and 77 EJ/yr in the median cases by 2020, 2030 and 2050, respectively. At the same time, traditional use of solid biomass is projected to decline the precise future role of bioenergy across the scenarios, leading to fairly wide deployment ranges in the different GHG stabilization categories. For 2030, primary biomass supply estimates for energy vary (rounded) between 30 and 200 EJ for the full range of results obtained. The 25th to 75th percentiles cover a range of 45 to 120 EJ, with a comparatively narrower range of 44 to 67 EJ/yr in the baselines and much wider ranges of 47 to 98 EJ/yr in the 440 to 600 ppm stabilization category and 73 to 120 EJ/yr in the <440 ppm category. By 2050, the contribution of biomass to primary energy supply in the two GHG stabilization categories ranges from 70 to 120 EJ/yr at the 25th percentile to about 150 to 190 EJ/yr at the 75th percentile, and to about 265-300 EJ/yr in the highest ranges. It should be noted that the net GHG mitigation impact of

(a)



(b)



	Abatement 2020	2030	2035
Road	83%	80%	80%
Increased Efficiency	67%	51%	43%
Switch to Gas	3%	1%	1%
Switch to Electricity	2%	11%	19%
Switch to Biofuels	11%	17%	17%
Aviation	14%	15%	15%
Increase Efficiency	14%	12%	11%
Switch to Biofuels	0%	3%	4%
Navigation	2%	3%	3%
Other Transport	2%	2%	1%
Total [Gt CO_2]	0.4	1.7	2.6

Figure 2.24 | (a) Evolution of fuel consumption in the transport sector including biofuels (*World Energy Outlook 2010*, © OECD/IEA, figure 14.12, page 429 in IEA (2010b)) and (b) shares of carbon mitigation by various technologies including biofuels for road and aviation transport from current policies baseline (upper red line) to the 450 ppm bottom curve of the mitigation scenario. (*World Energy Outlook 2010*, © OECD/IEA, figure 14.14, page 432 in IEA (2010b))

bioenergy deployment is not straightforward because different options result in different GHG savings, and savings depend on how land use is managed, which is a central reason for the wide ranges in the stabilization scenarios.

The sector-level penetration of bioenergy is best explained using a model with detailed transport sector representation such as the WEO (IEA, 2010b) that is also modelling both traditional and modern biomass applications, and includes second-generation biofuels evolution. Additionally, the WEO model takes into account anticipated industrial and government investments and goals. It projects very significant increases in modern bioenergy and a decrease in traditional biomass use, in qualitative agreement with the results from Chapter 10. By 2030, for the 450-ppm mitigation scenario, the model projects that 11% of global transport fuels will be provided by biofuels with second-generation biofuels contributing 60% of the projected 12 EJ, and half of this production is projected to be supplied owing to continuation of current policies (see Table 2.9). Biomass and renewable wastes would supply 5% of the world's electricity generation, or 1,380 TWh/yr (5 EJ/yr) of which 555 TWh/yr (2 EJ/yr) result from the 450 ppm strategy by 2030 (see Table 2.10). Biomass industrial heating applications for process steam and space and hot water heating for buildings would each double in absolute terms from 2008 levels. However, the total heating demand is projected to decrease because of assumed traditional biomass decline. Heating is seen as a key area for continued modern bioenergy growth.

The evolution of biofuels in the transport sector is shown in Figure 2.24a. Biofuels penetration is projected to be significant in both in global road transport and in air transport. Second-generation technologies are projected to provide 66% of the biofuels by 2035 and 14% of world transport energy demand in the 450-ppm scenario (see Figure 2.24a and Table 2.9). Figure 2.24b shows the projected GHG emissions mitigation of biofuels relative to projected road and air transport applications from the current policies to the 450 ppm scenario. For instance, by 2030, 17% of road transport emissions and 3% of air transport emissions could be mitigated by biofuels in the 450-ppm stabilization scenario. A biofuels technology roadmap was recently developed (IEA, 2011).

The potential demand of biomass for materials is not explicitly addressed by many of the scenarios, but it could become significant and add up to several dozens of EJ (Section 2.6.3.5; Hoogwijk et al., 2003).

The expected deployment of biomass for energy in the 2020 to 2050 time frame differs considerably between studies, also due to varying detail in bioenergy system representation in the relevant models. A key message from the review of available insights is that large-scale biomass deployment strongly depends on sustainable development of the resource base, governance of land use, development of infrastructure and cost reduction of key technologies, for example, efficient and complete use of primary biomass for energy from the most promising first-generation feedstocks and second-generation lignocellulosic biomass. The results discussed above are consistent with the *Energy Technology Perspectives* report (IEA, 2008a), which projects a rapid penetration of second-generation biofuels after 2010 and an almost complete phase-out of cereal- and corn-based ethanol production and oilseed-based biodiesel after 2030.[77]

2.8.4 Conditions and policies: Synthesis of resource potentials, technology and economics, and environmental and social impacts of bioenergy

2.8.4.1 Resource potentials

The inherent complexity of biomass resources makes the assessment of their combined technical potential controversial and difficult to characterize. Literature studies range from zero (no biomass potential available as energy) to around 1,500 EJ, the theoretical potential for terrestrial biomass based on modelling studies exploring the widest potential ranges of favourable conditions (Smeets et al., 2007).

Figure 2.25 presents a summary of technical potential found in major studies, including potential deployment data from the scenario analysis of Chapter 10 compared to global TPES (projections). To put technical potential in perspective, because global biomass used for energy currently amounts to approximately 50 EJ/yr, and all harvested biomass used for food, fodder, fibre and forest products, when expressed in equivalent heat content, equals 219 EJ/yr (2000 data, Krausmann et al., 2008), the entire current global biomass harvest would be required to achieve a 200 EJ/yr deployment level of bioenergy by 2050 (Section 2.2.1).

From a detailed assessment, the upper-bound technical potential of biomass was about 500 EJ with a minimum of about 50 EJ in the case that even residues had significant competition with other uses. The assessment of each contributing category performed by Dornburg et al. (2008, 2010) was based on literature up to 2007 (stacked bar of Figure 2.25) and is roughly in line with the conditions sketched in the IPCC SRES A1 and B1 storylines (IPCC, 2000), assuming sustainability and policy frameworks to secure good governance of land use and major improvements in agricultural management (summarized in Figure 2.26). The resources used are:

- Residues originating from forestry, agriculture and organic wastes (including the organic fraction of MSW, dung, process residues etc.) were estimated at around 100 EJ/yr. This part of the technical potential of biomass supply is relatively certain, but competing applications may push net availability for energy applications to the lower end of the range.
- Surplus forestry other than from forestry residues had an additional technical potential of about 60 to 100 EJ/yr.
- Biomass produced via cropping systems had a lower range estimate for energy crop production on possible surplus good quality agricultural and pasture lands of 120 EJ/yr. The potential contribution of water-scarce, marginal and degraded lands could amount to an additional 70 EJ/yr, corresponding to a large area where water scarcity provides limitations and soil degradation is more severe. Assuming strong learning in agricultural technology leading to improvements in agricultural and livestock management would add 140 EJ/yr.

Adding these categories together leads to a technical potential of up to about 500 EJ in 2050, with temporal data on the development of biomass potential ramping from 290 to 320 EJ/yr in 2020 to 330 to 400 EJ/yr in 2030 (Hoogwijk et al., 2005, 2009; Dornburg et al., 2008, 2010).

From the expert review of available scientific literature in this chapter, *potential deployment levels of biomass for energy by 2050 could be in the range of 100 to 300 EJ* (Sections 2.2.1, 2.2.2, and 2.2.5).

Values in this range are described in van Vuuren et al. (2009), which focused on an intermediate development scenario within the SRES scenario family. The lower estimates of Smeets et al. (2007) and Hoogwijk et al. (2005, 2009) are in line with those figures, and further confirmation for such a range is given by Beringer et al. (2011), who report a 26 to 116 EJ range for energy crops alone in 2050 without irrigation (and 52 to 174 EJ with irrigation), and Haberl et al. (2010), who report 160 to 270 EJ/yr in 2050 across all biomass categories. Krewitt et al. (2009), following Seidenberger et al. (2008), also estimated the technical potential to be 184 EJ/yr in 2050 using strong sustainability

77 Contrast these projections with the 2007 and 2008 WEO studies (IEA, 2007b, 2008b), where second-generation biofuels were excluded from the scenario analysis and thus biofuels at large played a marginal role in the 2030 projections.

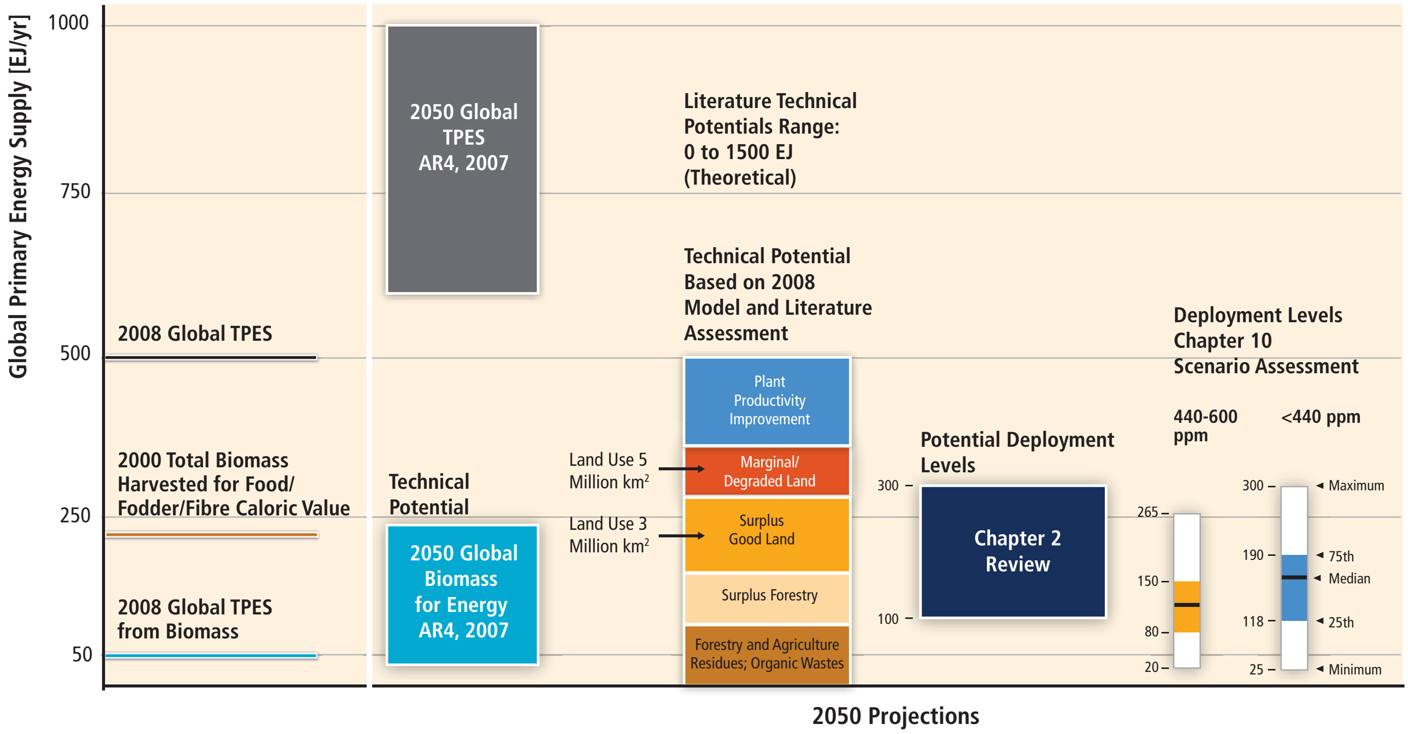


Figure 2.25 | On the left-hand side, the lines represent the 2008 global primary energy supply from biomass, the primary energy supply, and the equivalent energy of the world's total harvest for food, fodder and fibre in 2000. A summary of major global 2050 projections of primary energy supply from biomass is shown from left to right: (1) The global AR4 (IPCC, 2007d) estimates for primary energy supply and technical potential for primary biomass for energy; (2) the theoretical primary biomass potential for energy and the upper bound of biomass technical potential based on integrated global assessment studies using five resource categories indicated on the stacked bar chart and limitations and criteria with respect to biodiversity protection, water limitations, and soil degradation, assuming policy frameworks that secure good governance of land use (Dornburg et al., 2010, reproduced with permission from the Royal Society of Chemistry); (3) from the expert review of available scientific literature, potential deployment levels of terrestrial biomass for energy by 2050 could be in the range of 100 to 300 EJ; and (4) deployment levels of biomass for energy from long-term scenarios assessed in Chapter 10 in two cases of climate mitigation levels (CO_2 concentrations by 2100 of 440 to 600 ppm (orange) or <440 ppm (blue) bars or lines, see Figure 2.23(a)). Biomass deployment levels for energy from model studies described in (4) are consistent with the expert review of potential biomass deployment levels for energy depicted in (3).The most likely range is 80 to 190 EJ/yr with upper levels in the range of 265 to 300 EJ/yr.

criteria and including 88 EJ/yr from residues. They project a ramping-up to this potential from around 100 EJ/yr in 2020 and 130 EJ/yr in 2030.

The expert review conclusions based on available scientific literature (Sections 2.2.2 through 2.2.5) are:

- Important uncertainties include:
  - Population and economic/technology development; food, fodder and fibre demand (including diets); and development in agriculture and forestry;
  - Climate change impacts on future land use including its adaptation capability (IPCC, 2007a; Lobell et al., 2008; Fischer et al., 2009); and
  - Extent of land degradation, water scarcity, and biodiversity and nature conservation requirements (Molden, 2007; Bai et al., 2008; Berndes, 2008a,b; WBGU, 2009; Dornburg et al., 2010; Beringer et al., 2011).
- Residue flows in agriculture and forestry and unused (or extensively used thus becoming marginal/degraded) agricultural land are important sources for expansion of biomass production for energy, both in the near and longer term. Biodiversity-induced limitations and the need to ensure maintenance of healthy ecosystems and avoid soil degradation set limits on residue extraction in agriculture and forestry (Lal, 2008; Blanco-Canqui and Lal, 2009; WBGU, 2009).
- The cultivation of suitable (especially perennial) crops and woody species can lead to higher technical potential. These crops can produce bioenergy on lands less suited for the cultivation of conventional food crops that would also lead to larger soil carbon emissions than perennial crops and woody species. Multi-functional land use systems with bioenergy production integrated into agriculture and forestry systems could contribute to biodiversity conservation and help restore/maintain soil productivity and healthy ecosystems (Hoogwijk et al., 2005; Berndes et al., 2008; Folke et al., 2009; IAASTD, 2009; Malézieux et al., 2009; Dornburg et al., 2010).

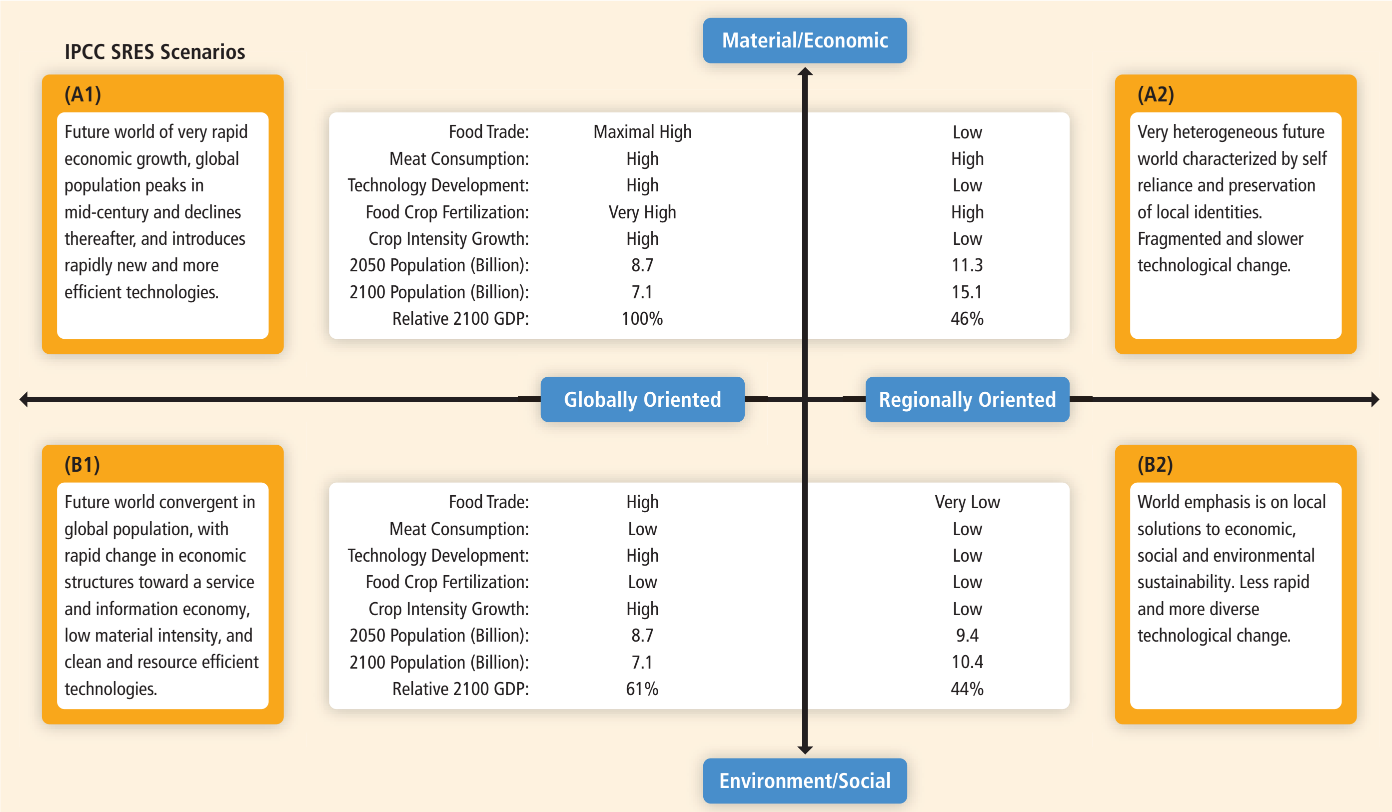


Figure 2.26 | Storylines for the key scenario variables of the IPCC SRES (IPCC, 2000) used to model biomass and bioenergy by Hoogwijk et al. (2005, reproduced with permission from Elsevier B.V.), the basis for the 2050 sketches adapted for this report and used to derive the stacked bar showing the upper bound of the biomass technical potential for energy in Figure 2.25.

- Regions experiencing water scarcity may have limited production. The possibility that conversion of lands to biomass plantations reduces downstream water availability needs to be considered. The use of suitable energy crops that are drought tolerant can help adaptation in water-scarce situations. Assessments of biomass resource potentials need to more carefully consider constraints and opportunities in relation to water availability and competing uses (Jackson et al., 2005; Zomer et al., 2006; Berndes et al., 2008; de Fraiture and Berndes, 2009).

To reach the *upper range of the deployment level* of 300 EJ/yr shown in Figure 2.25 would require major policy efforts, especially targeting improvements and efficiency increases in the agricultural sector and good governance, such as zoning, of land use.

Review scenario studies (as included in Dornburg et al., 2008) that calculate the amount of biomass used if energy demands are supplied cost-efficiently for different carbon tax regimes estimate that in 2050, between about 50 and 250 EJ/yr of biomass are used (cf. Figure 2.25). This is roughly in line with the scenarios reviewed in Chapter 10 (see Figure 2.23, which shows that the maximum demand is 300 EJ and the median value is about 155 EJ; note that the high end is only reached under the stringent mitigation scenarios of Categories I+II (<440 ppm CO_2) only).

2.8.4.2 Bioenergy technologies, supply chains and economics

A wide array of technologies and bioenergy systems exist to produce heat, electricity and fuels for transport, at commercial or development stages. Furthermore, biomass conversion to energy can be integrated with the production of biomaterials and biochemicals in cascading schemes that maximize the outputs of end products per unit input feedstock and land used.

The key currently commercial technologies are heat production at scales ranging from home cooking to district heating; power generation from biomass via combustion, CHP, or co-firing of biomass and fossil fuels; and first-generation liquid biofuels from oil crops (biodiesel) and sugar and starch crops (ethanol).

Modern biomass systems involve a wide range of feedstock types, including dedicated crops or trees, residues from agriculture and forestry, and various organic waste streams. Existing bioenergy systems rely mostly on wood, residues and waste for heat and power production and agricultural crops for liquid biofuels. The economics and yields of feedstocks vary widely across world regions and feedstock types. Energy yields per unit area range from 16 to 200 GJ/ha (1.6 to 20.0 TJ/km^2) for crops and oil seeds (biofuel feedstocks), from 80 to 415 GJ/ha (8.0 to 41.5 TJ/km^2) for lignocellulosic biomass, and from 2 to 155 GJ/ha

(0.2 to 15.5 TJ/km^2) for residues, while costs range from USD_{2005} 0.9 to 16/GJ (data from 2005 to 2007). Feedstock production competes with the forestry and food sectors, but integrated production systems such as agro-forestry or mixed cropping may provide synergies along with additional environmental services.

Handling and transport of biomass from production sites to conversion plants may contribute 20 to up to 50% of the total costs of biomass production. Factors such as scale increase, technological innovations and increased competition contributed to decrease the economic and energy costs of supply chains by more than 50%. Densification via pelletization or briquetting is required for transportation distances over 50 km. Charcoal made from biomass is a major fuel in developing countries, and it should benefit from the adoption of higher-efficiency kilns.

Different end-use applications require that biomass be processed through a variety of conversion steps depending on the physical nature and the chemical composition of feedstocks. Costs vary by world regions, feedstock types, feedstock supply costs for conversion processes, the scale of bioenergy production, and production time during the year. Examples of estimated commercial bioenergy levelized cost ranges are roughly USD 2 to 48/GJ for liquid and gaseous biofuels; roughly US $cents_{2005}$ 3.5 to 25/kWh (USD_{2005} 10 to 50/GJ) for electricity or CHP systems larger than about 2 MW (with feedstock costs of USD_{2005} 3/GJ based on high heating value and a heat value of USD_{2005} 5/GJ (steam) or USD_{2005} 12/GJ (hot water)); and roughly USD_{2005} 2 to 77/GJ for domestic or district heating systems with feedstock costs in the range of USD_{2005} 0 to 20/GJ (solid waste to wood pellets). These calculations refer to 2005 to 2008 data and are expressed in USD_{2005} at a 7% discount rate. Several bioenergy systems have deployed competitively, most notably sugarcane ethanol and heat and power generation from wastes and residues. Other biofuels have also undergone cost and environmental impact reductions but still require government subsidies.

In the medium term, the performance of existing bioenergy technologies can still be improved considerably, while new technologies offer the prospect of more efficient and competitive deployment of biomass for energy (as well as materials). Bioenergy systems, namely for ethanol and biopower production, show rates of technological learning and related cost reductions with learning comparable to those of other RE technologies. This applies to cropping systems (following progress in agricultural management when annual crops are concerned), to supply systems and logistics (as clearly observed in Scandinavia, as well as international logistics) and in conversion (e.g., ethanol production, power generation and biogas). Although not all bioenergy options discussed in this chapter have been investigated in detail with respect to technological learning, several important bioenergy systems have reduced their cost and improved environmental performance (Sections 2.3.4.2 and 2.7.2; Table 2.13). However, they usually still require government subsidies provided for economic development, poverty reduction and a secure energy supply or other country-specific reasons.

There is clear evidence that further improvements in power generation technologies (e.g., via biomass IGCC technology), supply systems for biomass, and production of perennial cropping systems can bring the costs of power (and heat or fuels) generation from biomass down to attractive cost levels in many regions. Nevertheless, the competitive production of bio-electricity (through methane or biofuels) depends on the integration with the end-use systems (Sections 8.2 and 8.3), performance of alternatives such as wind and solar energy, developing CCS technologies coupled with coal conversion, and nuclear energy (Sections 10.2.2.4, 10.2.2.6, 9.3, and 9.4). The implications of successful deployment of CCS in combination with biomass conversion could result in removal of GHG from the atmosphere and attractive mitigation cost levels but have so far received limited attention (Section 2.6.3.3).

With respect to lignocellulosic biofuels, recent analyses have indicated that the improvement potential is large enough for competition with oil at oil prices of USD_{2005} 60 to 80/barrel (USD_{2005} 0.38 to 0.44/litre). Currently available scenario analyses indicate that if shorter-term R&D and market support is strong, technological progress could allow for their commercialization around 2020 (depending on oil and carbon prices). Some scenarios also indicate that this would mean a major shift in the deployment of biomass for energy, because competitive production would decouple deployment from policy targets (mandates), and demand for biomass would move away from food crops to biomass residues, forest biomass and perennial cropping systems. The implications of such a (rapid) shift are so far poorly studied.

Integrated biomass gasification is a major avenue for the development of a variety of biofuels, with equivalent properties to gasoline, diesel and jet fuel (see Table 2.15.C for composition of hydrocarbon fuels). An option highlighted as promising in the literature is fuel product generation passing syngas through the catalytic reactor only once with the unreacted gas going to the power generation system instead of being recycled through the catalytic reactor. Other hybrid biochemical and thermochemical concepts have also been contemplated (Laser et al., 2009). Biomass pyrolysis routes and hydrothermal concepts are also developing in conjunction with the oil industry and have demonstrated that upgrading of oils to blendstocks of gasoline or diesel or even jet fuel quality products is technically possible (IATA, 2009).

Lignocellulosic ethanol development and demonstration continues in several countries. A key development step is pretreatment to overcome the recalcitrance of the cell wall of woody, herbaceous or agricultural residues to release the simple sugar components of biomass polymers and lignin. A review of the progress in this area suggests that a 40% reduction in cost could be expected by 2025 from process improvements, which would bring down the estimated cost of pilot plant production from USD_{2005} 18 to 22/GJ to USD_{2005} 12 to 15/GJ (Hamelinck et al., 2005a; Foust et al., 2009; NRC, 2009a) and into a competitive range.

Photosynthetic organisms, such as algae, use CO_2, water, and sunlight to biologically produce a variety of carbohydrates and lipids, chemicals, fuels like H_2, other molecules and oxygen with high photosynthetic efficiency and possibly high potentials (Sections 2.6.1, 3.3.5 and 3.7.6). Estimates of potential bioenergy supply from aquatic plants are very uncertain because of the lack of sufficient data for their assessment (Kheshgi et al., 2000; Smeets et al., 2009). Nevertheless these species need to be explored further because their development can utilize brackish waters and heavily saline soils and thus represent a strategy for low LUC impacts (Chisti, 2007; Weyer et al., 2009). The prospects of algae-based fuels and chemicals are at this stage uncertain, with wide ranges for potential production costs reported in the literature.

Data availability is limited with respect to production of biomaterials; cost estimates for chemicals from biomass are rare in the peer-reviewed literature, and future projections and LRs are even rarer. This condition is linked, in part, to the fact that successful bio-based products are entering the market place either as partial components of otherwise fossil-derived products or as fully new synthetic polymers, such as polylactides based on lactic acid derived from sugar fermentation. Analyses indicate that, in addition to producing biomaterials to replace fossil fuels, cascaded use of biomaterials and subsequent use of waste material for energy can offer more effective and larger mitigation impacts per hectare or tonne of biomass used (e.g., Dornburg and Faaij, 2005).

The benefits of biomass gasification and CCS alone or with coal are significant (see Figures 2.10 and 2.11). Similarly, capturing CO_2 from fermentation processes offers a significant option in many regions of the world, and coupling with CCS may become an attractive medium-term mitigation option. However, such concepts are not deployed at present and cost trends are not available in the literature, making investments in biomass (or coal) gasification technologies risky. Also, geologic sequestration reliability and the uncertainty of the regulatory environment pose further barriers. More detailed analysis is desired in this field.

2.8.4.3 Social and environmental impacts

The effects of bioenergy on social and environmental issues—ranging from health and poverty to biodiversity and water quality—may be positive or negative depending upon local conditions, the specific feedstock production system and technology paths chosen, how criteria and the alternative scenarios are defined, and how actual projects are designed and implemented, among other variables (Sections 9.2 through 9.5). Perhaps most important is the overall management and governance of land use when biomass is produced for energy on top of meeting food and other demands from agricultural production (as well as livestock). In cases where increases in land use due to biomass production are balanced out by improvements in agricultural management, undesirable iLUC effects can be avoided, while if unmanaged, conflicts may emerge. The overall performance of bioenergy production systems is therefore interlinked with management of land use and water resources. Trade-offs between those dimensions exist and need to be resolved through appropriate strategies and decision making. Such strategies are currently emerging due to many efforts targeting the deployment of sustainability frameworks and certification systems for bioenergy production (see also Section 2.4.5), setting standards for GHG performance (including LUC effects), addressing environmental issues and taking into consideration a number of social aspects.

Most bioenergy systems can contribute to climate change mitigation if they replace fossil-based energy that was causing high GHG emissions and if the bioenergy production emissions—including those arising due to LUC or temporal imbalance of terrestrial carbon stocks—are kept low (examples given in Sections 2.3 and 2.6). High N_2O emissions from feedstock production and the use of high carbon intensity fossil fuels in the biomass conversion process can strongly impact the GHG savings. Best fertilizer management practices, process integration minimizing losses, surplus heat utilization, and biomass use as a process fuel can reduce GHG emissions. But in cold climates the displacement efficiency (see Section 2.5.3) can become low when biomass is used both as feedstock and as fuel in the conversion process.

Given the lack of studies on how biomass resources may be distributed over various demand sectors, no detailed allocation of the different biomass supplies for various applications is suggested here. Furthermore, the net avoidance costs per tonne of CO_2 for biomass usage depend on various factors, including the biomass resource and supply (logistics) costs, conversion costs (which in turn depend on availability of improved or advanced technologies) and fossil fuel prices, most notably of oil.

A GHG performance evaluation of key biofuel production systems deployed today and possible second-generation biofuels using different calculation methods is available (Sections 2.5.2, 2.5.3 and 9.3.4; Hoefnagels et al., 2010). Recent insights converge by concluding that well-managed bioenergy production and utilization chains can deliver high GHG mitigation percentages (80 to 90%) compared to their fossil counterparts, especially for lignocellulosic biomass used for power generation and heat and, when the technology would be commercially available, for lignocellulosic biofuels. The use of most residues and organic wastes, principally animal residues, for energy result in such good performance. Also, most current biofuel production systems have positive GHG balances, and for some of them this situation persists even when significant iLUC effects are incorporated (see below).

LUC can strongly affect those scores, and when conversion of land with large carbon stocks takes place for the purpose of biofuel production, emission benefits can shift to negative levels in the near term. This is most extreme for palm oil-based biodiesel production, where extreme carbon emissions are obtained if peatlands are drained and converted to oil palm (Wicke et al., 2008). The GHG mitigation effect of biomass use for energy (and materials) therefore strongly depends on location (in particular avoidance of converting carbon-rich lands to carbon-poor cropping systems), feedstock choice and avoiding iLUC (see below). In contrast, using perennial cropping systems can store large amounts of carbon and enhance sequestration on marginal and degraded soils, and biofuel production can replace fossil fuel use. Governance of land use, proper zoning and choice of biomass production systems are therefore key factors to achieve good performance.

The assessment of available iLUC literature (Figures 2.13, 9.10, and 9.11) indicated that initial models were lacking in geographic resolution, leading to higher proportions than necessary of land use assigned to deforestation, as the models did not have other kinds of lands (e.g., pastures in Brazil) for use. While the early paper of Searchinger et al. (2008) claimed an iLUC factor of 0.8 (losing 0.8 ha of forest land for each hectare of land used for bioenergy), later (2010) studies that coupled macro-economic to biophysical models tuned that down to 0.15 to 0.3 (see, e.g., Al-Riffai et al., 2010). Models used to estimate iLUC effects vary in their estimates of land displacement. Partial and general equilibrium models have different assumptions and reflect different time frames, and thus they incorporate more or less adjustment. More detailed evaluations (e.g., Al-Riffai et al., 2010; Lapola et al., 2010; see Section 2.5.3) do estimate significant iLUC impacts but also suggest that any iLUC effect strongly (up to fully) depends on the rate of improvement in agricultural and livestock management and the rate of deployment of bioenergy production. This balance in development is also the basis for the recent European biomass resource potential analysis, for which expected gradual productivity increments in agriculture are the basis for possible land availability (as reported in Fischer et al. (2010) and de Wit and Faaij (2010); see Figure 2.5(a)) minimizing competition with food (or nature) as a starting point. Increased model sophistication to adapt to the complex type of analysis required and improved data on the actual dynamics of land distribution in the major biofuel-producing countries are now producing results that show lower overall LUC impacts (Figure 9.11) and acknowledge that land use management at large is key (Berndes et al., 2010).

Bioenergy projects can result in gains or losses in associated biospheric stocks and in both direct and indirect LUC, the latter being inherently difficult to quantify. Even so, it can be concluded that LUC can affect GHG balances in several ways, with beneficial or detrimental outcomes for bioenergy's contribution to climate change mitigation, depending on conditions and context. When land high in carbon (notably forests and especially peat soil forests) is converted to bioenergy, upfront emissions may cause a time lag of decades to centuries before net emission savings are achieved. But the establishment of bioenergy plantations can also lead to assimilation of CO_2 into soils and aboveground biomass in the short term. Increased utilization of forest biomass can reduce forest carbon stocks. The longer-term net effect on forest carbon stocks can be positive or negative depending on natural conditions (including disturbances such as insect outbreaks and fires) and forest management practices. The use of post-consumer organic waste and by-products from the agricultural and forest industries does not cause LUC if these biomass sources were not utilized for alternative purposes. Bioenergy feedstocks can be produced in combination with food and fibre, avoiding land use displacement and improving the productive use of land. Lignocellulosic feedstocks for bioenergy can decrease the pressure on prime cropping land. Stimulation of increased productivity in all forms of land use reduces the LUC pressure.

Air pollution effects of bioenergy depend on both the bioenergy technology (including pollution control technologies) and the displaced energy technology (e.g., inefficient coal versus modern natural gas combustion) (Figure 9.12). Improved biomass cookstoves for traditional biomass use can provide large and cost-effective mitigation of GHG emissions with substantial co-benefits in terms of health and living conditions, particularly for the 2.7 billion people in the world that rely on traditional biomass for cooking and heating (Sections 2.5.4, 9.3.4, 9.3.4.2 and 9.3.4.3). Efficient technologies for cooking are even cost-effective compared to other major interventions in health, such as those addressing tobacco, undernourishment or tuberculosis (Figures 2.14 and 9.13).

Other key environmental impacts cover water use, biodiversity and other emissions (Sections 2.5.5 and 9.3.4). Just as for GHG impacts, proper management determines emission levels to water, air and soil. Development of standards or criteria (and continuous improvement processes) will push bioenergy production to lower emissions and higher efficiency than today's systems.

Water is a critical issue that needs to be better analyzed at a regional level to understand the full impact of changes in vegetation and land use management. Recent studies (Berndes, 2002; Dornburg et al., 2008; Rost et al., 2009; Wu et al., 2009) indicate that considerable improvements can be made in water use efficiency in conventional agriculture, bioenergy crops and, depending on location and climate, perennial cropping systems, by improving water retention and lowering direct evaporation from soils (Figure 9.14). Nevertheless, without proper management, increased biomass production could come with increased competition for water in critical areas, which is highly undesirable (Fingerman et al., 2010).

Similar remarks can be made with respect to biodiversity, although more scientific uncertainty exists due to ongoing debates about methods of biodiversity impacts assessment. Clearly, development of large-scale monocultures at the expense of natural areas is detrimental for biodiversity (for example, highlighted in UNEP. 2008b). However, as discussed in Section 2.5, bioenergy can also lead to positive effects by integrating different perennial grasses and woody crops into agricultural landscapes, which could also increase soil carbon and productivity, reduce shallow landslides and local 'flash floods', reduce wind and water erosion, and reduce sediment and nutrients transported into river systems. Forest residue harvesting improves forest site conditions for replanting, and thinning generally improves productivity and growth of the remaining stand. Removal of biomass from overly-dense stands can reduce wildfire risk.

The impact assessments for all these areas deserve considerably more research, data collection and proper monitoring, as exemplified by ongoing activities of governments (see footnote 64) and roundtables[78] for pilot studies.

78 See Roundtable on Sustainable Biofuels pilot studies at www2.epfl.ch/energycenter-jahia4/page65660.html.

Social impacts from a large expansion of bioenergy are very complex and difficult to quantify. Crops grown as biofuel feedstock currently use less than 1% of the world's agricultural land, but demand for biofuels has represented one driver of demand growth and therefore contributed to global food price increases. Increased demand for food and feed, increases in oil prices, speculation on international food markets, and incidental poor harvests due to extreme weather events are examples of events that have likely also had an impact on global food prices. Even considering the benefit of increased prices to poor farmers, increased food prices adversely affect the level of poverty, food security, and malnourishment of children. On the other hand, biofuels can also provide opportunities for developing countries to make progress in rural development and agricultural growth, especially when this growth is economically sustainable.

In general, bioenergy options have a much larger positive impact on job creation in rural areas than other energy sources, for example, 50 to 2,200 jobs/PJ (Section 2.5.7.3). Also when the intensification of conventional agriculture frees up land that could be used for bioenergy, the total job impact and added value generated in rural regions increases when bioenergy production increases. Effective pasture/agriculture land use management could increase the rain-fed production potential significantly (see Table 2.3; Wicke et al., 2009). For many developing countries, the potential of bioenergy to generate employment, economic activity in rural areas, and fuel supply security are key drivers. In addition, expenditures on fossil fuel (imports) can be (strongly) reduced. However, whether such benefits end up with rural farmers depends largely on the way production chains are organized and how land use is governed.

The bioenergy options that are developed, the way they are developed, and under what conditions will have a profound influence on whether impacts will largely be positive or negative (Argentina scenarios; van Dam et al., 2009a,b). The development of standards or criteria (and continuous improvement processes) can push bioenergy production to lower or positive impacts and higher efficiency than today's systems. Bioenergy has the opportunity to contribute to climate change mitigation, a secure and diverse energy supply, and economic development in developed and developing countries alike, but the effects of bioenergy on environmental sustainability may be positive or negative depending upon local conditions, how criteria are defined, and how actual projects are designed and implemented, among many other factors.

2.8.5 Conclusions regarding deployment: Key messages about bioenergy

Bioenergy is currently the largest RE source and is likely to remain one of the largest RE sources for the first half of this century. There is considerable growth potential, but it requires active development.

- Assessments in the recent literature show that the technical potential of biomass for energy may be as large as 500 EJ/yr by 2050. However, large uncertainty exists about important factors such as market and policy conditions that affect this potential.

- The expert assessment in this chapter suggests potential deployment levels by 2050 in the range of 100 to 300 EJ/yr. Realizing this potential represents a major challenge but would make a substantial contribution to the world's primary energy demand in 2050—roughly equal to the equivalent heat content of today's worldwide biomass extraction in agriculture and forestry.

- Bioenergy has significant potential to mitigate GHGs if resources are sustainably developed and efficient technologies are applied. Certain current systems and key future options including perennial crops, forest products and biomass residues and wastes, and advanced conversion technologies, can deliver significant GHG mitigation performance—an 80 to 90% reduction compared to the fossil energy baseline. However, land conversion and forest management that lead to a large loss of carbon stocks and iLUC effects can lessen, and in some cases more than neutralize, the net positive GHG mitigation impacts.

- In order to achieve the high potential deployment levels of biomass for energy, increases in competing food and fibre demand must be moderate, land must be properly managed and agricultural and forestry yields must increase substantially. Expansion of bioenergy in the absence of monitoring and good governance of land use carries the risk of significant conflicts with respect to food supplies, water resources and biodiversity, as well as a risk of low GHG benefits. Conversely, implementation that follows effective sustainability frameworks could mitigate such conflicts and allow realization of positive outcomes, for example, in rural development, land amelioration and climate change mitigation, including opportunities to combine adaptation measures.

- The impacts and performance of biomass production and use are region- and site-specific. Therefore, as part of good governance of land use and rural development, bioenergy policies need to consider regional conditions and priorities along with the agricultural (crops and livestock) and forestry sectors. Biomass resource potentials are influenced by and interact with climate change impacts but the specific impacts are still poorly understood; there will be strong regional differences in this respect. Bioenergy and new (perennial) cropping systems also offer opportunities to combine adaptation measures (e.g., soil protection, water retention and modernization of agriculture) with production of biomass resources.

- Several important bioenergy options (i.e., sugarcane ethanol production in Brazil, select waste-to-energy systems, efficient biomass cookstoves, biomass-based CHP) are competitive today and can provide important synergies with longer-term options. Lignocellulosic biofuels replacing gasoline, diesel and jet fuels, advanced bioelectricity options and biorefinery concepts can offer competitive deployment of bioenergy for the 2020 to 2030 timeframe. Combining biomass conversion with CCS raises the possibility of achieving GHG removal from the atmosphere in the long term—a necessity for substantial GHG emission reductions. Advanced biomaterials are promising as well for the economics of bioenergy production and mitigation, though the potential is less well understood as is the potential role of aquatic biomass (algae), which is highly uncertain.

- Rapidly changing policy contexts, recent market-based activities, the increasing support for advanced biorefineries and lignocellulosic biofuel options, and in particular the development of sustainability criteria and frameworks, all have the potential to drive bioenergy systems and their deployment in sustainable directions. Achieving this goal will require sustained investments that reduce costs of key technologies, improved biomass production and supply infrastructure, and implementation strategies that can gain public and political acceptance.

In conclusion and for illustrating the interrelations between scenario variables (see Figure 2.26), key preconditions under which bioenergy production capacity is developed and what the resulting impacts may be, Figure 2.27 presents four different sketches for biomass deployment for energy on a global scale by 2050. The 100 to 300 EJ range that follows from the resource potential review delineates the lower and upper limit for deployment. The assumed storylines roughly follow the IPCC SRES definitions, applied to bioenergy and summarized in Figure 2.26 (Hoogwijk et al., 2005), that were also used to derive the technical potential shown on the stacked bar of Figure 2.25 (Dornburg et al., 2008, 2010).

Biomass and its multiple energy products can be developed alongside food, fodder, fibre and forest products in both sustainable and unsustainable ways. As viewed through the IPCC scenario storylines and sketches, high and low penetration levels can be reached with and without taking into account sustainable development and climate change mitigation pathways. Insights into bioenergy technology developments and integrated systems can be gleaned from these sketches.

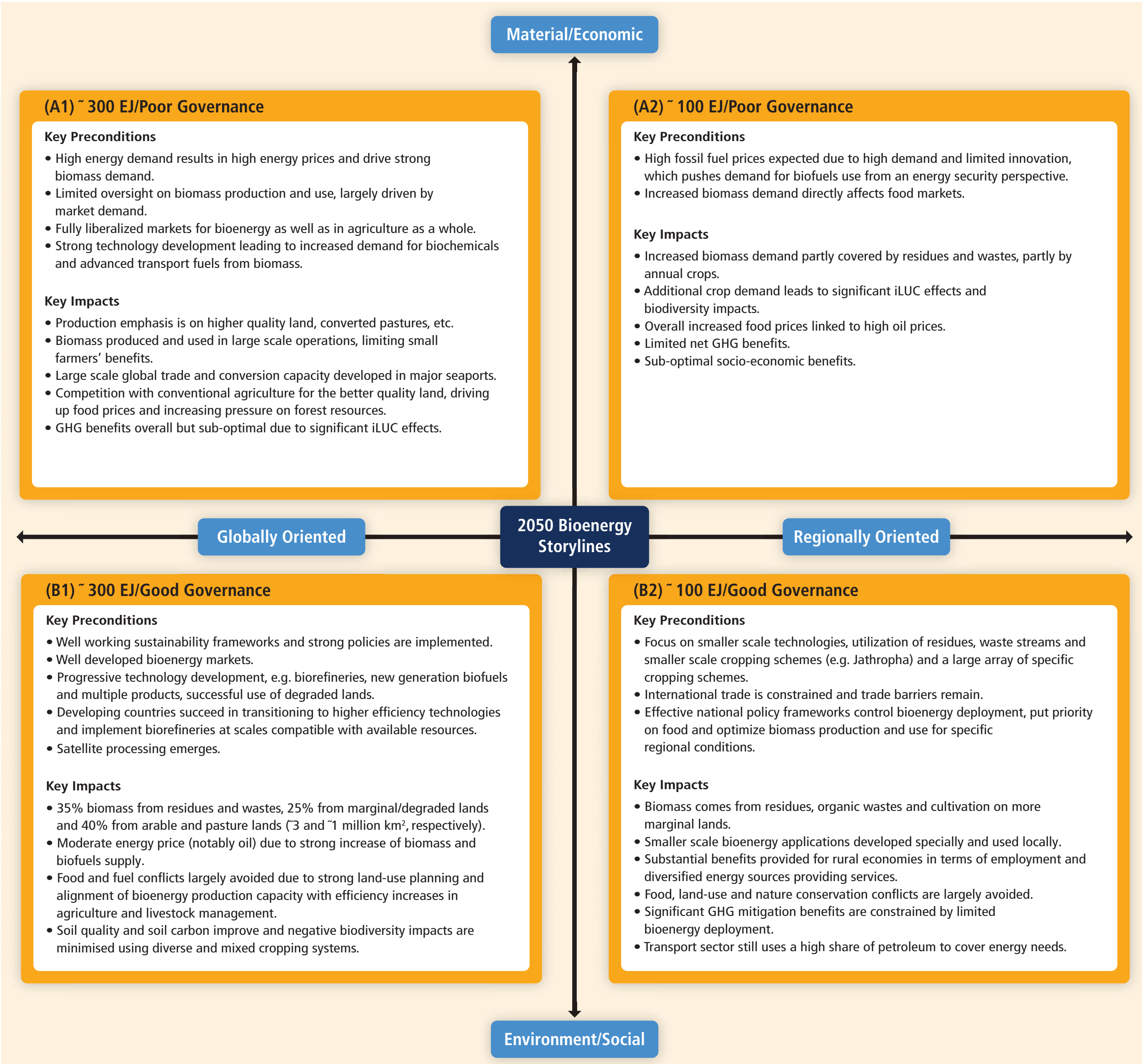


Figure 2.27 | Possible futures for 2050 biomass deployment for energy: Four illustrative contrasting sketches describing key preconditions and impacts following world conditions typical of the IPCC SRES storylines (IPCC, 2000) summarized in Figure 2.26.

References

Abbasi, T., and S.A. Abbasi (2010). Biomass energy and the environmental impacts associated with its production and utilization. *Renewable and Sustainable Energy Reviews*, **14**(3), pp. 919-937.

Adam, J.C. (2009). Improved and more environmentally friendly charcoal production system using a low-cost retort-kiln (Eco-charcoal). *Renewable Energy*, **34**(8), pp. 1923-1925.

Adams, P.W., G.P. Hammond, M.C. McManus, and W.G. Mezzullo (2011). Barriers to and drivers for UK bioenergy development. *Renewable and Sustainable Energy Reviews*, **15**(2), pp. 1217-1227.

Aden, A., M. Ruth, K. Ibsen, J. Jechura, K. Neeves, J. Sheehan, B. Wallace, L. Montague, A. Slayton, and J. Lukas (2002). *Lignocellulosic Biomass to Ethanol Process Design and Economics Utilizing Co-Current Dilute Acid Prehydrolysis and Enzymatic Hydrolysis for Corn Stover.* NREL/TP-510-32438, National Renewable Energy Laboratory, Golden, Colorado, USA, 154 pp.

Ahrens, T.D., D.B. Lobell, J.I. Ortiz-Monasterio, Y. Li, and P.A. Matson (2010). Narrowing the agronomic yield gap with improved nitrogen use efficiency: a modeling approach. *Ecological Applications*, **20**(1), pp. 91-100.

Ainsworth, E.A., and S.P. Long (2005). What have we learned from 15 years of free-air CO_2 enrichment (FACE)? A meta-analytic review of the responses of photosynthesis, canopy properties and plant production to rising CO_2. *New Phytologist*, **165**(2), pp. 351-372.

Al-Riffai, P., B. Dimaranan, and L. Laborde (2010). *Global Trade and Environmental Impact Study of the EU Biofuels Mandate.* Project Report - Specific Contract No SI2.537.787 implementing Framework Contract No TRADE/07/A2, International Food Policy Research Institute, Washington, DC, USA, 123 pp.

Alexandratos, N. (2009). World food and agriculture to 2030/50: highlights and views from mid-2009. In: *Proceedings of the Expert Meeting on How to Feed the World in 2050*, Rome, Italy, 24-26 June 2009. Economic and Social Development Department, Food and Agriculture Organization of the United Nations, Rome, Italy, pp. 78. Available at: www.fao.org/docrep/012/ak542e/ak542e00.htm.

Alfstad, T. (2008). *World Biofuels Study: Scenario Analysis of Global Biofuels Markets*. BNL-80238-2008, Brookhaven National Laboratory, New York, NY, USA, 67 pp.

Allen, J., M. Browne, A. Hunter, J. Boyd, and H. Palmer (1998). Logistics management and costs of biomass fuel supply. *International Journal of Physical Distribution & Logistics Management*, **28**(6), pp. 463-477.

Allen, M.R., D.J. Frame, C. Huntingford, C.D. Jones, J.A. Lowe, M. Meinshausen, and N. Meinshausen (2009). Warming caused by cumulative carbon emissions towards the trillionth tonne. *Nature*, **458**(7242), pp. 1163-1166.

Alper, H., and G. Stephanopoulos (2009). Engineering for biofuels: exploiting innate microbial capacity or importing biosynthetic potential? *Nature Reviews Microbiology*, **7**(10), pp. 715-723.

Anderson-Teixeira, K.J., S.C. Davis, M.D. Masters, and E.H. Delucia (2009). Changes in soil organic carbon under biofuel crops. *Global Change Biology Bioenergy*, **1**(1), pp. 75-96.

APEC (2003). *The New Brunswick Forest Industry: The Potential Economic Impact of Proposals to Increase the Wood Supply*. Atlantic Provinces Economic Council, Halifax, Canada.

Armendáriz, C.A., R.D. Edwards, M. Johnson, M. Zuk, L. Rojas, R.D. Jiménez, H. Riojas-Rodriguez, and O. Masera (2008). Reduction in personal exposures to particulate matter and carbon monoxide as a result of the installation of a Patsari improved cook stove in Michoacan Mexico. *Indoor Air*, **18**(2), pp. 93-105.

Arndt, C., R. Benfica, F. Tarp, and R. Uaiene (2010). Biofuels, poverty, and growth: A computable general equilibrium analysis of Mozambique. *Environment and Development Economics*, **15**(1), pp. 81-105.

Asikainen, A., H. Liiri, S. Peltola, T. Karjalainen, and J. Laitila (2008). *Forest Energy Potential in Europe (EU 27)*. Working Papers of the Finnish Forest Research Institute, No. 69, Finnish Forest Research Institute, Helsinki, Finland, 33 pp.

Asikainen, A., P. Anttila, J. Heinimö, T. Smith, I. Stupak, and W. Ferreira Quirino (2010). Forest and bioenergy production. In: *Forest and Society – Responding to Global Drivers of Change*. G. Mery, P. Katila, G. Galloway, R.I. Alfaro, M. Kanninen, M. Lobovikov, and J. Varjo (eds.). International Union of Forest Research Organizations, Vienna, Austria, pp. 183-200.

Astbury, G. (2008). A review of the properties and hazards of some alternative fuels. *Process Safety and Environmental Protection*, **86**(6), pp. 397-414.

Ausubel, J.H. (2000). The great reversal: nature's chance to restore land and sea. *Technology in Society*, **22**, pp. 289-301.

Azar, C., K. Lindgren, M. Obersteiner, K. Riahi, D. van Vuuren, K. den Elzen, K. Möllersten, and E. Larson (2010). The feasibility of low CO_2 concentration targets and the role of bio-energy with carbon capture and storage (BECCS). *Climatic Change*, **100**(1), pp. 195-202.

Bacovsky, D., M. Dallos, and M. Worgetter (2010a). *Status of 2nd Generation Biofuels Demonstration Facilities in June 2010*. T39-P1b, IEA Bioenergy Task 39, 126 pp. Available at: www.ascension-publishing.com/BIZ/IEATask39-0610.pdf.

Bacovsky, D., W. Mabee, and M. Wörgetter (2010b). How close are second-generation biofuels? *Biofuels, Bioproducts and Biorefining*, **4**(3), pp. 249-252.

Badger, P. (2000). New process for torrefied wood manufacturing. *Bioenergy Update*, **2**(4), pp. 1-4. Available at: www.bioenergyupdate.com/magazine/security/NL0400/gbinl0400.pdf.

Badgley, C., J. Moghtader, E. Quintero, E. Zakem, M.J. Chappell, K. Avilés-Vázquez, A. Samulon, and I. Perfecto (2007). Organic agriculture and the global food supply. *Renewable Agriculture and Food Systems*, **22**(02), pp. 86-86.

Baffes, J., and T. Haniotis (2010). *Placing the 2006/08 Commodity Price Boom into Perspective*. Policy Research Working Paper 5371, The World Bank Group, Washington, DC, USA, 42 pp.

Bai, Z.G., D.L. Dent, L. Olsson, and M.E. Schaepman (2008). Proxy global assessment of land degradation. *Soil Use and Management*, **24**(3), pp. 223-234.

Bailis, R., A. Cowan, V. Berrueta, and O. Masera (2009). Arresting the killer in the kitchen: The promises and pitfalls of commercializing improved cookstoves. *World Development*, **37**(10), pp. 1694-1705.

Bain, R.L. (2007). *World Biofuels Assessment, Worldwide Biomass Potential: Technology Characterizations*. NREL/MP-510-42467, National Renewable Energy Laboratory, Golden, CO, USA, 140 pp.

Bain, R.L. (2011). *Biopower Technologies in Renewable Electricity Alternative Futures*. National Renewable Energy Laboratory, Golden, CO, USA, in press.

Bain, R.L., W.P. Amos, M. Downing, and R.L. Perlack (2003). *Biopower Technical Assessment: State of the Industry and the Technology*. TP-510-33123, National Renewable Energy Laboratory, Golden, CO, USA, 277 pp.

Bairiganjan, S., R. Cheung, E.A. Delio, D. Fuente, S. Lall, and S. Singh (2010). *Power to the People: Investing in Clean Energy for the Base of the Pyramid in India*. Centre for Development Finance, c/o Institute for Financial Management and Research, World Resources Institute, Washington, DC, USA, 74 pp.

Balat, M. (2011). Potential alternatives to edible oils for biodiesel production - A review of current work. *Energy Conversion and Management*, **52**(2), pp. 1479-1492.

Ball, B.C., I. Bingham, R.M. Rees, C.A. Watson, and A. Litterick (2005). The role of crop rotations in determining soil structure and crop growth conditions. *Canadian Journal of Soil Science*, **85**, pp. 557-577.

Balmford, A., R.E. Green, and J.P.W. Scharlemann (2005). Sparing land for nature: exploring the potential impact of changes in agricultural yield on the area needed for crop production. *Global Change Biology*, **11**(10), pp. 1594-1605.

Barker, W.T., C.L. Lura, and J.L. Richardson (2009). Soil organic matter and native plant production on the Missouri Coteau. *North Dakota Farm Research*, **44**(2), pp. 14-21.

Barth, T., and M. Kleinert (2008). Motor fuels from biomass pyrolysis. *Chemical Engineering & Technology*, **31**(5), pp. 773-781.

Bauen, A., G. Berndes, M. Junginger, M. Londo, F. Vuille, R. Ball, T. Bole, C. Chudziak, A. Faaij, and H. Mozaffarian (2009a). *Bioenergy: A Sustainable and Reliable Energy Source: A Review of Status and Prospects*. IEA Bioenergy: ExCo:2009:06, 108 pp.

Bauen, A., F. Vuille, P. Watson, and K. Vad (2009b). *The RSB GHG accounting scheme. Feasibility of a meta-methodology and way forward*. E4tech version 4.1, Roundtable on Sustainable Biofuels., Lausanne, Switzerland, 91 pp. Available at: rsb.epfl.ch/files/content/sites/rsb2/files/Biofuels/Documents%20and%20Resources/09-10-08_E4Tech%20Report%20GHG%20Accounting_V4%201_08October09.pdf.

Baum, C., P. Leinweber, M. Weih, N. Lamersdorf, and I. Dimitriou (2009). Effects of short rotation coppice with willows and poplar on soil ecology. *Landbauforschung vTI Agriculture and Forestry Research*, **59**(3), pp. 183-186.

Baum, S., M. Weih, G. Busch, F. Kroiher, and A. Bolte (2009). The impact of Short Rotation Coppice plantations on phytodiversity. *Landbauforschung vTI Agriculture and Forestry Research*, **59**(3), pp. 163-170.

Beer, T., and T. Grant (2007). Life-cycle analysis of emissions from fuel ethanol and blends in Australian heavy and light vehicles. *Journal of Cleaner Production*, **15**(8-9), pp. 833-837.

Beer, T., T. Grant, R. Brown, J. Edwards, P. Nelson, H. Watson, and D. Williams (2000). *Life Cycle Emissions Analysis of Alternative Fuels for Heavy Vehicles.* Atmospheric Research Report C/0411/1.1/F2, Australian Commonwealth Scientific and Research Organization, Aspendale, Australia, 148 pp.

Beer, T., T. Grant, G. Morgan, J. Lapszewicz, P. Anyon, J. Edwards, P. Nelson, H. Watson, and D. Williams (2001). *Comparison of Transport Fuels*. EV45A/2/F3C, Australian Commonwealth Scientific and Research Organization, Aspendale, Australia, 485 pp.

Beringer, T.I.M., W. Lucht, and S. Schaphoff (2011). Bioenergy production potential of global biomass plantations under environmental and agricultural constraints. *Global Change Biology Bioenergy*, doi:10.1111/j.1757-1707.2010.01088.x.

Berndes, G. (2002). Bioenergy and water--the implications of large-scale bioenergy production for water use and supply. *Global Environmental Change*, **12**(4), pp. 253-271.

Berndes, G. (2008a). Future biomass energy supply: The consumptive water use perspective. *International Journal of Water Resources Development*, **24**(2), pp. 235-245.

Berndes, G. (2008b). *Water Demand for Global Bioenergy Production: Trends, Risks and Opportunities*. Report commissioned by the German Advisory Council on Global Change. Wissenschaftlicher Beirat der Bundesregierung Globale Umweltveränderungen, Berlin, Germany, 46 pp.

Berndes, G., and J. Hansson (2007). Bioenergy expansion in the EU: Cost-effective climate change mitigation, employment creation and reduced dependency on imported fuels. *Energy Policy*, **35**(12), pp. 5965-5979.

Berndes, G., M. Hoogwijk, and R. van den Broek (2003). The contribution of biomass in the future global energy supply: a review of 17 studies. *Biomass and Bioenergy*, **25**(1), pp. 1-28.

Berndes, G., F. Fredrikson, and P. Börjesson (2004). Cadmium accumulation and Salix-based phytoextraction on arable land in Sweden. *Agriculture, Ecosystems & Environment*, **103**(1), pp. 207-223.

Berndes, G., P. Börjesson, M. Ostwald, and M. Palm (2008). Multifunctional biomass production systems – an overview with presentation of specific applications in India and Sweden. *Biofuels, Bioproducts and Biorefining*, **2**(1), pp. 16-25.

Berndes, G., N. Bird, and A. Cowie (2010). *Bioenergy, Land Use Change and Climate Change Mitigation*. IEA Bioenergy: ExCo:2010:03, International Energy Agency, Whakarewarewa, Rotorua, New Zealand, 20 pp. Available at: www.iea-bioenergy.com/LibItem.aspx?id=6770.

Berrueta, V.M., R.D. Edwards, and O.R. Masera (2008). Energy performance of wood-burning cookstoves in Michoacan, Mexico. *Renewable Energy*, **33**(5), pp. 859-870.

Bessou, C., F. Ferchaud, B. Gabrielle, and B. Mary (2010). Biofuels, greenhouse gases and climate change. A review. *Agronomy for Sustainable Development*, doi:10.1051/agro/2009039,132 pp.

Bhagwat, S.A., K.J. Willis, H.J.B. Birks, and R.J. Whittaker (2008). Agroforestry: a refuge for tropical biodiversity? *Trends in Ecology & Evolution*, **23**(5), pp. 261-267.

Bhojvaid, P.P. (2007). Recent trends in biodiesel production. In: *Biofuels: Towards a Greener and Secure Energy Future.* P.P. Bhojvaid (ed.), The Energy and Resources Institute (TERI) Press, New Delhi, India, pp. 119-136.

Bickel, P., and R. Friedrich (eds.) (2005). *ExternE - Externalities of Energy: Methodology 2005 Update.* European Commission, Brussels, Belgium, 270 pp.

Biran, A., J. Abbot, and R. Mace (2004). Families and firewood: A comparative analysis of the costs and benefits of children in firewood collection and use in two rural communities in sub-Saharan Africa. *Human Ecology*, **32**(1), pp. 1-25.

Blanco-Canqui, H., and R. Lal (2009). Corn stover removal for expanded uses reduces soil fertility and structural stability. *Soil Science Society of America Journal*, **73**(2), pp. 418-426.

Blanco-Canqui, H., R. Lal, W.M. Post, R.C. Izaurralde, and L.B. Owens (2006). Rapid changes in soil carbon and structural properties due to stover removal from no-till corn plots. *Soil Science*, **171**(6), pp. 468-482.

BNDES/CGEE (2008). *Sugarcane-Based Bioethanol: Energy for Sustainable Development.* Brazilian Development Bank and Center for Strategic Studies and Management Science, Technology and Innovation, Rio de Janeiro, Brazil, 304 pp.

Bohlmann, G.M., and M.A. Cesar (2006). The Brazilian opportunity for biorefineries. *Industrial Biotechnology*, **2**(2), pp. 127-132.

Boman, C., B. Forsberg, and T. Sandström (2006). Shedding new light on wood smoke: a risk factor for respiratory health. *European Respiratory Journal*, **27**(3), pp. 446-447.

Bon, E.P.S., and M.A. Ferrara (2007). Bioethanol production via enzymatic hydrolysis of cellulosic biomass. In: *FAO Symposium on the Role of Agricultural Biotechnologies for Production of Bioenergy in Developing Countries*, 12 October 2007, Food and Agriculture Organization, Rome, Italy, 11 pp. Available at: http://www.fao.org/biotech/docs/bon.pdf.

Börjesson, P. (2000). Economic valuation of the environmental impact of logging residue recovery and nutrient compensation. *Biomass and Bioenergy*, **19**(3), pp. 137-152.

Börjesson, P. (2009). Good or bad bioethanol from a greenhouse gas perspective – What determines this? *Applied Energy*, **86**(5), pp. 589-594.

Börjesson, P., and G. Berndes (2006). The prospects for willow plantations for wastewater treatment in Sweden. *Biomass and Bioenergy*, **30**(5), pp. 428-438.

Borowitzka, M.A., R. Osinga, J. Tramper, J.G. Burgess, and R.H. Wijffels (1999). Commercial production of microalgae: ponds, tanks, and fermenters. *Progress in Industrial Microbiology*, **35**, pp. 313-321.

Bouwman, A.F., L.J.M. Boumans, and N.H. Batjes (2002). Emissions of N_2O and NO from fertilized fields: Summary of available measurement data. *Global Biogeochemical Cycles*, **16**(4), 13 pp.

Bradley, D., F. Diesenreiter, M. Wild, and E. Tromborg (2009). *World Biofuel Maritime Shipping Study.* IEA Bioenergy Task 40, IEA, Paris, France, 38 pp.

Bradley, R.L., A. Olivier, N. Thevathasan, and J. Whalen (2008). Environmental and economic benefits of tree-based intercropping systems. *Policy Options*, February, pp. 46-49. Available at: www.irpp.org/po/archive/feb08/bradley.pdf.

Bravo, R., O. Masera, T. Chalico, D. Pandey, E. Riegelhaupt, and A. Uhlig (2010). *Case-studies from Brazil, India and Mexico.* Food and Agriculture Organization, Rome, Italy, 80 pp.

Bridgwater, A., S. Czernik, J. Diebold, D. Meier, A. Oasmaa, C. Peacocke, J. Piskorz, and D. Radlein (2003). *Fast Pyrolysis of Biomass: A Handbook.* CPL Press, Berks, UK, 180 pp.

Bridgwater, A. Ed. (2007). *Success & Visions for Bioenergy: Thermal processing of biomass for bioenergy, biofuels and bioproducts.* CPL Scientific Publishing Services Ltd., CD-ROM, ISBN 9781872691282.

Bringezu, S., H. Schuetz, M. O Brien, L. Kauppi, R. Howarth, and J. McNeely (2009). *Towards Sustainable Production and Use of Resources: Assessing Biofuels.* United Nations Environment Programme, Paris, France, 102 pp.

Bruce, N., E. Rehfuess, S. Mehta, G. Hutton, and K.R. Smith (2006). Indoor air pollution. In: *Disease Control Priorities in Developing Countries.* 2nd ed. World Bank Group, Washington, DC, USA, pp. 793-815.

Bruinsma, J. (2009). The resource outlook to 2050: by how much do land, water and crop yields need to increase by 2050? In: *Expert Meeting on How to Feed the World in 2050*, 24-26 June 2009, Economic and Social Development Department, Food and Agriculture Organization of the United Nations, Rome, Italy, 33 pp.

Brunner, A.M., S.P. DiFazio, and A.T. Groover (2007). Forest genomics grows up and branches out. *New Phytologist*, **174**(4), pp. 710-713.

Buchholz, T., E. Rametsteiner, T. Volk, and V. Luzadis (2009). Multi Criteria Analysis for bioenergy systems assessments. *Energy Policy*, **37**(2), pp. 484-495.

Bureau, J.-C., H. Guyomard, F. Jacquet, and D. Tréguer (2010). European biofuel policy: How far will public support go? In: *Handbook of Bioenergy Economics and Policy.* M. Khanna, J. Scheffran, and D. Zilberman (eds.), Springer, Heidelberg, Germany, pp. 401-423.

Bush, D.R., and J.E. Leach (2007). Translational genomics for bioenergy production: There's room for more than one model. *The Plant Cell*, **19**(10), pp. 2971-2973.

Calder, I., J. Amezaga, J. Bosch, B. Aylward, and L. Fuller (2004). Forest and water policies: the need to reconcile public and science conceptions. *Geologica acta*, **2**(2), pp. 157-166.

Campbell, J.E., D.B. Lobell, and C.B. Field (2009). Greater transportation energy and GHG offsets from bioelectricity than ethanol. *Science*, **324**(5930), pp. 1055-1057.

CARB (2009). *Proposed Regulation to Implement the Low Carbon Fuel Standard.* California Environmental Protection Agency, Air Resources Board, Stationary Source Division, Sacramento, California, 374 pp.

Carlsson-Kanyama, A., and H. Shanahan (2003). Food and life cycle energy inputs: consequences of diet and ways to increase efficiency. *Ecological Economics*, **44**(2-3), pp. 293-307.

Carolan, J., S. Joshi, and B.E. Dale (2007). Technical and financial feasibility analysis of distributed bioprocessing using regional biomass pre-processing centers. *Journal of Agricultural & Food Industrial Organization*, **5**(2) Article 10, 29 pp. Available at: www.bepress.com/jafio/vol5/iss2/art10.

Carpita, N.C., and M.C. McCann (2008). Maize and sorghum: genetic resources for bioenergy grasses. *Trends in Plant Science*, **13**(8), pp. 415-420.

Carslaw, K.S., O. Boucher, D.V. Spracklen, G.W. Mann, J.G.L. Rae, S. Woodward, and M. Kulmala (2010). A review of natural aerosol interactions and feedbacks within the Earth system. *Atmospheric Chemistry and Physics*, **10**(4), pp. 1701-1737.

Cascone, R. (2008). Biobutanol: a replacement for bioethanol? In: *Chemical Engineering Progress Special Edition Biofuels*, **104**, pp. S4–S9.

Cassman, K.G. (1999). Ecological intensification of cereal production systems: Yield potential, soil quality, and precision agriculture. *Proceedings of the National Academy of Sciences of the United States of America*, **96**(11), pp. 5952-5959.

Cassman, K.G., A. Dobermann, D.T. Walters, and H. Yang (2003). Meeting cereal demand while protecting natural resources and improving environmental quality. *Annual Review of Environment and Resources*, **28**(1), pp. 315-358.

Castiglioni, P., D. Warner, R.J. Bensen, D.C. Anstrom, J. Harrison, M. Stoecker, M. Abad, G. Kumar, S. Salvador, R. D'Ordine, S. Navarro, S. Back, M. Fernandes, J. Targolli, S. Dasgupta, C. Bonin, M.H. Luethy, and J.E. Heard (2008). Bacterial RNA chaperones confer abiotic stress tolerance in plants and improved grain yield in maize under water-limited conditions. *Plant Physiology*, **147**(2), pp. 446-455.

CBOT (2006). *CBOT® Soybean Crush Reference Guide.* Board of Trade of the City of Chicago, Chicago, IL, USA.

Chakravorty, U., M. Hubert, and L. Nostbakken (2009). Fuel versus food. *Annual Review of Resource Economics*, **1**(1), pp. 645-663.

Chapotin, S.M., and J. Wolt (2007). Genetically modified crops for the bioeconomy: meeting public and regulatory expectations. *Transgenic Research*, **16**(6), pp. 675-688.

Chapple, C., M. Ladisch, and R. Meilan (2007). Loosening lignin's grip on biofuel production. *Nature Biotechnology*, **25**(7), pp. 746-748.

Cheng, J.J., and G.R. Timilsina (2010). *Advanced Biofuel Technologies: Status and Barriers.* Policy Research Working Paper 5411, The World Bank, Washington, DC, USA, 47 pp.

Cherubini, F., and A.H. Strømman (2010). Life cycle assessment of bioenergy systems: State of the art and future challenges. *Bioresource Technology*, **102**(2), pp. 437-451.

Cherubini, F., N.D. Bird, A. Cowie, G. Jungmeier, B. Schlamadinger, and S. Woess-Gallasch (2009a). Energy- and greenhouse gas-based LCA of biofuel and bioenergy systems: Key issues, ranges and recommendations. *Resources, Conservation and Recycling*, **53**(8), pp. 434-447.

Cherubini, F., G. Jungmeier, M. Mandl, M. Wellisch, C. Philips, and H. Joergensen (2009b). *Biorefineries: Adding Value to the Sustainable Utilisation of Biomass.* IEA Bioenergy Publication T42:2009:01, IEA Bioenergy Task 42 on Biorefineries, 16 pp.

Chisti, Y. (2007). Biodiesel from microalgae. *Biotechnology Advances*, **25**(3), pp. 294-306.

Chiu, Y.-W., B. Walseth, and S. Suh (2009). Water embodied in bioethanol in the United States. *Environmental Science & Technology*, **43**(8), pp. 2688-2692.

Chum, H.L., and R.P. Overend (2003). Biomass and bioenergy in the United States. In: *Advances in Solar Energy: An Annual Review of Research and Development.* Vol. 15. D.Y. Goswami (ed.), American Solar Energy Society (ASES), Boulder, CO, USA, pp. 83-148.

Cirne, D.G., A. Lehtomäki, L. Björnsson, and L.L. Blackall (2007). Hydrolysis and microbial community analyses in two-stage anaerobic digestion of energy crops. *Journal of Applied Microbiology*, **103**(3), pp. 516-527.

Clayton, R., G. McDougall, M. Perry, D. Doyle, J. Doyle, and D. O'Connor (2010). *A Study of Employment Opportunities from Biofuel Production in APEC Economies.* APEC#210-RE-01.9, APEC Energy Working Group, Asia-Pacific Economic Cooperation (APEC), Singapore, Singapore, 82 pp.

Clifton-Brown, J.C., and I. Lewandowski (2000). Water use efficiency and biomass partitioning of three different Miscanthus genotypes with limited and unlimited water supply. *Annals of Botany*, **86**(1), pp. 191-200.

Clifton-Brown, J., P.F. Stampfl, and M.B. Jones (2004). Miscanthus biomass production for energy in Europe and its potential contribution to decreasing fossil fuel carbon emissions. *Global Change Biology*, **10**(4), pp. 509-518.

Cline, W.R. (2007). *Global Warming and Agriculture: Impact Estimates by Country*. Peterson Institute for International Economics, Washington, DC, USA, 201 pp.

Colla, L.M., C. Oliveira Reinehr, C. Reichert, and J.A.V. Costa (2007). Production of biomass and nutraceutical compounds by Spirulina platensis under different temperature and nitrogen regimes. *Bioresource Technology*, **98**(7), pp. 1489-1493.

Cortright, R.D., R.R. Davda, and J.A. Dumesic (2002). Hydrogen from catalytic reforming of biomass-derived hydrocarbons in liquid water. *Nature*, **418**(6901), pp. 964-967.

Cremers, M.F.G. (2009). *Deliverable 4, Technical Status of Biomass Co-firing.* 50831165-Consulting 09-1654, IEA Bioenergy Task 32, Arnhem, The Netherlands, 43 pp.

Crutzen, P., A. Moiser, K. Smith, and W. Winiwarter (2007). N_2O release from agro-biofuel production negates global warming reduction by replacing fossil fuels. *Atmospheric Chemistry and Physics*, **7**, pp. 11191-11205.

Curtis, B. (2010). *2008-2009 Review U.S. Biofuels Industry: Mind the Gap.* Concentric Energies & Resource Group, Inc., Los Gatos, CA, USA, 52 pp.

Cusick, R.D., B. Bryan, D.S. Parker, M.D. Merrill, M. Mehanna, P.D. Kiely, G. Liu, and B.E. Logan (2011). Performance of a pilot-scale continuous flow microbial electrolysis cell fed winery wastewater. *Applied Microbiology and Biotechnology*, **89**, pp. 2053-2063.

da Costa Sousa, L., S.P.S. Chundawat, V. Balan, and B.E. Dale (2009). 'Cradle-to-grave' assessment of existing lignocellulose pretreatment technologies. *Current Opinion in Biotechnology*, **20**(3), pp. 339-347.

Dale, B.E., M.S. Allen, M. Laser, and L.R. Lynd (2009). Protein feeds coproduction in biomass conversion to fuels and chemicals. *Biofuels, Bioproducts and Biorefining*, **3**(2), pp. 219-230.

Dale, B.E., B.D. Bals, S. Kim, and P. Eranki (2010). Biofuels done right: Land efficient animal feeds enable large environmental and energy benefits. *Environmental Science & Technology*, **44**(22), pp. 8385-8389.

Dale, V.H., R.A. Efroymson, and K.L. Kline (2011). The land use-climate change-energy nexus. *Landscape Ecology*, in press.

Damen, K., and A. Faaij (2006). A greenhouse gas balance of two existing international biomass import chains. *Mitigation and Adaptation Strategies for Global Change*, **11**(5), pp. 1023-1050.

Danielsen, F., H. Beukema, N.D. Burgess, F. Parish, C.A. Brühl, P.F. Donald, D. Murdiyarso, B.E.N. Phalan, L. Reijnders, M. Struebig, and E.B. Fitzherbert (2009). Biofuel plantations on forested lands: Double jeopardy for biodiversity and climate (Plantaciones de biocombustible en terrenos boscosos: Doble peligro para la biodiversidad y el clima). *Conservation Biology*, **23**(2), pp. 348-358.

Dantas, D.N., F.F. Mauad, and A.R. Ometto (2009). Potential for generation of thermal and electrical energy from biomass of sugarcane: A exergetic analysis. In: *11th International Conference on Advanced Materials*, Rio de Janeiro, Brazil, 20-25 September 2009, p. 131.

Darzins, A., P. Pienkos, and L. Edye (2010). *Current Status and Potential for Algal Biofuels Production.* Report T39-02, IEA Bioenergy Task 39, 128 pp.

Daugherty, E. (2001). *Biomass Energy Systems Efficiency Analyzed through a LCA Study.* Masters Thesis, Lund University, Gothenburg, Sweden, 45 pp.

Davda, R.R., J.W. Shabaker, G.W. Huber, R.D. Cortright, and J.A. Dumesic (2005). A review of catalytic issues and process conditions for renewable hydrogen and alkanes by aqueous-phase reforming of oxygenated hydrocarbons over supported metal catalysts. *Applied Catalysis B: Environmental*, **56**(1-2), pp. 171-186.

Davidson, E.A. (2009). The contribution of manure and fertilizer nitrogen to atmospheric nitrous oxide since 1860. *Nature Geoscience*, **2**(9), pp. 659-662.

de Boer, J., M. Helms, and H. Aiking (2006). Protein consumption and sustainability: Diet diversity in EU-15. *Ecological Economics*, **59**(3), pp. 267-274.

de Fraiture, C., and G. Berndes (2009). Biofuels and water. In: *Biofuels: Environmental Consequences and Interactions with Changing Land Use.* R.W. Howarth and S. Bringezu (eds.), Proceedings of the SCOPE - Scientific Committee on Problems of the Environment International Biofuels Project Rapid Assessment, Gummersbach, Germany, 22-25 September 2009, pp. 139-152.

de Fraiture, C., M. Giordano, and Y. Liao (2008). Biofuels and implications for agricultural water uses: blue impacts of green energy. *Water Policy*, **10**(S1), pp. 67-81.

De La Torre Ugarte, D.G., and C.C. Hellwinckel (2010). The problem is the solution: The role of biofuels in the transition to a regenerative agriculture. In: *Plant Biotechnology for Sustainable Production of Energy and Co-products.* P.N. Mascia, J. Scheffran, and J.M. Widholm (eds.), Springer-Verlag, Berlin and Heidelberg, Germany, 475 pp.

De La Torre Ugarte, D.G., L. He, K.L. Jensen, and B.C. English (2010). Expanded ethanol production: Implications for agriculture, water demand, and water quality. *Biomass and Bioenergy*, **34**(11), pp. 1586-1596.

de Wit, M., and A. Faaij (2010). European biomass resource potential and costs. *Biomass and Bioenergy*, **34**(2), pp. 188-202.

de Wit, M., M. Junginger, S. Lensink, M. Londo, and A. Faaij (2010). Competition between biofuels: Modeling technological learning and cost reductions over time. *Biomass and Bioenergy*, **34**(2), pp. 203-217.

DEFRA (2009). *The 2007/08 Agricultural Price Spikes: Causes and Policy Implications.* Department for Environment Food and Rural Affairs (DEFRA), HM Government, London, UK, 123 pp.

Delta-T Corporation (1997). *Proprietary information.* Williamsburg, VA, USA.

DeLucchi, M.A. (2005). *A Multi-Country Analysis of Lifecycle Emissions from Transportation Fuels and Motor Vehicles.* UCD-ITS-RR-05-10, Institute of Transportation Studies, University of California at Davis, Davis, CA, USA, 205 pp.

DeLucchi, M.A. (2010). *A Conceptual Framework for Estimating Bioenergy-Related Land-Use Change and Its Impacts over Time.* Biomass and Bioenergy, 1-24, doi:10.1016/j.biombioe.2010.11.028 (2010).

DeLuchi, M.A. (1993). Greenhouse-gas emissions from the use of new fuels for transportation and electricity. *Transportation Research Part A*, **27A**(3), pp. 187-191.

DeMeo, E.A., and J.F. Galdo (1997). *Renewable Energy Technology Characterizations*. TR-109496, U.S. Department of Energy and Electric Power Research Institute, Washington, DC, USA, 283 pp.

Demirbas, A. (2009). Progress and recent trends in biodiesel fuels. *Energy Conversion and Management*, **50**, pp. 14-34.

den Elzen, M., D. van Vuuren, and J. van Vliet (2010). Postponing emission reductions from 2020 to 2030 increases climate risks and long-term costs. *Climatic Change*, **99**(1), pp. 313-320.

Dias de Moraes, M.A.F. (2007). Indicadores do mercado de trabalho do sistema agroindustrial da cana-de-açúcar do Brasil no período 1992-2005. *Estudos Econ. (São Paulo)*, **37**(4), pp. 875-902.

Diaz-Balteiro, L., and L.C.E. Rodriguez (2006). Optimal rotations on Eucalyptus plantations including carbon sequestration – A comparison of results in Brazil and Spain. *Forest Ecology and Management*, **229**(1-3), pp. 247-258.

DiTomaso, J.M., J.K. Reaser, C.P. Dionigi, O.C. Doering, E. Chilton, J.D. Schardt, and J.N. Barney (2010). Biofuel vs. bioinvasion: seeding policy priorities. *Environmental Science & Technology*, **44**(18), pp. 6906-6910.

Dominguez-Faus, R., S.E. Powers, J.G. Burken, and P.J. Alvarez (2009). The water footprint of biofuels: A drink or drive issue? *Environmental Science & Technology*, **43**(9), pp. 3005-3010.

Dondini, M., A. Hastings, G. Saiz, M.B. Jones, and P. Smith (2009). The potential of Miscanthus to sequester carbon in soils: comparing field measurements in Carlow, Ireland to model predictions. *Global Change Biology Bioenergy*, **1**(6), pp. 413-425.

Donner, S.D., and C.J. Kucharik (2008). Corn-based ethanol production compromises goal of reducing nitrogen export by the Mississippi River. *Proceedings of the National Academy of Sciences*, **105**(11), pp. 4513-4518.

Doornbosch, V., and R. Steenblik (2008). Biofuels: Is the cure worse than the disease? In: *Round Table on Sustainable Development*, 11-12 September 2007, Organisation for Economic Co-operation and Development, Paris, France.

Dornburg, V., and A.P.C. Faaij (2001). Efficiency and economy of wood-fired biomass energy systems in relation to scale regarding heat and power generation using combustion and gasification technologies. *Biomass and Bioenergy*, **21**(2), pp. 91-108.

Dornburg, V., and A.P.C. Faaij (2005). Cost and CO_2-emission reduction of biomass cascading: methodological aspects and case study of SRF poplar. *Climatic Change*, **71**(3), pp. 373-408.

Dornburg, V., and G. Marland (2008). Temporary storage of carbon in the biosphere does have value for climate change mitigation: a response to the paper by Miko Kirschbaum. *Mitigation and Adaptation Strategies for Global Change*, **13**(3), pp. 211-217.

Dornburg, V., J. Vandam, and A. Faaij (2007). Estimating GHG emission mitigation supply curves of large-scale biomass use on a country level. *Biomass and Bioenergy*, **31**(1), pp. 46-65.

Dornburg, V., A. Faaij, P. Verweij, H. Langeveld, G. van de Ven, F. Wester, H. van Keulen, K. van Diepen, M. Meeusen, M. Banse, J. Ros, D. van Vuuren, G.J. van den Born, M. van Oorschot, F. Smout, J. van Vliet, H. Aiking, M. Londo, H. Mozaffarian, K. Smekens, E. Lysen, and S. van Egmond (2008). *Assessment of Global Biomass Potentials and their Links to Food, Water, Biodiversity, Energy Demand and Economy.* WAB 500102 012, The Netherlands Environmental Assessment Agency, Bilthoven, The Netherlands, 108 pp.

Dornburg, V., D. van Vuuren, G. van de Ven, H. Langeveld, M. Meeusen, M. Banse, M. van Oorschot, J. Ros, G.J. van den Born, H. Aiking, M. Londo, H. Mozaffarian, P. Verweij, E. Lysen, and A. Faaij (2010). Bioenergy revisited: Key factors in global potentials of bioenergy. *Energy & Environmental Science*, **3**, pp. 258-267.

Drigo, R., G. Chirici, B. Lasserre, and M. Marchetti (2007). Analisi su base geografica della domanda e dell'offerta di combustibili legnosi in Italia. (Geographical analysis of demand and supply of woody fuel in Italy). *L'italia Forestale e Montana*, **LXII**(5/6), pp. 303-324.

Drigo, R., A. Anschau, N. Flores Marcos, and S. Carballo (2009). *Análisis del balance de energia derivada de biomasa en Argentina – WISDOM Argentina.* Project TCP/ARG/3103 of FAO Dendroenergy, FAO Forestry Department, Rome, Italy, 102 pp.

Dudley, T.L. (2000). Arundo donax. In: *Invasive Plants of California's Wildlands.* C. Bossard and J. Randall (eds.), University of California Press, Berkeley, CA, USA, pp. 53-58.

Dufey, A. (2006). *Biofuels Production, Trade and Sustainable Development: Emerging Issues.* International Institute for Environment and Development, London, UK, 62 pp.

Dupraz, C., and F. Liagre (2008). *Agroforestry: Trees and Crops.* La France Agricole, Paris, France.

Dutta, A., N. Dowe, K.N. Ibsen, D.J. Schell, and A. Aden (2010). An economic comparison of different fermentation configurations to convert corn stover to ethanol using *Z. mobilis* and *Saccharomyces*. *Biotechnology Progress*, **26**(1), pp. 64-72.

Duvick, D.N., and K.G. Cassman (1999). Post-green revolution trends in yield potential of temperate maize in the north-central United States. *Crop Science*, **39**(6), pp. 1622-1630.

Dymond, C.C., B.D. Titus, G. Stinson, and W.A. Kurz (2010). Future quantities and spatial distribution of harvesting residue and dead wood from natural disturbances in Canada. *Forest Ecology and Management*, **260**(2), pp. 181-192.

E4tech (2009). *Review of the Potential for Biofuels in Aviation.* Committee on Climate Change (CCC) of the U.K. Government, London, UK, 117 pp.

E4tech (2010). *Biomass Prices in the Heat and Electricity Sectors in the UK.* Report prepared for the UK Department of Energy and Climate Change. URN 10D/546, E4tech, London, UK, 33 pp.

Easterling, W.E., J. Morton, J.F. Soussana, J. Schmidhuber, F.N. Tubiello, P.K. Aggarwal, P. Batima, K.M. Brander, L. Erda, S.M. Howden, and A. Kirilenko (2007). Food, fibre and forest products. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability: Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson (eds.), Cambridge University Press, pp. 273-313.

Eaton, J., N. McGoff, K. Byrne, P. Leahy, and G. Kiely (2008). Land cover change and soil organic carbon stocks in the Republic of Ireland 1851–2000. *Climatic Change*, **91**(3), pp. 317-334.

Ecobilan (2002). *Energy and Greenhouse Gas Balances of Biofuels' Production Chains in France.* Ecobilan, Neuilly-sur-Seine Cedex, France, 9 pp.

Econ Poyry (2008). *Current Bioenergy Application and Conversion Technologies in the Nordic Countries.* 2008-052, Nordic Energy Research, Copenhagen, Denmark, 37 pp.

Edenhofer, O., B. Knopf, M. Leimbach, and N. Bauer (2010). The economics of low stabilization. *The Energy Journal*, **31**(Special Issue 1), pp. 57-90.

Edgerton, M.D. (2009). Increasing crop productivity to meet global needs for feed, food, and fuel. *Plant Physiology*, **149**(1), pp. 7-13.

Edwards, R., D. Mulligan, and L. Marelli (2010). *Indirect Land Use Change from Increased Biofuel Demand. Comparison of Models and Results for Marginal Biofuels Production from Different Feedstocks.* EUR 24485 EN-2010, European Commission, Joint Research Centre, Institute for Energy, Ispra, Italy, 150 pp.

Edwards, R., J.F. Larivé, V. Mahieu, and P. Rouveirolles (2007). *Well-To-Wheels Analysis of Future Automotive Fuels and Power Trains in the European Context.* Version 2c, Joint Research Center, Brussels, Belgium, 88 pp.

Edwards, R., J.F. Larivé, V. Mahieu, and P. Rouveirolles (2008). *Well-To-Wheels analysis of future automotive fuels and power trains in the European context.* Version 3, Joint Research Center, Brussels, Belgium, 43 pp.

EEA (2006). *How Much Bioenergy can Europe Produce without Harming the Environment?* European Environment Agency (EEA), Copenhagen, Denmark, 72 pp.

EEA (2007). *Estimating the Environmentally Compatible Bio-energy Potential from Agriculture.* European Environment Agency (EEA), Copenhagen, Denmark.

Egsgaard, H.U., P. Hansen, J. Arendt, P. Glarborg, and C. Nielsen (2009). Combustion and gasification technologies. In: *Risø Energy Report 2.* Risø, Roskilde, Denmark, pp. 35-39.

EIA (2009). *2006 Energy Consumption by Manufacturers – Data Table 7.2.* U.S. Energy Information Administration, U.S. Department of Energy, Washington, DC, USA.

EIA (2010a). *Annual Energy Review*, DOE/EIA-0384(2009) updated August 2011, Energy Information Administration, U.S. Department of Energy, Washington, DC, USA.

EIA (2010b). *Updated Capital Costs for Electricity Generation Plants.* U.S. Energy Information Administration, U.S. Department of Energy, Washington, DC, USA.

EISA, 2007. *Energy Independence and Security Act*, United States Congress, Public Law 110-140. U.S. Government Printing Office, Washington, DC, USA.

Eisenbies, M., E. Vance, W. Aust, and J. Seiler (2009). Intensive utilization of harvest residues in southern pine plantations: Quantities available and implications for nutrient budgets and sustainable site productivity. *BioEnergy Research*, **2**(3), pp. 90-98.

Elander, R., B. Dale, M. Holtzapple, M. Ladisch, Y. Lee, C. Mitchinson, J. Saddler, and C. Wyman (2009). Summary of findings from the Biomass Refining Consortium for Applied Fundamentals and Innovation (CAFI): corn stover pretreatment. *Cellulose*, **16**(4), pp. 649-659.

Elferink, E.V., and S. Nonhebel (2007). Variations in land requirements for meat production. *Journal of Cleaner Production*, **15**, pp. 1778-1786.

Elliott, D.C. (2008). Catalytic hydrothermal gasification of biomass. *Biofuels, Bioproducts, Biorefining*, **2**, pp. 254-265.

Elobeid, A., and C. Hart (2007). Ethanol expansion in the food versus fuel debate: How will developing countries fare? *Journal of Agricultural & Food Industrial Organization*, **5**(2), pp. 1-21.

EMBRAPA (2010). *Brazilian Sugarcane Agroecological Zoning (in English), Zoneamento Agroecológico da Cana de Açúcar (in Portuguese).* Empresa Brasileira de Pesquisa Agropecuária (Brazilian Agricultural Research Corporation, EMBRAPA), Brasilia, Brazil, 58 pp.

EPA (2010). *Renewable Fuel Standard Program (RFS2) Regulatory Impact Analysis.* EPA-420-R-10-006, Environmental Protection Agency, Washington, DC, USA, 1120 pp.

EPE (2008). *Plano Decenal De Expansao De Energia 2008 – 2017.* Ministry of Mines and Energy Secretariat of Planning and Energy Development, Brasilia, Brazil, 354 pp.

EPE (2010). *2010 Balanco Energetico Nacional - Ano Base 2009.* CDU 620.9:553.04(81), Ministry of Mines and Energy and Energy Planning Enterprise (EPE), Brasilia, Brazil, 271 pp.

EPRI (2008). *Technical Performance Indicators for Biomass Energy.* Electric Power Research Institute, Palo Alto, CA, USA, 86 pp.

Ericsson, K., and L.J. Nilsson (2006). Assessment of the potential biomass supply in Europe using a resource-focused approach. *Biomass and Bioenergy*, **30**(1), pp. 1-15.

Ericsson, K., H. Rosenqvist, and L.J. Nilsson (2009). Energy crop production costs in the EU. *Biomass and Bioenergy*, **33**(11), pp. 1577-1586.

Erikson, S., and M. Prior (1990). *The Briquetting of Agricultural Wastes for Fuel.* FAO paper No. 11, Food and Agriculture Organization, Rome, Italy.

EurObserv'ER (2010). Biofuels barometer/Baromètre Biocarburant Observ'ER. *Systèmes Solaires le journal des énergies renouvelables*, Paris, France, pp. 72-96.

European Commission (2009). *Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources.* European Commission, Brussels, Belgium.

European Commission (2010). *Report from the commission to the council and the European parliament on sustainability requirements for the use of solid and gaseous biomass sources in electricity, heating and cooling.* SEC(2010) 65, European Commission, Brussels, Belgium, 20 pp.

Evans, L.T. (2003). Agricultural intensification and sustainability. *Outlook on Agriculture*, **32**(2), pp. 83-89.

Evenson, R.E., and D. Gollin (2003). Assessing the impact of the Green Revolution, 1960 to 2000. *Science*, **300**(5620), pp. 758-762.

Ezeji, T., N. Quereshi, and H.P. Blaschek (2007a). Butanol production from agricultural residues: impact of degradation products on Clostridium beijerinckii growth and butanol fermentation. *Biotechnology and Bioengineering*, **97**(6), pp. 1460-1467.

Ezeji, T.C., N. Qureshi, and H.P. Blaschek (2007b). Bioproduction of butanol from biomass: from genes to bioreactors. *Current Opinion in Biotechnology*, **18**(3), pp. 220-227.

Ezzati, M., A. Lopez, S. Vander Hoorn, A. Rodgers, and C.L.J. Murray (2002). Comparative Risk Assessment Collaborative Group. Selected major risk factors and global regional burden of disease. *The Lancet*, **360**(9343), pp. 1347-1360.

Ezzati, M., R. Bailis, D.M. Kammen, T. Holloway, L. Price, L.A. Cifuentes, B. Barnes, A. Chaurey, and K.N. Dhanapala (2004). Energy management and global health. *Annual Review of Environment and Resources*, **29**(1), pp. 383-419.

Faaij, A. (2006). Modern biomass conversion technologies. *Mitigation and Adaptation Strategies for Global Change*, **11**(2), pp. 335-367.

Fagernäs, L., A. Johansson, C. Wilén, K. Sipilä, T. Mäkinen, S. Helynen, E. Daugherty, H. den Uil, J. Vehlow, T. Kåberger, and M. Rogulska (2006). *Bioenergy in Europe: Opportunities and Barriers.* VTT Res. Notes 2532, VTT, Espoo, Finland, 122 pp.

Fallot, A., L. Saint-Andre, G. Le Maire, J.-P. Laclau, Y. Nouvellon, C. Marsden, J.-P. Bouillet, T. Silva, M.-G. Piketty, and O. Hamel (2009). Biomass sustainability, availability and productivity. *Revue de Métallurgie Paris*, **106**(10), pp. 410-418.

FAO (1985). Industrial charcoal making technologies. In: *Industrial Charcoal Making.* FAO Forestry Paper 63, FAO Forestry Department, Food and Agriculture Organization, Rome, Italy. Available at: www.fao.org/docrep/X5555E/x5555e02.htm#1.1%20what%20are%20industrial%20charcoal%20making%20methods.

FAO (2004). *The State of Food and Agriculture 2003-2004 – Agricultural Biotechnology: Meeting the Needs of the Poor?* 0081-4539, Food and Agriculture Organization, Rome, Italy, 196 pp.

FAO (2005). *World Forest Assessment.* Food and Agriculture Organization, Rome, Italy, 166 pp.

FAO (2006). *Energy and Gender in Rural Sustainable Development.* Food and Agriculture Organization, Rome, Italy, 46 pp.

FAO (2008a). *The State of Food and Agriculture 2008 – Biofuels: Prospects, Risks, and Opportunities.* Food and Agriculture Organization, Rome, Italy, 138 pp.

FAO (2008b). The role of agricultural biotechnologies for production of bioenergy in developing countries. In: *Background Document to Conference 15 of the FAO Biotechnology Forum*, 10 November to 14 December 2008, Food and Agriculture Organization, Rome, Italy.

FAO (2010a). *What Woodfuels can do to Mitigate Climate Change.* 0258-6150, Food and Agricultural Organization (FAO), Rome, Italy, 98 pp.

FAO (2010b). *Criteria and Indicators for Sustainable Biofuels.* FAO Forestry Paper 160, Food and Agricultural Organization (FAO), Rome, Italy, 102 pp.

FAOSTAT (2011). *FAOSTAT.* Food and Agriculture Organization, Rome, Italy. Available at: faostat.fao.org/default.aspx.

FAPRI (2009). *FAPRI 2009: U.S. and World Agricultural Outlook.* Food and Agricultural Policy Research Institute, Ames, Iowa, 411 pp.

Fargione, J., J. Hill, D. Tilman, S. Polasky, and P. Hawthorne (2008). Land clearing and the biofuel carbon debt. *Science*, **319**(5867), pp. 1235-1238.

Farley, K.A., E.G. Jobbagy, and R.B. Jackson (2005). Effects of afforestation on water yield: a global synthesis with implications for policy. *Global Change Biology*, **11**(10), pp. 1565-1576.

Farrell, A.E., R.J. Plevin, B.T. Turner, A.D. Jones, M. O'Hare, and D.M. Kammen (2006). Ethanol can contribute to energy and environmental goals. *Science*, **311**(5760), pp. 506-508.

Fearnside, P.M. (2008). The roles and movements of actors in the deforestation of Brazilian Amazonia. *Ecology and Society*, **13**(23), pp. 23-55.

Feng, Z., K.J. Stadt, and V.J. Lieffers (2006). Linking juvenile white spruce density, dispersion, stocking, and mortality to future yield. *Canadian Journal of Forest Research*, **36**, pp. 3173-3182.

Field, C.B., J.E. Campbell, and D.B. Lobell (2008). Biomass energy: the scale of the potential resource. *Trends in Ecology & Evolution*, **23**(2), pp. 65-72.

Fingerman, K.R., M.H. Torn, M.S. O'Hare, and D.M. Kammen (2010). Accounting for the water impacts of ethanol production. *Environmental Research Letters*, **5**(1), 014020 (7pp.).

Firbank, L. (2008). Assessing the ecological impacts of bioenergy projects. *BioEnergy Research*, **1**(1), pp. 12-19.

Fischer, G., and L. Schrattenholzer (2001). Global bioenergy potentials through 2050. *Biomass and Bioenergy*, **20**(3), pp. 151-159.

Fischer, G., H. van Velthuizen, M. Shah, and F. Nachtergaele (2002). *Global Agro-ecological Assessment for Agriculture in the 21st Century: Methodology and Results.* RR-02-02, International Institute for Applied Systems Analysis, Laxenburg, Austria, 156 pp.

Fischer, G., F. Nachtergaele, S. Prieler, F. Teixeira, H. van Velthuizen, L. Verelst, and D. Wiberg (2008). *Global Agro-ecological Zones Assessment for Agriculture (GAEZ 2008).* Version 2, International Institute for Applied Systems Analysis and Food and Agriculture Organization, Laxenburg, Austria and Rome, Italy, 43 pp.

Fischer, G., E. Hizsnyik, S. Prieler, M. Shah, and H. van Velthuizen (2009). *Biofuels and Food Security.* The OPEC Fund for International Development (OFID) and International Institute of Applied Systems Analysis (IIASA), Vienna, Austria, 228 pp.

Fischer, G., S. Prieler, H. van Velthuizen, G. Berndes, A. Faaij, M. Londo, and M. de Wit (2010). Biofuel production potentials in Europe: Sustainable use of cultivated land and pastures, Part II: Land use scenarios. *Biomass and Bioenergy*, **34**(2), pp. 173-187.

Fitzherbert, E.B., M.J. Struebig, A. Morel, F. Danielsen, C.A. Brühl, P.F. Donald, and B. Phalan (2008). How will oil palm expansion affect biodiversity? *Trends in Ecology & Evolution*, **23**(10), pp. 538-545.

Fleming, J.S., S. Habibi, and H.L. MacLean (2006). Investigating the sustainability of lignocellulose-derived fuels for light-duty vehicles. *Transportation Research Part D: Transport and Environment*, **11**(2), pp. 146-159.

Foley, J.A., R. DeFries, G.P. Asner, B. Carol, G. Bonan, S.R. Carpenter, F.S. Chapin, M.T. Coe, G.C. Daily, H.K. Gibbs, J.H. Helkowski, T. Holloway, E.A. Howard, C.J. Kucharik, C. Monfreda, J.A. Patz, I.C. Prentice, N. Ramankutty, and P.K. Snyder (2005). Global consequences of land use. *Science*, **309**(5734), pp. 570-574.

Folha (2005). Bagaço da cana será usado para fabricação de papel. *Folha da Região - Araçatuba.* São Paulo, Brazil.

Folke, C., S. Carpenter, B. Walker, M. Scheffer, T. Elmqvist, L. Gunderson, and C.S. Holling (2004). Regime shifts, resilence, and biodiversity in ecosystem management. *Annual Review of Ecology, Evolution, and Systematics*, **35**(1), pp. 557-581.

Folke, C., F.S. Chapin, and P. Olsson (2009). Transformations in ecosystem stewardship. In: *Principles of Ecosystem Stewardship: Resilience-Based Natural Resource Management in a Changing World.* F.S. Chapin III, G.P. Kofinas, and C. Folke (eds.), Springer Verlag, New York, NY, USA, pp. 103-128.

Forman, J. (2003). The introduction of American plant species into Europe: issues and consequences. In: *Plant Invasions: Ecological Threats and Management Solutions.* L. Child, J. H. Brock, G. Brundu, K. Prach, P. Pysek, P. M. Wade, and M. Williamson (eds.), Backhuys Publishers, Leiden, Netherlands, pp. 17-39.

Foust, T.D., A. Aden, A. Dutta, and S. Phillips (2009). Economic and environmental comparison of a biochemical and a thermochemical lignocellulosic ethanol conversion process. *Cellulose*, **16**, pp. 547-565.

Francis, G., R. Edinger, and K. Becker (2005). A concept for simultaneous wasteland reclamation, fuel production, and socio-economic development in degraded areas in India: Need, potential and perspectives of Jatropha plantations. *Natural Resources Forum*, **29**(1), pp. 12-24.

Fritsche, U., K. Hennenberg, and K. Hünecke (2010). *The "iLUC factor" as a Means to Hedge Risks of GHG Emissions from Indirect Land Use Change.* Öko Institute, Darmstadt, Germany, 64 pp.

Fulton, L., T. Howes, and J. Hardy (2004). *Biofuels for Transport - An International Perspective.* Organization for Economic Cooperation and Development and International Energy Agency, Paris, France, 210 pp.

GAIN (2009a). *Biofuel's Impact on Food Crops (China).* CH9059, Global Agriculture Information Network, United States Department of Agriculture, Washington, DC, USA, 14 pp.

GAIN (2009b). *Biofuel's Impact on Food Crops (Indonesia).* ID9017, Global Agriculture Information Network, United States Department of Agriculture, Washington, DC, 7 pp.

GAIN (2009c). *Biofuel's Impact on Food Crops (Thailand).* TH9047, Global Agriculture Information Network, United States Department of Agriculture, Washington, DC, USA, 11 pp.

GAIN (2010a). *Biofuel's Impact on Food Crops (Argentina).* Global Agriculture Information Network, United States Department of Agriculture, Washington, DC, USA, 15 pp.

GAIN (2010b). *Biofuel's Impact on Food Crops (Brazil).* BR10006, Global Agriculture Information Network, United States Department of Agriculture, Washington, DC, USA, 52 pp.

GAIN (2010c). *Biofuel's Impact on Food Crops (Canada).* CA0023, Global Agriculture Information Network, United States Department of Agriculture, Washington, DC, USA, 34 pp.

GAIN (2010d). *Biofuel's Impact on Food Crops (India).* IN1058, Global Agriculture Information Network, United States Department of Agriculture, Washington, DC, USA, 11 pp.

GAIN (2010e). *Biofuel's Impact on Food Crops (Korea).* KS1001, Global Agriculture Information Network, United States Department of Agriculture, Washington, DC, USA, 6 pp.

GAIN (2010f). *Biofuel's Impact on Food Crops (Malaysia).* MY0008, Global Agriculture Information Network, United States Department of Agriculture, Washington, DC, USA, 9 pp.

GAIN (2010g). *Biofuel's Impact on Food Crops (Peru).* Global Agriculture Information Network, United States Department of Agriculture, Washington, DC, USA, 7 pp.

GAIN (2010h). *Biofuel's Impact on Food Crops (Philippines).* Global Agriculture Information Network, United States Department of Agriculture, Washington, DC, USA, 21 pp.

GAIN (2010i). *Biofuel's Impact on Food Crops (Thailand).* TH0098, Global Agriculture Information Network, United States Department of Agriculture, Washington, DC, USA, 15 pp.

GAIN (2010j). *Biofuel's Impact on Food Crops (Turkey).* Global Agriculture Information Network, United States Department of Agriculture, Washington, DC, USA, 6 pp.

Galdos, M.V., C.C. Cerri, R. Lal, M. Bernoux, B. Feigl, and C.E.P. Cerri (2010). Net greenhouse gas fluxes in Brazilian ethanol production systems. *Global Change Biology Bioenergy*, **2**(1), pp. 37-44.

Gallagher, E. (2008). *The Gallagher Review of the Indirect Effects of Biofuels Production.* Renewable Fuels Agency, London, UK, 92 pp.

Gallagher, P., M. Dikeman, J. Fritz, E. Wailes, W. Gauther, and H. Shapouri (2003). *Biomass from Crop Residues: Cost and Supply Estimates.* Agricultural Economic Report No. 819, Economic Research Service, United States Department of Agriculture, Washington, DC, USA, 30 pp.

Gan, J. (2007). Supply of biomass, bioenergy, and carbon mitigation: Method and application. *Energy Policy*, **35**(12), pp. 6003-6009.

Gan, J., and C. Smith (2010). Integrating biomass and carbon values with soil productivity loss in determining forest residue removals. *Biofuels*, **1**(4), pp. 539-546.

García-Frapolli, E., A. Schilmann, V.M. Berrueta, H. Riojas-Rodríguez, R.D. Edwards, M. Johnson, A. Guevara-Sanginés, C. Armendariz, and O. Masera (2010). Beyond fuelwood savings: Valuing the economic benefits of introducing improved biomass cookstoves in the Purépecha region of Mexico. *Ecological Economics*, **69**(12), pp. 2598-2605.

Garg, V.K. (1998). Interaction of tree crops with a sodic soil environment: potential for rehabilitation of degraded environments. *Land Degradation & Development*, **9**(1), pp. 81-93.

Garrison, T. (2008). *Essentials of Oceanography.* 5th ed., Brooks/Cole Cengage Learning, Belmont, CA, USA, 464 pp.

GBEP (2008). *A Review of the Current State of Bioenergy Development in G8+5 Countries.* Global Bioenergy Partnership (GBEP), Food and Agriculture Organization of the United Nations, Rome, Italy, 278 pp.

Gerasimov, Y., and T. Karjalainen (2009). *Estimation of supply and delivery cost of energy wood from Northwest Russia.* Working Papers of the Finnish Forest Research Institute Number 123, Finnish Forest Research Institute, Vantaa, Finland, 21 pp.

Gerbens-Leenes, P., and S. Nonhebel (2002). Consumption patterns and their effects on land required for food. *Ecological Economics*, **42**(1-2), pp. 185-199.

Gerbens-Leenes, W., A.Y. Hoekstra, and T.H. van der Meer (2009). The water footprint of bioenergy. *Proceedings of the National Academy of Sciences*, **106**(25), pp. 10219-10223.

Gerber, N. (2008). *Bioenergy and Rural Development in Developing Countries: A Review of Existing Studies.* Discussion Papers On Development Policy No. 122, Center for Development Research (ZEF), Bonn, Germany, 58 pp.

Gerten, D., W. Lucht, S. Schaphoff, W. Cramer, T. Hickler, and W. Wagner (2005). Hydrologic resilience of the terrestrial biosphere. *Geophysical Research Letters*, **32**(21), L21408.

Gibbs, H.K., M. Johnston, J.A. Foley, T. Holloway, C. Monfreda, N. Ramankutty, and D. Zaks (2008). Carbon payback times for crop-based biofuel expansion in the tropics: the effects of changing yield and technology. *Environmental Research Letters*, **3**(3), 034001 (10 pp.).

Gielen, D., J. Newman, and M.K. Patel (2008). Reducing industrial energy use and CO_2 emissions: The role of materials science. In: *MRS Bulletin Harnessing Materials for Energy*, **33**, pp. 471-477.

Gisladottir, G., and M. Stocking (2005). Land degradation control and its global environmental benefits. *Land Degradation & Development*, **16**(2), pp. 99-112.

Glass, R. (2006). Disease control priorities in developing countries. *The New England Journal of Medicine*, **355**(10), pp. 1074-1075.

Godfray, H.C.J., C. Toulmin, J.R. Beddington, I.R. Crute, L. Haddad, D. Lawrence, J.F. Muir, J. Pretty, S. Robinson, and S.M. Thomas (2010). Food security: The challenge of feeding 9 billion people. *Science*, **327**(5967), pp. 812-818.

Goldemberg, J., S.T. Coelho, P.M. Nastari, and L. O (2004). Ethanol learning curve - the Brazilian experience. *Biomass and Bioenergy*, **26**, pp. 301-304.

Gorissen, L., V. Buytaert, D. Cuypers, T. Dauwe, and L. Pelkmans (2010). Why the debate about land use change should not only focus on biofuels. *Environmental Science & Technology*, **44**(11), pp. 4046-4049.

Grann, H. (1997). The industrial symbiosis at Kalundborg, Denmark. In: *The Industrial Green Game. Implications for Environmental Design and Management.* D.J. Richards (ed.), National Academy Press, Washington, DC, USA, pp. 117-123.

Grassi, G., A. Nardi, and S. Vivarelli (2006). Low cost production of bioethanol from sweet sorghum. In: *Proceedings of the 14th European Biomass Conference*, Paris, France, 17-21 October 2005, pp. 91-95.

Green, R.E., S.J. Cornell, J.P.W. Scharlemann, and A. Balmford (2005). Farming and the fate of wild nature. *Science*, **307**(5709), pp. 550-555.

Gronowska, M., S. Joshi, and H.L. MacLean (2009). A review of U.S. and Canadian biomass supply studies. *BioResources*, **4**(1), pp. 341-369.

Grove, S. and J. Hanula (eds) (2006). *Insect Biodiversity and Dead Wood: Proceedings of the 22nd International Congress of Entomology.* Report SRS–93, United States Department of Agriculture, Asheville, NC, USA, 109 pp.

Guille, T. (2007). *Evaluation of the Potential Uses of Agricultural Residues for Energy Purposes.* Master's Thesis, Montpellier SupAgro, Paris, France.

Gunderson, P. (2008). Biofuels and North American agriculture - Implications for the health and safety of North American producers. *Journal of Agromedicine*, **13**(4), pp. 219-224.

Gurbuz, E.I., E.L. Kunkes, and J.A. Dumesic (2010). Dual-bed catalyst system for C–C coupling of biomass-derived oxygenated hydrocarbons to fuel-grade compounds. *Green Chemistry*, **12**(2), pp. 223-227.

Gustavsson, L., J. Holmberg, V. Dornburg, R. Sathre, T. Eggers, K. Mahapatra, and G. Marland (2007). Using biomass for climate change mitigation and oil use reduction. *Energy Policy*, **35**(11), pp. 5671-5691.

Haas, M.J., A.J. McAloon, W.C. Yee, and T.A. Foglia (2006). A process model to estimate biodiesel production costs. *Bioresource Technology*, **97**(4), pp. 671-678.

Haberl, H., K.H. Erb, F. Krausmann, V. Gaube, A. Bondeau, C. Plutzar, S. Gingrich, W. Lucht, and M. Fischer-Kowalski (2007). Quantifying and mapping the human appropriation of net primary production in earth's terrestrial ecosystems. *Proceedings of the National Academy of Sciences*, **104**(31), pp. 12942-12947.

Haberl, H., T. Beringer, S.C. Bhattacharya, K.-H. Erb, and M. Hoogwijk (2010). The global technical potential of bio-energy in 2050 considering sustainability constraints. *Current Opinion in Environmental Sustainability*, **2**(5-6), pp. 394-403.

Hakala, K., M. Kontturi, and K. Pahkala (2009). Field biomass as global energy source. *Agricultural and Food Science*, **18**, pp. 347-365.

Hamelinck, C.N. (2004). *Outlook for Advanced Biofuels.* Master's Thesis, University of Utrecht, Utrecht, The Netherlands, 232 pp.

Hamelinck, C.N., and A.P.C. Faaij (2002). Future prospects for production of methanol and hydrogen from biomass. *Journal of Power Sources*, **111**(1), pp. 1-22.

Hamelinck, C.N., and A.P.C. Faaij (2006). Outlook for advanced biofuels. *Energy Policy*, **34**(17), pp. 3268-3283.

Hamelinck, C.N., A.P.C. Faaij, H. den Uil, and H. Boerrigter (2004). Production of FT transportation fuels from biomass; technical options, process analysis and optimisation, and development potential. *Energy*, **29**(11), pp. 1743-1771.

Hamelinck, C.N., G.v. Hooijdonk, and A.P.C. Faaij (2005a). Ethanol from lignocellulosic biomass: techno-economic performance in short-, middle- and long-term. *Biomass and Bioenergy*, **28**(4), pp. 384-410.

Hamelinck, C.N., R.A.A. Suurs, and A.P.C. Faaij (2005b). International bioenergy transport costs and energy balance. *Biomass and Bioenergy*, **29**(2), pp. 114-134.

Hartley, M.J. (2002). Rationale and methods for conserving biodiversity in plantation forests. *Forest Ecology and Management*, **155**(1-3), pp. 81-95.

Headey, D., and S. Fan (2008). Anatomy of a crisis: the causes and consequences of surging food prices. *Agricultural Economics*, **39**, pp. 375-391.

Heggenstaller, A.H., R.P. Anex, M. Liebman, D.N. Sundberg, and L.R. Gibson (2008). Productivity and nutrient dynamics in bioenergy double-cropping systems. *Agronomy Journal*, **100**(6), pp. 1740-1748.

Heinimö, J., and M. Junginger (2009). Production and trading of biomass for energy – An overview of the global status. *Biomass and Bioenergy*, **33**(9), pp. 1310-1320.

Helynen, S., M. Flyktman, T. Mäkinen, K. Sipilä, and P. Vesterinen (2002). *The possibilities of bioenergy in reducing greenhouse gases.* VTT Tiedotteita 2145, VTT Technical Research Centre of Finland, Espoo, Finland, 110 pp.

Hemakanthi, D.A., and D.N. Heller (2010). Multiclass, multiresidue method for the detection of antibiotic residues in distillers grains by liquid chromatography and ion trap tandem mass spectrometry. *Journal of Chromatography A*, **1217**(18), pp. 3076-3084.

Herrero, M., J. van de Steeg, J. Lynam, P.P. Rao, S. Macmillan, B. Gerard, J. McDermott, C. Sere, M. Rosegrant, P.K. Thornton, A.M. Notenbaert, S. Wood, S. Msangi, H.A. Freeman, D. Bossio, J. Dixon, and M. Peters (2010). Smart investments in sustainable food production: Revisiting mixed crop-livestock systems. *Science*, **327**(5967), pp. 822-825.

Hertel, T.W., A.A. Golub, A.D. Jones, M. O'Hare, R.J. Plevin, and D.M. Kammen (2010a). Effects of US maize ethanol on global land use and greenhouse gas emissions: Estimating market mediated responses. *BioScience*, **60**(3), pp. 223-231.

Hertel, T.W., W.E. Tyner, and D.K. Birur (2010b). Global impacts of biofuels. *Energy Journal*, **31**(1), pp. 35-100.

Hettinga, W.G., H.M. Junginger, M. Hoogwijk, A. McAloon, and T. Hickler (2007). Technological learning in U.S. ethanol production. In: *15th European Biomass Conference and Exhibition*, Berlin, Germany, 7-11 May 2007.

Hettinga, W.G., H.M. Junginger, S.C. Dekker, M. Hoogwijk, A.J. McAloon, and K.B. Hicks (2009). Understanding the reductions in US corn ethanol production costs: An experience curve approach. *Energy Policy*, **37**(1), pp. 190-203.

Hiederer, R., F. Ramos, C. Capitani, R. Koeble, V. Blujdea, O. Gomez, D. Mulligan, and L. Marelli (2010). *Biofuels: A New Methodology to Estimate GHG Emissions from Global Land Use Change, A methodology involving spatial allocation of agricultural land demand and estimation of CO_2 and N_2O emissions.* EUR 24483 EN - 2010, Joint Research Center, European Commission, Ispa, Italy, 168 pp.

Hill, J. (2007). Environmental costs and benefits of transportation biofuel production from food- and lignocellulose-based energy crops. A review. *Agronomy for Sustainable Development*, **27**(1), pp. 1-12.

Hill, J., E. Nelson, D. Tilman, S. Polasky, and D. Tiffany (2006). Environmental, economic, and energetic costs and benefits of biodiesel and ethanol biofuels. *Proceedings of the National Academy of Sciences*, **103**(30), pp. 11206-11210.

Hill, J., S. Polasky, E. Nelson, D. Tilman, H. Huo, L. Ludwig, J. Neumann, H. Zheng, and D. Bonta (2009). Climate change and health costs of air emissions from biofuels and gasoline. *Proceedings of the National Academy of Sciences*, **106**(6), pp. 2077-2082.

Hillier, J., C. Whittaker, G. Dailey, M. Aylott, E. Casella, G.M. Richter, A. Riche, R. Murphy, G. Taylor, and P. Smith (2009). Greenhouse gas emissions from four bioenergy crops in England and Wales: Integrating spatial estimates of yield and soil carbon balance in life cycle analyses. *Global Change Biology Bioenergy*, **1**(4), pp. 267-281.

Hilman, H.J., E. Gidwani, P. Morris, S. Sagar, and S. Chowdhary (2007). *Using Microfinance to Expand Access to Energy Services: The Emerging Experiences in Asia of Self-Employed Women's Association Bank (SEWA), Sarvodaya Economic Enterprise Development Services (SEEDS), Nirdhan Utthan Bank Limited (NUBL), and AMRET.* The SEEP Network, Washington, DC, USA, 124 pp.

Himmel, M.E., Q. Xu, Y. Luo, S.-Y. Ding, R. Lamed, and E.A. Bayer (2010). Microbial enzyme systems for biomass conversion: emerging paradigms. *Biofuels*, **1**(2), pp. 323-341.

Hoefnagels, R., E. Smeets, and A. Faaij (2010). Greenhouse gas footprints of different biofuel production systems. *Renewable and Sustainable Energy Reviews*, **14**(7), pp. 1661-1694.

Hoekstra, A.Y., P.W. Gerbens-Leenes, and T.H. Van der Meer (2010). The water footprint of bio-energy. In: *Climate Change and Water: International Perspectives on Mitigation and Adaptation.* C. Howe, J.B. Smith, and J. Henderson (eds.), American Water Works Association, IWA Publishing, London, UK, pp. 81-95.

Hollebone, B.P., and Z. Yang (2009). Biofuels in the environment: A review of behaviours, fates, effects and possible remediation techniques. In: *Proceedings of the 32nd Arctic and Marine Oil Spill Program (AMOP) Technical Seminar on Environmental Contamination and Response*, Emergencies Science Division, Environment Canada, Ottawa, Canada, pp. 127-139.

Holmgren, J., R. Marinangeli, P. Nair, D. Elliott, and R. Bain (2008). Consider upgrading pyrolysis oils into renewable fuels. *Hydrocarbon Processing*, **87**(9), pp. 95-113.

Hoogwijk, M. (2004). *On the Global and Regional Potential of Renewable Energy Sources*. PhD Thesis, Utrecht University, Utrecht, The Netherlands, 257 pp.

Hoogwijk, M., A. Faaij, R. van den Broek, G. Berndes, D. Gielen, and W. Turkenburg (2003). Exploration of the ranges of the global potential of biomass for energy. *Biomass and Bioenergy*, **25**(2), pp. 119-133.

Hoogwijk, M., A. Faaij, B. Eickhout, B. de Vries, and W. Turkenburg (2005). Potential of biomass energy out to 2100, for four IPCC SRES land-use scenarios. *Biomass and Bioenergy*, **29**(4), pp. 225-257.

Hoogwijk, M., A. Faaij, B. de Vries, and W. Turkenburg (2009). Exploration of regional and global cost-supply curves of biomass energy from short-rotation crops at abandoned cropland and rest land under four IPCC SRES land-use scenarios. *Biomass and Bioenergy*, **33**(1), pp. 26-43.

Hooijer, A., M. Silvius, H. Wösten, and S. Page (2006). *PEAT- CO_2, Assessment of CO_2 Emissions from Drained Peatlands in SE Asia.* Delft Hydraulics report Q3943, WL Delft Hydraulics, Delft, The Netherlands, 41 pp.

Howard, D., and S. Ziller (2008). Alien alert – plants for biofuel may be invasive. *Bioenergy Business*, July/August, pp. 14-16.

Howarth, R.W., S. Bringezu, L.A. Martinelli, R. Santoro, D. Messem, and O.E. Sala (2009). Introduction: biofuels and the environment in the 21st century. In: *Biofuels: Environmental Consequences and Interactions with Changing Land Use.* R.W. Howarth and S. Bringezu (eds.), Proceedings of the SCOPE - Scientific Committee on Problems of the Environment International Biofuels Project Rapid Assessment, Gummersbach, Germany, 22-25 September 2009, pp. 15-36.

Hsu, D.D., D. Inman, G.A. Heath, E.J. Wolfrum, M.K. Mann, and A. Aden (2010). Life cycle environmental impacts of selected U.S. ethanol production and use pathways in 2022. *Environmental Science & Technology*, **44**, pp. 5289-5297.

Hu, Q., M. Sommerfeld, E. Jarvis, M. Ghirardi, M. Posewitz, M. Seibert, and A. Darzins (2008). Microalgal triacylglycerols as feedstocks for biofuel production: perspectives and advances. *The Plant Journal*, **54**, pp. 621-639.

Huber, G.W., R.D. Cortright, and J.A. Dumesic (2004). Renewable alkanes by aqueous-phase reforming of biomass-derived oxygenates. *Angewandte Chemie*, **116**(12), pp. 1575-1577.

Huber, G.W., J.N. Chheda, C.J. Barrett, and J.A. Dumesic (2005). Production of liquid alkanes by aqueous-phase processing of biomass-derived carbohydrates. *Science*, **308**(5727), pp. 1446-1450.

Huber, G.W., S. Iborra, and A. Corma (2006). Synthesis of transportation fuels from biomass: chemistry, catalysts, and engineering. *Chemical Reviews*, **106**(9), pp. 4044-4098.

Huertas, D.A., G. Berndes, M. Holmen, and G. Sparovek (2010). Sustainability certification of bioethanol. How is it perceived by Brazilian stakeholders? *Biomass and Bioenergy*, **4**(4), pp. 369-384.

Huo, H., M. Wang, C. Bloyd, and V. Putsche (2009). Life-cycle assessment of energy use and greenhouse gas emissions of soybean-derived biodiesel and renewable fuels. *Environmental Science & Technology*, **43**(3), pp. 750-756.

IAASTD (2009). *Agriculture at a Crossroads.* International Assessment of Agricultural Knowledge, Science and Technology for Development, Washington, DC, USA, 606 pp.

IATA (2009). *Report on Alternative Fuels.* International Air Transport Association, Montreal, Canada, 92 pp.

Ibsen, K., R. Wallace, S. Jones, and T. Werpy (2005). *Evaluating Progressive Technology Scenarios in the Development of the Advanced Dry Mill Biorefinery.* FY05-630, National Renewable Energy Laboratory, Golden, CO, USA, 35 pp.

IEA (2000). *Experience Curves for Energy Technology Policy.* International Energy Agency, Paris, France, 133 pp.

IEA (2006). *World Energy Outlook 2006.* International Energy Agency, Paris, France, 601 pp.

IEA (2007a). *World Energy Outlook 2007.* International Energy Agency, Paris, France, 600 pp.

IEA (2007b). *Biomass for Power Generation and CHP.* Energy Technology Essentials ETE03, International Energy Agency, Paris, France, 4pp.

IEA (2008a). *Energy Technology Perspectives 2008. Scenarios and Strategies to 2050.* International Energy Agency, Paris, France, 646 pp.

IEA (2008b). *World Energy Outlook 2008.* International Energy Agency, Paris, France, 578 pp.

IEA (2009). *World Energy Outlook 2009.* International Energy Agency, Paris, France, 696 pp.

IEA (2010a). *World Energy Statistics 2010.* International Energy Agency, Paris, France.[1]

IEA (2010b). *World Energy Outlook 2010.* International Energy Agency, Paris, France, 736 pp.

IEA (2010c). *Renewables Information 2010 with 2009 Data.* International Energy Agency, Paris, France, 428 pp (ISBN 978-92-64-08416-2).

IEA (2011). *Technology Roadmap: Biofuels for Transport.* International Energy Agency, Renewable Energy Division, Paris, France, 52 pp.

IEA Bioenergy (2007). *Potential Contribution of Bioenergy to the World's Future Energy Demand.* IEA Bioenergy: ExCo: 2007:02, 12 pp.

1 Combination of four IEA publications: IEA energy balances and statistics databases for most of the OECD countries for the years 1960 to 2008, with supply estimates for 2009, and energy statistics and balances for more than 100 non-OECD countries for the years 1971 to 2008.

IEA Bioenergy (2009). *Bioenergy: A Sustainable and Reliable Energy Source. Main Report.* IEA Bioenergy: ExCo:2009:06, 108 pp.

IEA Bioenergy (2010). *Algae – The Future for Bioenergy?* Summary and conclusions from the IEA Bioenergy ExCo64 Workshop. IEA Bioenergy: ExCo: 2010:02, 16 pp.

IEA Renewable Energy Division (2010). *Sustainable Production of Second-Generation Biofuels: Potential and Perspectives in Major Economies and Developing Countries.* International Energy Agency, Paris, France, 217 pp.

IFPRI (2008). *High Food Prices: The What, Who, and How of Proposed Policy Actions.* International Food Policy Research Institute, Washington, DC, USA, 12 pp.

Ileleji, K.E., S. Sokhansanj, and J.S. Cundiff (2010). Farm-gate to plant-gate delivery of lignocellulosic feedstocks from plant biomass for biofuel production. In: *Biofuels from Agricultural Wastes and Byproducts.* H.P. Blaschek, T. Ezeji, and J. Scheffran (eds.), Wiley-Blackwell, Oxford, UK, pp. 117-159.

Imhoff, M.L., L. Bounoua, T. Ricketts, C. Loucks, R. Harriss, and W.T. Lawrence (2004). Global patterns in human consumption of net primary production. *Nature*, **429**(6994), pp. 870-873.

IPCC (1996). *Climate Change 1995: Impacts, Adaptation, and Mitigation: Scientific-Technical Analyses.* R.T. Watson, M.C. Zinyowera, and R.H. Moss (eds.), Cambridge University Press, 878 pp.

IPCC (2000a). *Special Report on Emissions Scenarios.* N. Nakicenovic and R. Swart (eds.), Cambridge University Press, 570 pp.

IPCC (2000b). *Land Use, Land Use Change and Forestry.* R.T. Watson, I.R. Noble, B. Bolin, N.H. Ravindranath, D.J. Verardo and D.J. Dokken (eds.), Cambridge University Press, 375 pp.

IPCC (2005). *Special Report on Carbon Dioxide Capture and Storage.* B. Metz, O. Davidson, H. de Coninck, M. Loos, and L. Meyer (eds.), Cambridge University Press, 431 pp.

IPCC (2007a). *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson (eds.),Cambridge University Press, 979 pp.

IPCC (2007b). *Climate Change 2007: Synthesis Report. Contributions of Working Groups I, II and II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Core Writing Team, R.K. Pachauri, and A. Reisinger (eds.), Cambridge University Press, 104 pp.

IPCC (2007c). *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller (eds.), Cambridge University Press, 996 pp.

IPCC (2007d). *Climate Change 2007: Mitigation of Climate Change. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, and L.A. Meyer (eds.), Cambridge University Press, 851 pp.

IUCN (2009). *Guidelines on Biofuels and Invasive Species.* IUCN, Gland, Switzerland, 20 pp. (ISBN: 978-2-8317-1222-2).

Ivanic, M., and W. Martin (2008). Implications of higher global food prices for poverty in low-income countries. *Agricultural Economics*, **39**, pp. 405-416.

Jackson, R.B., B.C. Murray, E.G. Jobbagy, R. Avissar, S.B. Roy, D.J. Barrett, C.W. Cook, K.A. Farley, D.C. le Maitre, and B.A. McCarl (2005). Trading water for carbon with biological carbon sequestration. *Science*, **310**(5756), pp. 1944-1947.

Jacobsen, N.B. (2006). Industrial symbiosis in Kalundborg, Denmark: A quantitative assessment of economic and environmental aspects. *Journal of Industrial Ecology*, **10**(1-2), pp. 239-255.

Jaggard, K.W., A. Qi, and E.S. Ober (2010). Possible changes to arable crop yields by 2050. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **365**(1554), pp. 2835-2851.

Jauhiainen, J., S. Limin, H. Silvennoinen, and H. Vasander (2008). Carbon dioxide and methane fluxes in drained tropical peat before and after hydrological restoration. *Ecology*, **89**(12), pp. 3503-3514.

Jechura, J. (2005). *Dry Mill Cost-By-Area: ASPEN Case Summary.* National Renewable Energy Laboratory, Golden, CO, USA, 2 pp.

Jeffries, T.W. (2006). Engineering yeasts for xylose metabolism. *Current Opinion in Biotechnology*, **17**(3), pp. 320-326.

Jeffries, T.W., I.V. Grigoriev, J. Grimwood, J.M. Laplaza, A. Aerts, A. Salamov, J. Schmutz, E. Lindquist, P. Dehal, H. Shapiro, Y.-S. Jin, V. Passoth, and P.M. Richardson (2007). Genome sequence of the lignocellulose-bioconverting and xylose-fermenting yeast Pichia stipitis. *Nature Biotechnology*, **25**(3), pp. 319-326.

Jensen, E.S. (1996). Grain yield, symbiotic N_2 fixation and interspecific competition for inorganic N in pea-barley intercrops. *Plant and Soil*, **182**(1), pp. 25-38.

Jetter, J.J., and P. Kariher (2009). Solid-fuel household cook stoves: Characterization of performance and emissions. *Biomass and Bioenergy*, **33**(2), pp. 294-305.

Johansson, D., and C. Azar (2007). A scenario based analysis of land competition between food and bioenergy production in the US. *Climatic Change*, **82**(3), pp. 267-291.

Johnson, J.M.F., D. Reicosky, B. Sharratt, M. Lindstrom, W. Voorhees, and L. Carpenter-Boggs (2004). Characterization of soil amended with the by-product of corn stover fermentation. *Soil Science Society of America Journal*, **68**(1), pp. 139-147.

Johnson, M., R. Edwards, A. Ghilardi, V. Berrueta, D. Gillen, C.A. Frenk, and O. Masera (2009). Quantification of carbon savings from improved biomass cookstove projects. *Environmental Science & Technology*, **43**(7), pp. 2456-2462.

Johnson, T.M., C. Alatorre, Z. Romo, and F. Liu (2009). *Low-Carbon Development for Mexico.* The International Bank for Reconstruction and Development, The World Bank, Washington, DC, USA.

Johnston, M., and T. Holloway (2007). A global comparison of national biodiesel production potentials. *Environmental Science & Technology*, **41**(23), pp. 7967-7973.

Johnston, M., J.A. Foley, T. Holloway, C. Kucharik, and C. Monfreda (2009). Resetting global expectations from agricultural biofuels. *Environmental Research Letters*, **4**(1), 014004.

Jongschaap, R.E.E., W.J. Corré, P.S. Bindraban, and W.A. Brandenburg (2007). *Claims and Facts on Jatropha curcas L. Global Jatropha curcas Evaluation, Breeding And Propagation Programme.* Report 158, Plant Research International BV, Wageningen, The Netherlands and Stichting Het Groene Woudt, Laren, The Netherlands, 66 pp.

Junginger, M. (2007). *Lessons from (European) Bioenergy Policies; Results of a Literature Review for IEA Bioenergy Task 40.* Utrecht University, Utrecht, Netherlands, 14 pp. Available at: www.bioenergytrade.org/downloads/jungingerlessonsfromeuropeanbioenergypolicies.pdf.

Junginger, M., A. Faaij, R. van den Broek, A. Koopmans, and W. Hulscher (2001). Fuel supply strategies for large-scale bio-energy projects in developing countries. Electricity generation from agricultural and forest residues in Northeastern Thailand. *Biomass and Bioenergy*, **21**(4), pp. 259-275.

Junginger, M., A. Faaij, R. Björheden, and W.C. Turkenburg (2005). Technological learning and cost reductions in wood fuel supply chains in Sweden. *Biomass and Bioenergy*, **29**(6), pp. 399-418.

Junginger, M., E. de Visser, K. Hjort-Gregersen, J. Koornneef, R. Raven, A. Faaij, and W. Turkenburg (2006). Technological learning in bioenergy systems. *Energy Policy*, **34**(18), pp. 4024-4041.

Junginger, M., T. Bolkesjø, D. Bradley, P. Dolzan, A. Faaij, J. Heinimö, B. Hektor, Ø. Leistad, E. Ling, M. Perry, E. Piacente, F. Rosillo-Calle, Y. Ryckmans, P.-P. Schouwenberg, B. Solberg, E. Trømborg, A.d.S. Walter, and M.d. Wit (2008). Developments in international bioenergy trade. *Biomass and Bioenergy*, **32**(8), pp. 717-729.

Junginger, M., A. Faaij, J. van Dam, S. Zarrilli, A. Mohammed, and D. Marchal (2010). *Opportunities and Barriers for International Bioenergy Trade and Strategies to Overcome Them.* IEA Bioenergy Task 40, 17 pp. Available at: www.bioenergytrade.org/downloads/t40opportunitiesandbarriersforbioenergytradefi.pdf.

Jungk, N., and G. Reinhardt (2000). *Landwirtschaftliche Referenzsysteme in Ökologischen Bilanzierungen: eine Basis Analyse.* Institute für Energie- und Umweltforschung, Heidelberg, Germany.

Kaliyan, N., R.V. Morey, and D.G. Tiffany (2010). Reducing life cycle greenhouse gas emissions of corn ethanol by integrating biomass to produce heat and power at ethanol plants. *Biomass and Bioenergy*, **35**(3), pp. 1103-1113.

Kalnes, T.N., K.P. Koers, T. Marker, and D.R. Shonnard (2009). A technoeconomic and environmental life cycle comparison of green diesel to biodiesel and syndiesel. *Environmental Progress & Sustainable Energy*, **28**(1), pp. 111-120.

Kamm, B., P.R. Gruber, and M. Kamm (eds.) (2006). *Biorefineries - Industrial Processes and Products: Status Quo and Future Directions.* Wiley-VCH, Weinheim, UK, 949 pp.

Kang, S., M. Khanna, J. Scheffran, D. Zilberman, H. Önal, Y. Ouyang, and Ü.D. Tursun (2010). Optimizing the biofuels infrastructure: Transportation networks and biorefinery locations in Illinois. In: *Handbook of Bioenergy Economics and Policy.* M. Khanna, J. Scheffran, and D. Zilberman (eds.), Springer New York, New York, NY, USA, pp. 151-173.

Karekezi , S., and L. Majoro (2002). Improving modern energy services for Africa's urban poor. *Energy Policy*, **30**(11-12), pp. 1015-1028.

Karekezi, S., and P. Turyareeba (1995). Woodstove dissemination in Eastern Africa - a review. *Energy for Sustainable Development*, **1**(6), pp. 12-19.

Karlen, D.L. (2010). Corn stover feedstock trials to support predictive modeling. *Global Change Biology Bioenergy*, **2**(5), pp. 235-247.

Karp, A., and I. Shield (2008). Bioenergy from plants and the sustainable yield challenge. *New Phytologist*, **179**(1), pp. 15-32.

Kartha, S., P. Hazel, and R.K. Pachauri (2006). Environmental effects of bioenergy. In: *Bioenergy and Agriculture: Promises and Challenges.* P.B.R. Hazell and R.K. Pachauri (eds.), International Food Policy Research Institute, Washington, D.C., USA, 2 pp.

Kazi, F.K., J.A. Fortman, R.P. Anex, D.D. Hsu, A. Aden, A. Dutta, and G. Kothandaraman (2010). Techno-economic comparison of process technologies for biochemical ethanol production from corn stover. *Fuel*, **89**(Supplement 1), pp. S20-S28.

Keasling, J.D., and H. Chou (2008). Metabolic engineering delivers next-generation biofuels. *Nature Biotechnology*, **26**(3), pp. 298-299.

Keeney, D., and T.W. Hertel (2008). *Yield Response to Prices: Implications for Policy Modeling.* Working paper 08/13, Department of Agricultural Economics, Purdue University, West Lafayette, IN, USA, 37 pp.

Keeney, D., and T.W. Hertel (2009). The indirect land use impacts of United States biofuel policies: The importance of acreage, yield, and bilateral trade responses. *American Journal of Agricultural Economics*, **91**, pp. 895-909.

Keeney, D., and M. Muller (2006). *Water Use by Ethanol Plants: Potential Challenges.* Institute for Agriculture and Trade Policy, Minneapolis, MN, USA, 7 pp.

Keeney, R., and T. Hertel (2005). *GTAP-AGR : A Framework for Assessing the Implications of Multilateral Changes in Agricultural Policies.* GTAP Technical Paper No.24, Center for Global Trade Analysis, Department of Agricultural Economics, Purdue University, West Lafayette, IN, USA, 61 pp.

Kendall, A., B. Chang, and B. Sharpe (2009). Accounting for time-dependent effects in biofuel life cycle greenhouse gas emissions calculations. *Environmental Science & Technology*, **43**(18), pp. 7142-7147.

Keys, E., and W. McConnell (2005). Global change and the intensification of agriculture in the tropics. *Global Environmental Change*, **15**(4), pp. 320-337.

Kheshgi, H.S., R.C. Prince, and G. Marland (2000). The potential of biomass fuels in the context of global climate change: Focus on transportation fuels. *Annual Review of Energy and the Environment*, **25**(1), pp. 199-244.

Kim, H., S. Kim, and B.E. Dale (2009). Biofuels, land use change, and greenhouse gas emissions: Some unexplored variables. *Environmental Science & Technology*, **43**(3), pp. 961-967.

Kim, S., and B. Dale (2002). Allocation procedure in ethanol production system from corn grain i. system expansion. *The International Journal of Life Cycle Assessment*, **7**(4), pp. 237-243.

Kim, S., and B.E. Dale (2004). Global potential bioethanol production from wasted crops and crop residues. *Biomass and Bioenergy*, **26**(4), pp. 361-375.

Kinchin, C. and R.L. Bain (2009). *Hydrogen Production from Biomass via Indirect Gasification: The Impact of NREL Process Development Unit Gasifier Correlations.* NREL Report No. TP-510-44868. National Renewable Energy Laboratory, Golden, CO, USA, 27 pp.

King, C.W., and M.E. Webber (2008). Water intensity of transportation. *Environmental Science & Technology*, **42**(21), pp. 7866-7872.

King, D., O.R. Inderwildi, and A. Williams (2010). *The Future of Industrial Biorefineries.* 210610, World Economic Forum White Paper, Cologn/Geneva, Switzerland, 40 pp.

Kirkels, A., and G. Verbong (2011). Biomass gasification: Still promising? A 30-year global overview. *Renewable and Sustainable Energy Reviews*, **15**(1), pp. 471-481.

Kirkinen, J., A. Sahay, and I. Savolainen (2009). Greenhouse impact of fossil, forest residues and Jatropha diesel: a static and dynamic assessment. *Progress in Industrial Ecology, An International Journal*, **6**, pp. 185-206.

Kirschbaum, M.U.F. (2003). To sink or burn? A discussion of the potential contributions of forests to greenhouse gas balances through storing carbon or providing biofuels. *Biomass and Bioenergy*, **24**(4-5), pp. 297-310.

Kirschbaum, M.U.F. (2006). Temporary carbon sequestration cannot prevent climate change. *Mitigation and Adaptation Strategies for Global Change*, **11**(5), pp. 1151-1164.

Kishore, V.V.N., P.M. Bhandari, and P. Gupta (2004). Biomass energy technologies for rural infrastructure and village power – opportunities and challenges in the context of global climate change concerns. *Energy Policy*, **32**(6), pp. 801-810.

Kituyi, E. (2004). Towards sustainable production and use of charcoal in Kenya: exploring the potential in life cycle management approach. *Journal of Cleaner Production*, **12**(8-10), pp. 1047-1057.

Kline, K.L., and V.H. Dale (2008). Biofuels: Effects on land and fire. *Science*, **321**(5886), pp. 199-201.

Kline, K.L., G. Oladosu, A. Wolfe, R.D. Perlack, and M. McMahon (2007). *Biofuel Feedstock Assessment for Selected Countries.* ORNL/TM-2007/224, Oak Ridge National Laboratory, Oak Ridge, TN, USA, 243 pp.

Knothe, G. (2010). Biodiesel and renewable diesel: a comparison. *Progress in Energy and Combustion Science*, **36**(3), pp. 364-373.

Knowler, D.J. (2004). The economics of soil productivity: local, national and global perspectives. *Land Degradation & Development*, **15**(6), pp. 543-561.

Koh, L.P., and J. Ghazoul (2008). Biofuels, biodiversity, and people: Understanding the conflicts and finding opportunities. *Biological Conservation*, **141**(10), pp. 2450-2460.

Köhlin, G., and M. Ostwald (2001). Impact of plantations on forest use and forest status in Orissa, India. *AMBIO*, **30**(1), pp. 37-42.

Koizumi, T., and K. Ohga (2008). Biofuels policies in Asian countries: Impact of the expanded biofuels programs on world agricultural markets. *Journal of Agricultural & Food Industrial Organization*, **5**(2), Article 8, 22 pp.

Koning, N. (2008). Long-term global availability of food: continued abundance or new scarcity? *NJAS - Wageningen Journal of Life Sciences*, **55**(3), pp. 229-292.

Körner, C., J.A. Morgan, and R.J. Norby (2007). CO_2 fertilization: When, where and how much? In: *Terrestrial ecosystems in a changing world.* Springer, Berlin, Germany, pp. 9-22.

Koukouzas, N., A. Katsiadakis, E. Karlopoulos, and E. Kakaras (2008). Co-gasification of solid waste and lignite - A case study for Western Macedonia. *Waste Management*, **28**(7), pp. 1263-1275.

Krausmann, F., K.-H. Erb, S. Gingrich, C. Lauk, and H. Haberl (2008). Global patterns of socioeconomic biomass flows in the year 2000: A comprehensive assessment of supply, consumption and constraints. *Ecological Economics*, **65**(3), pp. 471-487.

Kreutz, T.G., E.D. Larson, G. Liu, and R.H. Williams (2008). Fischer-Tropsch fuels from coal and biomass. In: *Proceedings of the 25th International Pittsburgh Coal Conference.* Princeton Environmental Institute, Pittsburgh, PA, 29 September – 2 October 2008.

Krewitt, W., K. Nienhaus, C. Kleßmann, C. Capone, E. Stricker, W. Graus, M. Hoogwijk, N. Supersberger, U. von Winterfeld, and S. Samadi (2009). *Role and Potential of Renewable Energy and Energy Efficiency for Global Energy Supply.* ISSN 1862-4359, Federal Environment Agency, Dessau-Roßlau, Germany, 336 pp.

Krey, V., and L. Clarke (2011). Role of renewable energy in climate change mitigation: A synthesis of recent scenarios. *Climate Policy*, in press.

Krich, K., D. Augenstein, J.P. Batmale, J. Benemann, B. Rutledge, and D. Salour (2005). *Biomethane from Dairy: A Sourcebook for the Production and Use of Renewable Natural Gas in California.* Report prepared for Western United Dairymen with funding from USDA Rural Development, Washington, DC, USA, 282 pp. Available at: www.suscon.org/cowpower/biomethaneSourcebook/Full_Report.pdf.

Kumar, B.M. (2006). Agroforestry: the new old paradigm for Asian food security. *Journal of Tropical Agriculture*, **44**(1-2), pp. 1-14.

Kumar, L.N.V., and S. Maithel (2007). Alternative feedstock for Bio-ethanol production in India. In: *Biofuels: Towards a Greener and Secure Energy Future.* P.P. Bhojvaid (ed.), The Energy Resources Institute Press (TERI Press), New Delhi, India, pp. 89-104.

Kurz, W.A., G. Stinson, and G. Rampley (2008a). Could increased boreal forest ecosystem productivity offset carbon losses from increased disturbances? *Philosophical Transactions of the Royal Society B: Biological Sciences*, **363**(1501), pp. 2259-2268.

Kurz, W.A., C.C. Dymond, G. Stinson, G.J. Rampley, E.T. Neilson, A.L. Carroll, T. Ebata, and L. Safranyik (2008b). Mountain pine beetle and forest carbon feedback to climate change. *Nature*, **452**(7190), pp. 987-990.

Kuuva, K., and L. Ruska (2009). *Final Report of Feed-in Tariff Task Force.* 59/2009, Ministry of Employment and the Economy of Finland, Helsinki, Finland, 101 pp.

Laird, D.A. (2008). The charcoal vision: A win-win-win scenario for simultaneously producing bioenergy, permanently sequestering carbon, while improving soil and water quality. *Agronomy Journal*, **100**(1), pp. 178-181.

Laird, D.A., R.C. Brown, J.E. Amonette, and J. Lehmann (2009). Review of the pyrolysis platform for coproducing bio-oil and biochar. *Biofuels, Bioproducts and Biorefining*, **3**(5), pp. 547-562.

Lal, R. (2003). Offsetting global CO_2 emissions by restoration of degraded soils and intensification of world agriculture and forestry. *Land Degradation & Development*, **14**(3), pp. 309-322.

Lal, R. (2004). Soil carbon sequestration impacts on global climate change and food security. *Science*, **304**(5677), pp. 1623-1627.

Lal, R. (2005). World crop residues production and implications of its use as a biofuel. *Environment International*, **31**(4), pp. 575-584.

Lal, R. (2008). Crop residues as soil amendments and feedstock for bioethanol production. *Waste Management*, **28**(4), pp. 747-758.

Lal, R., and D. Pimentel (2007). Bio-fuels from crop residues. *Soil & Tillage Research*, **93**(2), pp. 237-238.

Lamers , P., C. Hamelinck, M. Junginger, and A. Faaij (2011). International Bioenergy, Trade - A Review of Past Developments in the Liquid Biofuels Market. *Renewable and Sustainable Energy Reviews*, **15**(6), pp. 2655-2676.

Lapola, D.M., R. Schaldach, J. Alcamo, A. Bondeau, J. Koch, C. Koelking, and J.A. Priess (2010). Indirect land-use changes can overcome carbon savings from biofuels in Brazil. *Proceedings of the National Academy of Sciences*, **107**(8), pp. 3388-3393.

Larson, E. (2006). A review of life-cycle analysis studies on liquid biofuel systems for the transport sector. *Energy for Sustainable Development*, **10**(2), pp. 109-126.

Larson, E.D., G. Fiorese, G. Liu, R.H. Williams, T.G. Kreutz, and S. Consonni (2009). Co-production of synfuels and electricity from coal + biomass with zero net carbon emissions: An Illinois case study. *Energy Procedia*, **1**(1), pp. 4371-4378.

Larson, E.D., G. Fiorese, G. Liu, R.H. Williams, T.G. Kreutz, and S. Consonni (2010). Co-production of decarbonized synfuels and electricity from coal + biomass with CO_2 capture and storage: an Illinois case study. *Energy & Environmental Science*, **3**(1), pp. 28-42.

Laser, M., E. Larson, B. Dale, M. Wang, N. Greene, and L.R. Lynd (2009). Comparative analysis of efficiency, environmental impact, and process economics for mature biomass refining scenarios. *Biofuels, Bioproducts and Biorefining*, **3**(2), pp. 247-270.

Lattimore, B., C.T. Smith, B.D. Titus, I. Stupak, and G. Egnell (2009). Environmental factors in woodfuel production: Opportunities, risks, and criteria and indicators for sustainable practices. *Biomass and Bioenergy*, **33**(10), pp. 1321-1342.

Laurance, W.F. (2007). Switch to corn promotes Amazon deforestation. *Science*, **318**(5857), pp. 1721-1724.

Lawrence, C.J., and V. Walbot (2007). Translational genomics for bioenergy production from fuelstock grasses: Maize as the model species. *Plant Cell*, **19**(7), pp. 2091-2094.

Lee, D.R., C.B. Barrett, and J.G. McPeak (2006). Policy, technology, and management strategies for achieving sustainable agricultural intensification. *Agricultural Economics*, **34**(2), pp. 123-127.

Lee, J. (1997). Biological conversion of lignocellulosic biomass to ethanol. *Journal of Biotechnology*, **56**(1), pp. 1-24.

Lee, S.K., H. Chou, T.S. Ham, T.S. Lee, and J.D. Keasling (2008). Metabolic engineering of microorganisms for biofuels production: from bugs to synthetic biology to fuels. *Current Opinion in Biotechnology*, **19**(6), pp. 556-563.

Leemans, R., A. van Amstel, C. Battjes, E. Kreileman, and S. Toet, (1996). The land cover and carbon cycle consequences of large-scale utilizations of biomass as an energy source. *Global Environmental Change*, **6**(4), pp. 335-357.

Legros, G., I. Havet, N. Bruce, and S. Bonjour (2009). *The Energy Access Situation in Developing Countries: A Review Focusing on the Least Developed Countries and Sub-Saharan Africa.* United Nations Development Programme and the World Health Organization, New York, NY, USA, 142 pp.

Lehtomäki, A., S. Huttunen, and J.A. Rintala (2007). Laboratory investigations on co-digestion of energy crops and crop residues with cow manure for methane production: Effect of crop to manure ratio. *Resources, Conservation and Recycling*, **51**(3), pp. 591-609.

Leng, R., C. Wang, C. Zhang, D. Dai, and G. Pu (2008). Life cycle inventory and energy analysis of cassava-based fuel ethanol in China. *Journal of Cleaner Production*, **16**(3), pp. 374-384.

Levasseur, A., P. Lesage, M. Margni, L. Deschênes, and R. Samson (2010). Considering time in LCA: Dynamic LCA and its application to global warming impact assessments. *Environmental Science & Technology*, **44**(8), pp. 3169-3174.

Lewis, S.L., G. Lopez-Gonzalez, B. Sonke, K. Affum-Baffoe, T.R. Baker, L.O. Ojo, O.L. Phillips, J.M. Reitsma, L. White, J.A. Comiskey, M.-N.D. K, C.E.N. Ewango, T.R. Feldpausch, A.C. Hamilton, M. Gloor, T. Hart, A. Hladik, J. Lloyd, J.C. Lovett, J.-R. Makana, Y. Malhi, F.M. Mbago, H.J. Ndangalasi, J. Peacock, K.S.H. Peh, D. Sheil, T. Sunderland, M.D. Swaine, J. Taplin, D. Taylor, S.C. Thomas, R. Votere, and H. Woll (2009). Increasing carbon storage in intact African tropical forests. *Nature*, **457**(7232), pp. 1003-1006.

Li, W., R. Fu, and R.E. Dickinson (2006). Rainfall and its seasonality over the Amazon in the 21st century as assessed by the coupled models for the IPCC AR4. *Journal of Geophysical Research*, **111**(D2), D02111.

Liebig, M., M. Schmer, K. Vogel, and R. Mitchell (2008). Soil carbon storage by switchgrass grown for bioenergy. *BioEnergy Research*, **1**(3), pp. 215-222.

Lindenmayer, D.B., and H.A. Nix (1993). Ecological principles for the design of wildlife corridors. *Conservation Biology*, **7**(3), pp. 627-631.

Lindner, M., M. Maroschek, S. Netherer, A. Kremer, A. Barbati, J. Garcia-Gonzalo, R. Seidl, S. Delzon, P. Corona, M. Kolström, M.J. Lexer, and M. Marchetti (2010). Climate change impacts, adaptive capacity, and vulnerability of European forest ecosystems. *Forest Ecology and Management*, **259**(4), pp. 698-709.

Lioubimtseva, E., and J.M. Adams (2004). Possible implications of increased carbon dioxide levels and climate change for desert ecosystems. *Environmental Management*, **33**(Supplement 1), pp. S388-S404.

Liska, A.J., and R.K. Perrin (2010). Securing foreign oil: A case for including military operations in the climate change impact of fuels. *Environment: Science and Policy for Sustainable Development*, **52**(4), pp. 9-12.

Lobell, D.B., and M.B. Burke (2008). Why are agricultural impacts of climate change so uncertain? The importance of temperature relative to precipitation. *Environmental Research Letters*, **3**(3), 034007.

Lobell, D.B., M.B. Burke, C. Tebaldi, M.D. Mastrandrea, W.P. Falcon, and R.L. Naylor (2008). Prioritizing climate change adaptation needs for food security in 2030. *Science*, **319**(5863), pp. 607-610.

Londo, M., A. Faaij, M. Junginger, G. Berndes, S. Lensink, A. Wakker, G. Fischer, S. Prieler, H. van Velthuizen, and M. de Wit (2010). The REFUEL EU road map for biofuels in transport: Application of the project's tools to some short-term policy issues. *Biomass and Bioenergy*, **34**(2), pp. 244-250.

López, R., and G.I. Galinato (2007). Should governments stop subsidies to private goods? Evidence from rural Latin America. *Journal of Public Economics*, **91**(5-6), pp. 1071-1094.

Lotze-Campen, H., A. Popp, T. Beringer, C. Müller, A. Bondeau, S. Rost, and W. Lucht (2009). Scenarios of global bioenergy production: The trade-offs between agricultural expansion, intensification and trade. *Ecological Modelling*, **221**(18), pp. 2188-2196.

Loustau, D., A. Bosc, A. Colin, J. Ogee, H. Davi, C. Francois, E. Dufrene, M. Deque, E. Cloppet, D. Arrouays, C. Le Bas, N. Saby, G. Pignard, N. Hamza, A. Granier, N. Breda, P. Ciais, N. Viovy, and F. Delage (2005). Modeling climate change effects on the potential production of French plains forests at the sub-regional level. *Tree Physiology*, **25**(7), pp. 813-823.

Low, T., and C. Booth (2007). *The Weedy Truth about Biofuels.* Invasive Species Council, Melbourne, Fairfield, Australia, 46 pp.

Luyssaert, S., E.D. Schulze, A. Börner, A. Knohl, D. Hessenmöller, B.E. Law, P. Ciais, and J. Grace (2008). Old-growth forests as global carbon sinks. *Nature*, **455**(7210), pp. 213-215.

Lywood, W. (2008). *Indirect Effects of Biofuels.* Renewable Fuels Agency, East Sussex, UK.

Lywood, W., J. Pinkney, and S.A.M. Cockerill (2009a). Impact of protein concentrate coproducts on net land requirement for European biofuel production. *Global Change Biology Bioenergy*, **1**(5), pp. 346-359.

Lywood, W., J. Pinkney, and S.A.M. Cockerill (2009b). The relative contributions of changes in yield and land area to increasing crop output. *Global Change Biology Bioenergy*, **1**(5), pp. 360-369.

Macedo, I.C., and J.E.A. Seabra (2008). Mitigation of GHG emissions using sugarcane bioethanol. In: *Sugarcane Ethanol: Contributions to Climate Change Mitigation and the Environment.* P. Zuubier and J. van de Vooren (eds.), Wageningen Academic Publishers, Wageningen, The Netherlands, pp. 95-112.

Macedo, I.C., J.E.A. Seabra, and J.E.A.R. Silva (2008). Green house gases emissions in the production and use of ethanol from sugarcane in Brazil: The 2005/2006 averages and a prediction for 2020. *Biomass and Bioenergy*, **32**(7), pp. 582-595.

Madsen, A.M. (2006). Exposure to airborne microbial components in autumn and spring during work at Danish biofuel plants. *Annals of Occupational Hygiene*, **50**(8), pp. 821-831.

Madsen, A.M., L. Martensson, T. Schneider, and L. Larsson (2004). Microbial dustiness and particle release of different biofuels. *Annals of Occupational Hygiene*, **48**(4), pp. 327-338.

Maes, W., W. Achten, and B. Muys (2009). Use of inadequate data and methodological errors lead to a dramatic overestimation of the water footprint of *Jatropha curcas*. *Nature Precedings*, hdl:10101/npre.2009.3410.1, 3 pp.

Malézieux, E., Y. Crozat, C. Dupraz, M. Laurans, D. Makowski, H. Ozier-Lafontaine, B. Rapidel, S. de Tourdonnet, and M. Valantin-Morison (2009). Mixing plant species in cropping systems: concepts, tools and models. A review. *Agronomy for Sustainable Development*, **29**(1), pp. 43-62.

Malmer, A., D. Murdiyarso, L.A.S. Bruijnzeel, and U. Lstedt (2010). Carbon sequestration in tropical forests and water: a critical look at the basis for commonly used generalizations. *Global Change Biology*, **16**(2), pp. 599-604.

Markewitz, D. (2006). Fossil fuel carbon emissions from silviculture: Impacts on net carbon sequestration in forests. *Forest Ecology and Management*, **236**(2-3), pp. 153-161.

Marlair, G., P. Rotureau, S. Breulet, and S. Brohez (2009). Booming development of biofuels for transport: Is fire safety of concern? *Fire and Materials*, **33**(1), pp. 1-19.

Marland, G., and B. Schlamadinger (1997). Forests for carbon sequestration or fossil fuel substitution? A sensitivity analysis. *Biomass and Bioenergy*, **13**(6), pp. 389-397.

Marland, G., M. Obersteiner, and B. Schlamadinger (2007). The carbon benefits of fuels and forests. *Science*, **318**(5853), pp. 1066.

Martens, W., and R. Böhm (2009). Overview of the ability of different treatment methods for liquid and solid manure to inactivate pathogens. *Bioresource Technology*, **100**(22), pp. 5374-5378.

Martinelli, L.A., and S. Filoso (2007). Polluting effects of Brazil's sugar-ethanol industry. *Nature*, **445**(7126), pp. 364-364.

Masera, O.R., and J. Navia (1997). Fuel switching or multiple cooking fuels: Understanding interfuel substitution patterns in rural Mexican households. *Biomass and Bioenergy*, **12**(5), pp. 347-361.

Masera, O.R., B.D. Saatkamp, and D.M. Kammen (2000). From linear fuel switching to multiple cooking strategies: A critique and alternative to the energy ladder model. *World Development*, **28**(12), pp. 2083-2103.

Masera, O.R., R. Diaz, and V. Berrueta (2005). From cookstoves to cooking systems: the integrated program on sustainable household energy use in Mexico. *Energy for Sustainable Development*, **9**(1), pp. 25-36.

Masera, O., A. Ghilardi, R. Drigo, and M. Angel Trossero (2006). WISDOM: A GIS-based supply demand mapping tool for woodfuel management. *Biomass and Bioenergy*, **30**(7), pp. 618-637.

Matsuoka, S., J. Ferro, and P. Arruda (2009). The Brazilian experience of sugarcane ethanol industry. *In Vitro Cellular & Developmental Biology - Plant*, **45**(3), pp. 372-381.

Matthews, H.D., and K. Caldeira (2008). Stabilizing climate requires near-zero emissions. *Geophysical Research Letters*, **35**(4), L04705.

Matthews, H.D., N.P. Gillett, P.A. Stott, and K. Zickfeld (2009). The proportionality of global warming to cumulative carbon emissions. *Nature*, **459**(7248), pp. 829-832.

Maués, J.A. (2007). Maximizacao da geracao eletrica a partir do bagaco e palha em usinas de acucar e alcool. *Revista Engenharia*, **583**, pp. 88-98.

Mayfield, C.A., C.D. Foster, C.T. Smith, J. Gan, and S. Fox (2007). Opportunities, barriers, and strategies for forest bioenergy and bio-based product development in the Southern United States. *Biomass & Bioenergy*, **31**, pp. 631-637.

McAloon, A., F. Taylor, W. Lee, K. Ibsen, and R. Wooley (2000). *Determining the Cost of Producing Ethanol from Corn Starch and Lignocellulosic Feedstocks.* NREL/TP-580-28893, National Renewable Energy Laboratory, Golden, CO, USA, 43 pp.

McCoy, M. (2006). Glycerin surplus. *Chemical & Engineering News*, **83**(4), pp. 21-22.

McDonald, A., and L. Schrattenholzer (2001). Learning rates for energy technologies. *Energy Policy*, **29**(4), pp. 255-261.

McGowin, C. (2008). *Renewable Energy Technical Assessment Guide.* TAG-RE:2007, Electric Power Research Institute, Palo Alto, CA, USA.

McKeough, P., and E. Kurkela (2008). *Process Evaluations and Design Studies in the UCG Project 2004-2007.* VTT Research Notes 2434, VTT Technical Research Centre of Finland, Espoo, Finland, 49 pp.

McKeough, P., Y. Solantausta, H. Kyllönen, A. Faaij, C. Hamelinck, M. Wagener, D. Beckman and B. Kjellström (2005). *Technoeconomic Analysis of Biotrade Chains: Upgraded Biofuels from Russia and Canada to the Netherlands.* VTT Research Notes 2312, VTT Technical Research Centre of Finland, Espoo, Finland, 65 pp.

McLeod, J.E., J.E. Nunez, and S.S. Rivera (2008). A discussion about how to model biofuel plants for the risk optimization. In: *Proceedings of the World Congress on Engineering 2008, Vol. II*, London, UK, 2-4 July 2008, pp. 1214-1219.

McWhorter, C. (1971). Introduction and spread of johnsongrass in the United States. *Weed Science*, **19**(5), pp. 496-500.

Melillo, J.M., J.M. Reilly, D.W. Kicklighter, A.C. Gurgel, T.W. Cronin, S. Paltsev, B.S. Felzer, X. Wang, A.P. Sokolov, and C.A. Schlosser (2009). Indirect emissions from biofuels: How important? *Science*, **326**(5958), pp. 1397-1399.

Menichetti, E., and M. Otto (2009). Energy balance and greenhouse gas emissions of biofuels from a product life-cycle perspective. In: *Biofuels: Environmental Consequences and Interactions with Changing Land Use.* R.W. Howarth and S. Bringezu (eds.), Proceedings of the SCOPE - Scientific Committee on Problems of the Environment International Biofuels Project Rapid Assessment, Gummersbach, Germany, 22-25 September 2009, pp. 81-109.

Metzger, J.O., and A. Hüttermann (2009). Sustainable global energy supply based on lignocellulosic biomass from afforestation of degraded areas. *Naturwissenschaften*, **96**(2), pp. 279-288.

Milbrandt, A., and R.P. Overend (2008). *Future of Liquid Biofuels for APEC Economies.* NREL/TP-6A2-43709, report prepared for Asia-Pacific Economic Cooperation by the National Renewable Energy Laboratory, Golden, CO, USA, 103 pp. Available at: www.biofuels.apec.org/pdfs/ewg_2008_liquid_biofuels.pdf.

Millennium Ecosystem Assessment (2005). *Ecosystems and Human Well-being.* Island Press, Washington, DC, USA, 36 pp.

Mishra, V., X. Dai, K. Smith, and L. Mike (2004). Maternal exposure to biomass smoke and reduced birth weight in Zimbabwe. *Annals of Epidemiology*, **14**(10), pp. 740-747.

Mitchell, D. (2008). *A Note on Rising Food Prices.* Policy Research Working Paper 4682, The World Bank Group, Washington, DC, USA, 22 pp.

Molden, D. (ed.) (2007). *Water for Food, Water for Life: A Comprehensive Assessment of Water Management in Agriculture.* Earthscan, London, UK.

Molina Grima, E., E.H. Belarbi, F.G. Acien Fernandez, A. Robles Medina, and Y. Chisti (2003). Recovery of microalgal biomass and metabolites: process options and economics. *Biotechnology Advances*, **20**(7-8), pp. 491-515.

Möllersten, K., J. Yan, and J. R. Moreira (2003). Potential market niches for biomass energy with CO_2 capture and storage – Opportunities for energy supply with negative CO_2 emissions. *Biomass and Bioenergy*, **25**(3), pp. 273-285.

Molofsky, J., S.L. Morrison, and C.J. Goodnight (1999). Genetic and environmental controls on the establishment of the invasive grass, Phalaris arundinacea. *Biological Invasions*, **1**(2), pp. 181-188.

Moral, R., C. Paredes, M.A. Bustamante, F. Marhuenda-Egea, and M.P. Bernal (2009). Utilisation of manure composts by high-value crops: Safety and environmental challenges. *Bioresource Technology*, **100**(22), pp. 5454-5460.

Moreira, J.R. (2006). *Bioenergy and Agriculture, Promises and Challenges: Brazil's Experience with Bioenergy.* International Food Policy Research Institute, Washington, DC, USA, 2 pp.

Mosier, A., C. Kroeze, C. Nevison, O. Oenema, S. Seitzinger, and O. van Cleemput (1998). Closing the global N_2O budget: nitrous oxide emissions through the agricultural nitrogen cycle. *Nutrient Cycling in Agroecosystems*, **52**(2-3), pp. 1385-1314.

Mosier, N., C. Wyman, B. Dale, R. Elander, Y.Y. Lee, M. Holtzapple, and M. Ladisch (2005). Features of promising technologies for pretreatment of lignocellulosic biomass. *Bioresource Technology*, **96**(6), pp. 673-686.

Mozaffarian, H., R.W.R. Zwart, H. Boerrigeter, and E.P. Deurwaarder (2004). Biomass and waste-related SNG production technologies; technical, economic and ecological feasibility. In: *2nd World Conference and Technology Exhibition on Biomass for Energy, Industry and Climate Protection*, Rome, Italy, 10-14 May 2004. Available at: www.biosng.com/fileadmin/biosng/user/documents/reports/rx04024.pdf.

Mukunda, H.S., S. Dasappa, P.J. Paul, N.K.S. Rajan, M. Yagnaraman, D.R. Kumar, and M. Deogaonkar (2010). Gasifier stoves - science, technology and field outreach. *Current Science (Bangalore)*, **98**(5), pp. 627-638.

Müller, C. (2007). *Anaerobic Digestion of Biodegradable Solid Waste in Low- and Middle-Income Countries - Overview Over Existing Technologies and Relevant Case Studies.* Eawag Aquatic Research, Dübendorf, Switzerland, 63 pp.

Myles, R. (2001). Implementation of Household Biogas Plant by NGOs in India-Practical Experience in Implementation Household Biogas Technology, Lessons Learned, Key Issues and Future Approach for Sustainable Village Development. In: *VODO International Conference on Globalisation and Sustainable Development*, Antwerp, Brussels, 19-21 Nov 2001, 19 pp. Available at: www.inseda.org/Additional%20material/Lessons%20learnt%20NGOs%20Biogas%20programme.pdf.

Nabuurs, G.-J., A. Pussinen, T. Karjalainen, M. Erhard, and K. Kramer (2002). Stemwood volume increment changes in European forests due to climate change—a simulation study with the EFISCEN model. *Global Change Biology*, **8**(4), pp. 304-316.

Nabuurs, G.J., O. Masera, K. Andrasko, P. Benitez-Ponce, R. Boer, M. Dutschke, E. Elsiddig, J. Ford-Robertson, P. Frumhoff, T. Karjalainen, O. Krankina, W.A. Kurz, M. Matsumoto, W. Oyhantcabal, N.H. Ravindranath, M.Z. Sanz Sanchez, and X. Zhang (2007). Forestry. In: *Climate Change 2007: Mitigation of Climate Change. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, and L.A. Meyer (eds.), Cambridge University Press, pp. 541-584.

Nagatomi, Y., Y. Hiromi, Y. Kenji, I. Hiroshi, and Y. Koichi (2008). A system analysis of energy utilization and competing technology using oil palm residue in Malaysia. *Journal of Japan Society of Energy and Resources*, **29**(5), pp. 1-7.

Narayanan, D., Y. Zhang, and M.S. Mannan (2007). Engineering for Sustainable Development (ESD) in bio-diesel production. *Process Safety and Environmental Protection*, **85**(5), pp. 349-359.

Näslund-Eriksson, L., and L. Gustavsson (2008). Biofuels from stumps and small roundwood – Costs and CO_2 benefits. *Biomass and Bioenergy*, **32**(10), pp. 897-902.

Nassar, A., L. Harfurch, M.M.R. Moreira, L.C. Bachion, L.B. Antoniazzi, and G. Sparovek (2009). *Impacts on Land Use and GHG Emissions from a Shock on Brazilian Sugarcane Ethanol Exports to the United States using the Brazilian Land Use Model (BLUM).* EPA HQ OAR 2005 0161, Institute for International Negotiations, Geneva, Switzerland, 32 pp.

Nassar, A., L.B. Antoniazzi, M.R. Moreira, L. Chiodi, and L. Harfurch (2010). *An Allocation Methodology to Assess GHG Emissions Associated with Land Use Change.* Institute for International Negotiations, Geneva, Switzerland, 31 pp.

NRC (2008). *Water Implications of Biofuels Production in the United States.* National Research Council, The National Academies Press, Washington, DC, USA, 88 pp.

NRC (2009a). *Liquid Transportation Fuels from Coal and Biomass Technological Status, Costs, and Environmental Impacts.* National Research Council, National Academies Press, Washington, DC, USA, 50 pp.

NRC (2009b). *America's Energy Future: Electricity from Renewable Resources: Status, Prospects, and Impediments.* National Research Council, The National Academies Press, Washington, DC, 367 pp.

NRC (2010). *Impact of Genetically Engineered Crops on Farm Sustainability in the United States, 2010.* Committee on the Impact of Biotechnology on Farm-Level Economics and Sustainability; National Research Council, Washington, DC, USA, 35 pp.

Nehlsen, J., M. Mukherjee, and R.V. Porcelli (2007). Apply an integrated approach to catalytic process design. *Chemical Engineering Progress*, **103**(2), pp. 31-41.

Nelson, D.E., P.P. Repetti, T.R. Adams, R.A. Creelman, J. Wu, D.C. Warner, D.C. Anstrom, R.J. Bensen, P.P. Castiglioni, M.G. Donnarummo, B.S. Hinchey, R.W. Kumimoto, D.R. Maszle, R.D. Canales, K.A. Krolikowski, S.B. Dotson, N. Gutterson, O.J. Ratcliffe, and J.E. Heard (2007). Plant nuclear factor Y (NF-Y) B subunits confer drought tolerance and lead to improved corn yields on water-limited acres. *Proceedings of the National Academy of Sciences*, **104**(42), pp. 16450-16455.

NETL (2008). *Development of Baseline Data and Analysis of Life Cycle Greenhouse Gas Emissions of Petroleum-Based Fuels.* DOE/NETL-2009/1362, National Energy Technology Laboratory, Pittsburgh, PA, USA.

NETL (2009a). *An Evaluation of the Extraction, Transport and Refining of Imported Crude Oils and the Impact on Life Cycle Greenhouse Gas Emissions.* DOE/NETL-2009/1362, National Energy Technology Laboratory, Pittsburgh, PA, USA.

NETL (2009b). *Affordable, Low Carbon Diesel Fuel from Domestic Coal and Biomass.* DOE/NETL-2009/1349, National Energy Technology Laboratory, Pittsburgh, PA, USA.

Neumann, K., P.H. Verburg, E. Stehfest, and C. Müller (2010). The yield gap of global grain production: A spatial analysis. *Agricultural Systems*, **103**(5), pp. 316-326.

Nguyen, T.L.T., and S.H. Gheewala (2008). Life cycle assessment of fuel ethanol from Cassava in Thailand. *International Journal of Life Cycle Assessment*, **13**(2), pp. 147-154.

Nishi, T., M. Konishi, and S. Hasebe (2005). An autonomous decentralized supply chain planning system for multi-stage production processes. *Journal of Intelligent Manufacturing*, **16**(3), pp. 259-275.

Nohrstedt, H.O. (2001). Response of coniferous forest ecosystems on mineral soils to nutrient additions: A review of Swedish experiences. *Scandinavian Journal of Forest Research*, **16**(6), pp. 555-573.

Nusser, M., B. Hüsing, and S. Wydra (2007). *Potenzialanalyse der Industriellen, Weißen Biotechnologie, Karlsruhe.* Fraunhofer-Institut für System- und Innovationsforschung, Karlsruhe, Germany, 426 pp.

O'Hare, M., R.J. Plevin, J.I. Martin, A.D. Jones, A. Kendall, and E. Hopson (2009). Proper accounting for time increases crop-based biofuels' greenhouse gas deficit versus petroleum. *Environmental Research Letters*, **4**(2), 024001 (7 pp.).

OANDA (2011). *Historical Exchange Rates.* Oanda Corporation, New York, NY, USA. Available at: www.oanda.com/currency/historical-rates/.

Obernberger, I., and G. Thek (2004). *Techno-economic evaluation of selected decentralised CHP applications based on biomass combustion in IEA partner countries.* BIOS Bioenergiesysteme GmbH, Graz, Austria, 87 pp.

Obernberger, I., G. Thek, and D. Reiter (2008). *Economic evaluation of decentralised CHP applications based on biomass combustion and biomass gasification.* BIOS Bioenergiesysteme GmbH, Graz, Austria, 19 pp.

Obersteiner, M., K. Mollersten, J. Moreira, S. Nilsson, P. Read, K. Riahi, B. Schlamadinger, Y. Yamagata, J. Yan, J.P. Ypserle, C. Azar, and P. Kauppi (2001). Managing climate risk. *Science*, **294**(5543), pp. 786-787.

OECD-FAO (2008). *Agricultural Outlook 2008-2017.* Organisation for Economic Cooperation and Development and Food and Agriculture Organization, Paris, France, 73 pp.

Okada, M., C. Lanzatella, M.C. Saha, J. Bouton, R. Wu, and C.M. Tobias (2010). Complete switchgrass genetic maps reveal subgenome collinearity, preferential pairing and multilocus interactions. *Genetics*, **185**(3), pp. 745-760.

Oliveira, F.C.R. (2009). *Ocupação, emprego e remuneração na cana-de-açúcar e em outras atividades agropecuárias no Brasil, de 1992 a 2007.* Master's Thesis, Universidade de São Paulo, São Paulo, Brazil, 168 pp.

Oliver, R.J., J.W. Finch, and G. Taylor (2009). Second generation bioenergy crops and climate change: a review of the effects of elevated atmospheric CO_2 and drought on water use and the implications for yield. *Global Change Biology Bioenergy*, **1**(2), pp. 97-114.

Oliverio, J.L. (2006). Technological evolution of the Brazilian sugar and alcohol sector: Dedini's contribution. *International Sugar Journal*, **108**(1287), pp. 120-129.

Oliverio, J.L., and J.E. Ribeiro (2006). Cogeneration in Brazilian sugar and bioethanol mills: Past, present and challenges. *International Sugar Journal*, **108**(191), pp. 391-401.

Openshaw, K. (2000). A review of Jatropha curcas: an oil plant of unfulfilled promise. *Biomass and Bioenergy*, **19**(1), pp. 1-15.

Pacca, S., and J.R. Moreira (2009). Historical carbon budget of the Brazilian ethanol program. *Energy Policy*, **37**(11), pp. 4863-4873.

Patel, M.K., M. Crank, V. Dornburg, B. Hermann, L. Roes, B. Hüsing, L. van Overbeek, F. Terragni, and E. Recchia (2006). *Medium and Long-Term Opportunities and Risks of the Biotechnological Production of Bulk Chemicals from Renewable Resources.* Copernicus Institute for Sustainable Development and Innovation, Utrecht, The Netherlands, 420 pp.

Paustian, K., J.M. Antle, J. Sheehan, and A.P. Eldor (2006). *Agriculture's Role in Greenhouse Gas Mitigation.* Pew Center on Global Climate Change, Arlington, VA, USA.

Peksa-Blanchard, M., P. Dolzan, A. Grassi, J. Heinimö, M. Junginger, T. Ranta, and A. Walter (2007). *Global Wood Pellets Markets and Industry: Policy Drivers, Market Status and Raw Material Potential.* IEA Bioenergy Task 40 Publication, 120 pp. Available at: www.canbio.ca/documents/publications/ieatask40pelletandrawmaterialstudynov2007final.pdf.

Perlack, R.D., L.L. Wright, A.F. Turhollow, R.L. Graham, B.J. Stokes, and D.C. Erbach (2005). *Biomass as Feedstock for a Bioenergy and Bioproducts Industry: The Technical Feasibility of a Billion-Ton Annual Supply.* ORNL/TM-2005/66, Oak Ridge National Laboratory, Oak Ridge, TN, USA, 78 pp.

Perry, J.A. (2009). Catastrophic incident prevention and proactive risk management in the new biofuels industry. *Environmental Progress & Sustainable Energy*, **28**(1), pp. 72-82.

Persson, U.M., and C. Azar (2010). Preserving the world's tropical forests – A price on carbon may not do. *Environmental Science & Technology*, **44**(1), pp. 210-215.

Petersson, A. and A. Wellinger (2009). *Biogas Upgrading Technologies – Developments and Innovations.* IEA Bioenergy Task 37 publication, Malmo, Sweden, 20 pp. Available at: www.biogasmax.com/media/iea_2biogas_upgrading_tech__025919000_1434_30032010.pdf.

Phillips, S., A. Aden, J. Jechura, D. Dayton, and T. Eggeman (2007). *Thermochemical Ethanol via Indirect Gasification and Mixed Alcohol Synthesis of Lignocellulosic Biomass.* NREL/TP-510-41168, National Renewable Energy Laboratory, Golden, CO, USA, 132 pp.

Pimentel, D., S. McNair, J. Janecka, J. Wightman, C. Simmonds, C. O'Connell, E. Wong, L. Russel, J. Zern, T. Aquino, and T. Tsomondo (2001). Economic and environmental threats of alien plant, animal, and microbe invasions. *Agriculture, Ecosystems & Environment*, **84**(1), pp. 1-20.

Pimentel, D., P. Hepperly, J. Hanson, D. Douds, and R. Seidel (2005). Environmental, energetic, and economic comparisons of organic and conventional farming systems. *BioScience*, **55**(7), pp. 573-582.

Pingali, P.L., and P.W. Heisey (1999). *Cereal Crop Productivity in Developing Counties: Past Trends and Future Prospects.* Working Paper 99-03, International Maize and Wheat Improvement Center, Texcoco, Mexico, 34 pp.

Plevin, R.J. (2009). Modeling corn ethanol and climate. *Journal of Industrial Ecology*, **13**(4), pp. 495-507.

Plevin, R.J., O.H. Michael, A.D. Jones, M.S. Torn, and H.K. Gibbs (2010). Greenhouse gas emissions from biofuels indirect land use change are uncertain but may be much greater than previously estimated. *Environmental Science & Technology*, **44**(21), pp. 8015-8021.

Practical Action Consulting (2009). *Small Scale Bioenergy can Benefit Poor: Brief Description and Preliminary Lessons on Livelihood Impacts from Case Studies in Asia, Latin America and Africa.* Food and Agriculture Organization and Policy Innovation Systems for Clean Energy Security, Rome, Italy, 142 pp.

Purdon, M., S. Bailey-Stamler, and R. Samson (2009). Better bioenergy: Rather than picking bioenergy "winners," effective policy should let a lifecycle analysis decide. *Alternatives Journal*, **35**(2), pp. 23-29.

Rabaey, K., and W. Verstraete (2005). Microbial fuel cells: novel biotechnology for energy generation. *Trends in Biotechnology*, **23**(6), pp. 291-298.

Ragauskas, A.J., C.K. Williams, B.H. Davison, G. Britovsek, J. Cairney, C.A. Eckert, W.J. Frederick, Jr., J.P. Hallett, D.J. Leak, C.L. Liotta, J.R. Mielenz, R. Murphy, R. Templer, and T. Tschaplinski (2006). The path forward for biofuels and biomaterials. *Science*, **311**(5760), pp. 484-489.

Raghu, S., R.C. Anderson, C.C. Daehler, A.S. Davis, R.N. Wiedenmann, D. Simberloff, and R.N. Mack (2006). Adding biofuels to the invasive species fire? *Science*, **313**(5794), pp. 1742.

Rajagopal, D., G. Hochman, and D. Zilberman (2011). Indirect fuel use change (IFUC) and the lifecycle environmental impact of biofuel policies. *Energy Policy*, **39**(1), pp. 228-233.

Ramanathan, V., and G. Carmichael (2008). Global and regional climate changes due to black carbon. *Nature Geoscience*, **1**(4), pp. 221-227.

Randall, J.M. (1996). Plant Invaders: How Non-native Species Invade & Degrade Natural Areas Invasive Plants. In: *Weeds of the Global Garden.* J. Marinelli and J.M. Randall (eds.), Brooklyn Botanic Garden, Brooklyn, NY, pp. 7-12.

Ranius, T., and L. Fahrig (2006). Targets for maintenance of dead wood for biodiversity conservation based on extinction thresholds. *Scandinavian Journal of Forest Research*, **21**(3), pp. 201-208.

Rauch, R. (2010). *Indirect Gasification. In: IEA Bioenergy Joint Tasks 32 &33 Workshop, State-of-the-Art Technologies for Small Biomass Co-generation*, International Energy Agency, Copenhagen, Denmark, 7 Oct 2010. Available at: www.ieabcc.nl/meetings/task32_Copenhagen/09%20TU%20Vienna.pdf.

Ravindranath, N.H., P. Balachandra, S. Dasappa, and K. Usha Rao (2006). Bioenergy technologies for carbon abatement. *Biomass and Bioenergy*, **30**(10), pp. 826-837.

Regalbuto, J.R. (2009). Cellulosic biofuels – got gasoline? *Science*, **325**(5942), pp. 822-824.

Reijnders, L. (2008). Ethanol production from crop residues and soil organic carbon. *Resources, Conservation and Recycling*, **52**(4), pp. 653-658.

Reinhardt, G. (1991). *Biofuels: Energy and GHG balances: Methodology and Case Study Rape Seed Biodiesel.* Institut für Energie- und Umweltforschung Heidelberg, Heidelberg, Germany.

Reinhardt, G., S. Gartner, A. Patyk, and N. Rettenmaier (2006). *Ökobilanzen zu BTL: Eine ökologische Einschätzung.* 2207104, ifeu Institut für Energie- und Umweltforschung Heidelberg gGmbH, Heidelberg, Germany, 108 pp.

REN21 (2007). *Global Status Report.* Renewable Energy Policy Network for the 21st Century Secretariat, Paris, France, 54 pp.

REN21 (2009). *Renewables Global Status Report: 2009 Update.* Renewable Energy Policy Network for the 21st Century Secretariat, Paris, France, 42 pp.

Rendleman, C.M., and H. Shapouri (2007). *New Technologies in Ethanol Production.* Report Number 842, United States Department of Agriculture, Washington, DC, USA.

RFA (2010). *U.S. Cellulosic.* Renewable Fuels Association, Washington, DC, USA. Available at: www.ethanolrfa.org/pages/cellulosic-ethanol

RFA (2011). *Biorefinery Plant Locations.* Renewable Fuels Association, Washington, DC, USA. Available at: www.ethanolrfa.org/bio-refinery-locations/.

Rentizelas, A.A., A.J. Tolis, and I.P. Tatsiopoulos (2009). Logistics issues of biomass: The storage problem and the multi-biomass supply chain. *Renewable and Sustainable Energy Reviews*, **13**(4), pp. 887-894.

Reynolds, M.P., and N.E. Borlaug (2006). Applying innovations and new technologies for international collaborative wheat improvement. *The Journal of Agricultural Science*, **144**(02), pp. 95-95.

Rhodes, J.S., and D.W. Keith (2008). Biomass with capture: negative emissions within social and environmental constraints: an editorial comment. *Climatic Change*, **87**(3-4), pp. 321-328.

Righelato, R., and D.V. Spracklen (2007). Carbon mitigation by biofuels or by saving and restoring forests? *Science*, **317**(5840), pp. 902.

Ringer, M., V. Putsche, and J. Scahill (2006). *Large-Scale Pyrolysis Oil Production: A Technology Assessment and Economic Analysis.* TP-510-37779, National Renewable Energy Laboratory, Golden, CO, USA, 93 pp.

Riviére, C., and G. Marlair (2009). BIOSAFUEL®, a pre-diagnosis tool of risks pertaining to biofuels chains. *Journal of Loss Prevention in the Process Industries*, **22**(2), pp. 228-236.

Riviére, C., and G. Marlair (2010). The use of multiple correspondence analysis and hierarchical clustering to identify incident typologies pertaining to the biofuel industry. *Biofuels, Bioproducts and Biorefining*, **4**(1), pp. 53-65.

Robertson, G.P., V.H. Dale, O.C. Doering, S.P. Hamburg, J.M. Melillo, M.M. Wander, W.J. Parton, P.R. Adler, J.N. Barney, R.M. Cruse, C.S. Duke, P.M. Fearnside, R.F. Follett, H.K. Gibbs, J. Goldemberg, D.J. Mladenoff, D. Ojima, M.W. Palmer, A. Sharpley, L. Wallace, K.C. Weathers, J.A. Wiens, and W.W. Wilhelm (2008). Sustainable biofuels redux. *Science*, **322**(5898), pp. 49-50.

Rockström, J., M. Lannerstad, and M. Falkenmark (2007). Assessing the water challenge of a new green revolution in developing countries. *Proceedings of the National Academy of Sciences*, **104**(15), pp. 6253-6260.

Rockström, J., L. Karlberg, S.P. Wani, J. Barron, N. Hatibu, T. Oweis, A. Bruggeman, J. Farahani, and Z. Qiang (2010). Managing water in rainfed agriculture – The need for a paradigm shift. *Agricultural Water Management*, **97**(4), pp. 543-550.

Romieu, I., H. Riojas-Rodriguez, A.T. Marron-Mares, A. Schilmann, R. Perez-Padilla, and O. Masera (2009). Improved biomass stove intervention in rural Mexico: Impact on the respiratory health of women. *American Journal of Respiratory and Critical Care Medicine*, **180**(7), pp. 649-656.

Rosegrant, M.W., T. Zhu, S. Msangi, and T. Sulser (2008). Biofuels: Long-run implications for food security and the environment. *Review of Agricultural Economics*, **30**(3), pp. 495-505.

Rosillo-Calle, F., S.V. Bajay, and H. Rothman (eds.) (2000). *Industrial Uses of Biomass Energy: The Example of Brazil.* Taylor & Francis, London, UK.

Ross, A.B., K. Anastasakis, M. Kubacki, and J.M. Jones (2009). Investigation of the pyrolysis behaviour of brown algae before and after pre-treatment using PY-GC/MS and TGA. *Journal of Analytical and Applied Pyrolysis*, **85**(1-2), pp. 3-10.

Rost, S., D. Gerten, H. Hoff, W. Lucht, M. Falkenmark, and J. Rockstrom (2009). Global potential to increase crop production through water management in rainfed agriculture. *Environmental Research Letters*, **4**(4), 044002 (9 pp.).

Rowe, R., J. Whitaker, J. Chapman, D. Howard, and G. Talor (2008). *Life-Cycle Assessment in Bioenergy Sector: Developing a Systematic Review Working Paper.* UKERC/WP/FSE/2008/002, UK Energy Research Centre, London, UK, 20 pp.

Royal Society (2008). *Sustainable Biofuels: Prospects and Challenges.* Policy document 01/08,The Royal Society, London, UK, 90 pp.

Rude, M.A., and A. Schirmer (2009). New microbial fuels: a biotech perspective. *Current Opinion in Microbiology*, **12**(3), pp. 274-281.

$(S\&T)^2$ Consultants (2009). *An Examination of the Potential for Improving Carbon/Energy Balance of Bioethanol.* T39-TR1, $(S\&T)^2$ Consultants Inc., Delta, Canada, 72 pp.

Saarinen, V.-M. (2006). The effects of slash and stump removal on productivity and quality of forest regeneration operations – preliminary results. *Biomass and Bioenergy*, **30**(4), pp. 349-356.

Saarsalmi, A., and E. Mälkönen (2001). Forest fertilization research in Finland: A literature review. *Scandinavian Journal of Forest Research*, **16**(6), pp. 514-535.

Sala, O.E., A. Kinzig, R. Leemans, D.M. Lodge, H.A. Mooney, M. Oesterheld, N.L. Poff, M.T. Sykes, B.H. Walker, M. Walker, D.H. Wall, F.S. Chapin, J.J. Armesto, E. Berlow, J. Bloomfield, R. Dirzo, E. Huber-Sanwald, L.F. Huenneke, and R.B. Jackson (2000). Global biodiversity scenarios for the year 2100. *Science*, **287**(5459), pp. 1770-1774.

Sánchez, Ó.J., and C.A. Cardona (2008). Trends in biotechnological production of fuel ethanol from different feedstocks. *Bioresource Technology*, **99**(13), pp. 5270-5295.

Sannigrahi, P., A.J. Ragauskas, and G.A. Tuskan (2010). Poplar as a feedstock for biofuels: A review of compositional characteristics. *Biofuels, Bioproducts and Biorefining*, **4**(2), pp. 209-226.

Sawin, J.L. (2004). *National Policy Instruments: Policy Lessons for the Advancement and Diffusion of Renewable Energy Technologies around the World.* World Watch Institute, Washington, DC, USA.

SCBD (2006). *Global Biodiversity Outlook 2.* Secretariat of the Convention on Biological Diversity, Montreal, Canada, 92 pp. (ISBN-92-9225-040-X).

Schei, M.A., J.O. Hessen, K.R. Smith, N. Bruce, J. McCracken, and V. Lopez (2004). Childhood asthma and indoor woodsmoke from cooking in Guatemala. *Journal of Exposure Analysis and Environmental Epidemiology*, **14**, pp. S110-S117.

Schlamadinger, B., F. Bohlin, L. Gustavsson, G. Jungmeier, G. Marlandii, K. Pingoudt, and I. Savolaine (1997). Towards a standard methodology for greenhouse gas balances of bioenergy systems in comparison with fossil energy systems. *Biomass and Bioenergy*, **13**(6), pp. 359-375.

Schlamadinger, B., M. Grubb, C. Azar, A. Bauen, and G. Berndes (2001). Carbon sinks and the CDM: could a bioenergy linkage offer a constructive compromise? *Climate Policy*, **1**, pp. 411-417.

Schlamadinger, B., B. Bosquet, C. Streck, I. Noble, M. Dutschke, and N. Bird (2005). Can the EU emission trading scheme support CDM forestry. *Climate Policy*, **5**, pp. 199-208.

Schmidhuber, J. (2008). Impact of an increased biomass use on agricultural markets, prices and food security: A longer-term perspective. In: *Energy Security in Europe: Proceedings from the Conference 'Energy Security in Europe'*, Lund, Sweden, 24-25 September 2007, Lund University, Lund, Sweden, pp. 133-170. Available at: www.cfe.lu.se/upload/LUPDF/CentrumforEuropaforskning/Confpap2.pdf.

Schneider, U.E., B. A. McCarl, and E. Schmid (2007). Agricultural sector analysis on greenhouse gas mitigation in US agriculture and forestry. *Agricultural Systems*, **94** (2), pp. 128-140

Schouten, J.C., E.V. Rebrov, and M.H.J.M. de Croon (2002). Miniaturization of heterogeneous catalytic reactors: prospects for new developments in catalysis and process engineering. *CHIMIA International Journal for Chemistry*, **56**(11), pp. 627-635.

Schulz, U., O. Brauner, and H. Gruss (2009). Animal diversity on short-rotation coppices – a review. *Landbauforschung vTI Agriculture and Forestry Research 3*, **59**(3), pp. 171-182.

Schwaiger, H.P., and D.N. Bird (2010). Integration of albedo effects caused by land use change into the climate balance: Should we still account in greenhouse gas units? *Forest Ecology and Management*, **260**(3), pp. 278-286.

Schwilch, G., F. Bachmann, and H. Liniger (2009). Appraising and selecting conservation measures to mitigate desertification and land degradation based on stakeholder participation and global best practices. *Land Degradation & Development*, **20**(3), pp. 308-326.

Scolforo, J.R. (2008). *Mundo Eucalipto – Os Fatos E Mitos De Sua Cultura.* Editora Mar de Ideias, Rio de Janeiro, Brazil, 72 pp.

Seabra, J.E.A., L. Tao, H.L. Chum, and I.C. Macedo (2010). A techno-economic evaluation of the effects of centralized cellulosic ethanol and co-products refinery options with sugarcane mill clustering. *Biomass and Bioenergy*, **34**(8), pp. 1065-1078.

Searchinger, T., R. Heimlich, R.A. Houghton, F. Dong, A. Elobeid, J. Fabiosa, S. Tokgoz, D. Hayes, and T.H. Yu (2008). Use of U.S. croplands for biofuels increases greenhouse gases through emissions from land-use change. *Science*, **319**, pp. 1238-1240.

Seidenberger, T., D. Thran, R. Offermann, U. Seyfert, M. Buchhorn, and J. Zeddies (2008). *Global Biomass Potentials.* Report prepared for Greenpeace International by the German Biomass Research Center, Leipzig, Germany, 137 pp.

Semere, T., and F. Slater (2007). Ground flora, small mammal and bird species diversity in miscanthus (*Miscanthus×giganteus*) and reed canary-grass (*Phalaris arundinacea*) fields. *Biomass and Bioenergy*, **31**(1), pp. 20-29.

Sepp, S. (2008). *Analysis of Charcoal Value Chains – General Considerations.* GTZ Household Energy Programme, Eschborn, Germany, 11 pp.

Shah, S. (2007). Modular mini-plants: A new paradigm. *Chemical Engineering Progress*, **103**(3), pp. 36-41.

Shapouri, H., and M. Salassi (2006). *The Economic Feasibility of Ethanol Production in the United States.* United States Department of Agriculture, Washington, DC, USA, 69 pp.

Sharma, M.M. (2002). Strategies of conducting reactions on a small scale. Selectivity engineering and process intensification. *Pure and Applied Chemistry*, **74**(12), pp. 2265-2269.

Sheehan, J., T. Dunahay, J. Benemann, G. Roessler, and C. Weissman (1998a). *A Look Back at the U.S. Department of Energy's Aquatic Species Program: Biodiesel from Algae.* NREL/TP-580-24190, National Renewable Energy Laboratory, Golden, CO, USA, 295 pp.

Sheehan, J., V. Camobreco, J. Duffield, M. Graboski, and H. Shapouri (1998b). *Life Cycle Inventory of Biodiesel and Petroleum Diesel for Use in an Urban Bus.* NREL/SR-580-24089, National Renewable Energy Laboratory, Golden, CO, USA, 314 pp.

Sheehan, J., A. Aden, K. Paustian, K. Killian, J. Brenner, M. Walsh, and R. Nelson (2003). Energy and environmental aspects of using corn stover for fuel ethanol. *Journal of Industrial Ecology*, **7**(3-4), pp. 117-146.

Shen, L., J. Haufe, and M.K. Patel (2009). *Product Overview and Market Projection of Emerging Bio-based Plastics: PRO-BIP 2009.* Copernicus Institute for Sustainable Development and Innovation for the European Polysaccharide Network of Excellence (EPNOE) and European Bioplastics, Utrecht University, Utrecht, The Netherlands, 78 pp.

Sikkema, R., M. Junginger, W. Pichler, S. Hayes, and A.P.C. Faaij (2010). The international logistics of wood pellets for heating and power production in Europe: Costs, energy-input and greenhouse gas balances of pellet consumption in Italy, Sweden and the Netherlands. *Biofuels, Bioproducts and Biorefining*, **4**(2), pp. 132-153.

Sikkema, R., M. Steiner, M. Junginger, W. Hiegl, M.T. Hansen, and A. Faaij (2011). The European wood pellet markets: current status and prospects for 2020. *Biofuels, Bioproducts and Biorefining*, doi:10.1002/bbb.277.

Simpson, T.W., A.N. Sharpley, R.W. Howarth, H.W. Paerl, and K.R. Mankin (2008). The new gold rush: Fueling ethanol production while protecting water quality. *Journal of Environmental Quality*, **37**(2), pp. 318-324.

Simpson, T.W., L.A. Martinelli, A.N. Sharpley, R.W. Howarth, and S. Bringezu (2009). Impact of ethanol production on nutrient cycles and water quality: the United States and Brazil as case studies. In: *Biofuels: Environmental Consequences and Interactions with Changing Land Use.* R.W. Howarth and S. Bringezu (eds.), Proceedings of the SCOPE - Scientific Committee on Problems of the Environment International Biofuels Project Rapid Assessment, Gummersbach, Germany, 22-25 September 2009,, pp. 153-167.

Sims, R. (ed.) (2007). *Renewables for Heating and Cooling. An Untapped Potential.* Joint report for the Renewable Energy Technology Deployment Implementing Agreement and the Renewable Energy Working Party published by the International Energy Agency, Paris, France, 210 pp.

Sims, R., M. Taylor, J. Saddler, W. Mabee, and J. Riese (2008). *From 1st-to 2nd Generation Biofuel Technologies. An overview of current industry and R&D activities.* IEA Bioenergy, Paris, France, 124 pp.

Sims, R.E.H., W. Mabee, J.N. Saddler, and M. Taylor (2010). An overview of second generation biofuel technologies. *Bioresource Technology*, **101**(6), pp. 1570-1580.

Skjoldborg, B. (2010). Optimization of I/S Skive District Heating Plant. In: IEA Joint Task 32 & 33 Workshop, *State-of-the-Art Technologies for Small Biomass Co-generation*, International Energy Agency, Copenhagen, Denmark, 7 Oct 2010. Available at: www.ieabcc.nl/meetings/task32_Copenhagen/11%20Skive.pdf.

Smeets, E.M.W., and A.P.C. Faaij (2007). Bioenergy potentials from forestry in 2050. *Climatic Change*, **81**(3-4), pp. 353-390.

Smeets, E.M.W., A. Faaij, I. Lewandowski, and W. Turkenburg (2007). A bottom-up assessment and review of global bio-energy potentials to 2050. *Progress in Energy and Combustion Science*, **33**(1), pp. 56-106.

Smeets, E.M.W., L.F. Bouwman, E. Stehfest, D.P. van Vuuren, and A. Posthuma (2009). Contribution of N_2O to the greenhouse gas balance of first-generation biofuels. *Global Change Biology*, **15**(1), pp. 1-23.

Smil, V. (2002). Worldwide transformation of diets, burdens of meat production and opportunities for novel food proteins. *Enzyme and Microbial Technology*, **30**(3), pp. 305-311.

Smith, K.R., and E. Haigler (2008). Co-benefits of climate mitigation and health protection in energy systems: Scoping methods. *Annual Review of Public Health*, **29**(1), pp. 11-25.

Smith, K.R., R. Uma, V.V.N. Kishore, J. Zhang, V. Joshi, and M.A.K. Khalil (2000). Greenhouse implications of household stoves: An analysis for India. *Annual Review of Energy and the Environment*, **25**(1), pp. 741-763.

Soimakallio, S., R. Antikainen, and R. Thun (2009a). *Assessing the Sustainability of Liquid Biofuels from Evolving Technologies.* VTT Research Notes 2482, VTT Technical Research Centre of Finland, Espoo, Finland, 268 pp.

Soimakallio, S., T. Mäkinen, T. Ekholm, K. Pahkala, H. Mikkola, and T. Paappanen (2009b). Greenhouse gas balances of transportation biofuels, electricity and heat generation in Finland – Dealing with the uncertainties. *Energy Policy*, **37**(1), pp. 80-90.

Solomon, S., G.K. Plattner, R. Knutti, and P. Friedlingstein (2009). Irreversible climate change due to carbon dioxide emissions. *Proceedings of the National Academy of Sciences*, **106**(6), pp. 1704-1709.

Sparovek, G., G. Berndes, A. Egeskog, F.L.M. de Freitas, S. Gustafsson, and J. Hansson (2007). Sugarcane ethanol production in Brazil: an expansion model sensitive to socioeconomic and environmental concerns. *Biofuels, Bioproducts and Biorefining*, **1**(4), pp. 270-282.

Spatari, S., and H.L. MacLean (2010). Characterizing model uncertainties in the life cycle of lignocellulose-based ethanol fuels. *Environmental Science & Technology*, **44**(22), pp. 8773-8780.

Spranger, T., J.P. Hettelingh, J. Slootweg, and M. Posch (2008). Modelling and mapping long-term risks due to reactive nitrogen effects: An overview of LRTAP convention activities. *Environmental Pollution*, **154**(3), pp. 482-487.

Steenblik, R. (2007). *Subsidies: The Distorted Economics of Biofuels.* Discussion Paper No. 2007-3, International Transport Forum, Organisation for Economic Co-operation and Development, Geneva, Switzerland, 66 pp.

Stehfest, E., and L. Bouwman (2006). N_2O and NO emission from agricultural fields and soils under natural vegetation: summarizing available measurement data and modeling of global annual emissions. *Nutrient Cycling in Agroecosystems*, **74**(3), pp. 207-228.

Stehfest, E., L. Bouwman, D.P. Vuuren, M.G.J. Elzen, B. Eickhout, and P. Kabat (2009). Climate benefits of changing diet. *Climatic Change*, **95**(1-2), pp. 83-102.

Still, D., M. Pinnell, D. Ogle, and B. van Appel (2003). Insulative ceramics for improved cooking stoves. *Boiling Point*, **49**, pp. 7-10.

Stoft, S. (2010). *Renewable Fuel and the Global Rebound Effect.* Research Paper No. 10-06, Global Energy policy Center, Berkeley, CA, USA, 19 pp.

Strengers, B., R. Leemans, B. Eickhout, B. Vries, and L. Bouwman (2004). The land-use projections and resulting emissions in the IPCC SRES scenarios as simulated by the IMAGE 2.2 model. *GeoJournal*, **61**(4), pp. 381-393.

Sulser, T.B., C. Ringler, T. Zhu, S. Msangi, E. Bryan, and M.W. Rosegrant (2010). Green and blue water accounting in the Ganges and Nile basins: Implications for food and agricultural policy. *Journal of Hydrology*, **384**(3-4), pp. 276-291.

Sumner, S.A., and P.M. Layde (2009). Expansion of renewable energy industries and implications for occupational health. *Journal of the American Medical Association*, **302**(7), pp. 787-789.

Sustainable Transport Solutions (2006). *Biogas as a Road Transport Fuel: An Assessment of the Potential Role of Biogas as a Renewable Transport Fuel.* National Society for Clean Air and Environmental Protection, London, UK, 66 pp.

Swanson, R.M., A. Platon, J.A. Satrio, and R.C. Brown (2010). Techno-economic analysis of biomass-to-liquids production based on gasification. *Fuel*, **89**(Supplement 1), pp. S11-S19.

Tabeau, A., B. Eickhout, and H. van Meijl (2006). Endogenous agricultural land supply: estimation and implementation in the GTAP model. In: *Ninth Annual Conference on Global Economic Analysis*, Addis Ababa, Ethiopia, 15-17 June 2006. Available at: https://www.gtap.agecon.purdue.edu/resources/res_display.asp?RecordID=2007.

Tao, L., and A. Aden (2009). The economics of current and future biofuels. *In Vitro Cellular & Developmental Biology - Plant*, **45**(3), pp. 199-217.

Thorn, J., J. Brisman, and K. Toren (2001). Adult-onset asthma is associated with self-reported mold or environmental tobacco smoke exposures in the home. *Allergy*, **56**(4), pp. 287-292.

Thornley, P., J. Rogers, and Y. Huang (2008). Quantification of employment from biomass power plants. *Renewable Energy*, **33**(8), pp. 1922-1927.

Thornley, P., P. Upham, Y. Huang, S. Rezvani, J. Brammer, and J. Rogers (2009). Integrated assessment of bioelectricity technology options. *Energy Policy*, **37**(3), pp. 890-903.

Tilman, D., K.G. Cassman, P.A. Matson, R. Naylor, and S. Polasky (2002). Agricultural sustainability and intensive production practices. *Nature*, **418**(6898), pp. 671-677.

Tilman, D., J. Hill, and C. Lehman (2006a). Carbon-negative biofuels from low-input high-diversity grassland biomass. *Science*, **314**(5805), pp. 1598-1600.

Tilman, D., P.B. Reich, and J.M.H. Knops (2006b). Biodiversity and ecosystem stability in a decade-long grassland experiment. *Nature*, **441**(7093), pp. 629-632.

Titus, B.D., D.G. Maynard, C.C. Dymond, G. Stinson, and W.A. Kurz (2009). Wood energy: Protect local ecosystems. *Science*, **324**(5933), pp. 1389-1390.

Tobias, C.M., G. Sarath, P. Twigg, E. Lindquist, J. Pangilinan, B.W. Penning, K. Barry, M.C. McCann, N.C. Carpita, and G.R. Lazo (2008). Comparative genomics in switchgrass using 61,585 high-quality expressed sequence tags. *The Plant Genome*, **1**(2), pp. 111-124.

Tonkovich, A.Y., S. Perry, Y. Wang, D. Qiu, T. LaPlante, and W.A. Rogers (2004). Microchannel process technology for compact methane steam reforming. *Chemical Engineering Science*, **59**(22-23), pp. 4819-4824.

Towle, D.W., and J.S. Pearse (1973). Production of the giant kelp, Macrocystis, estimated by in situ incorporation of ^{14}C in polyethylene bags. *American Society of Limnology and Oceanography*, **18**(1), pp. 155-159.

Turhollow, A. (1994). The economics of energy crop production. *Biomass and Bioenergy*, **6**(3), pp. 229-241.

Tyner, W.E., and F. Taheripour (2008). Policy options for integrated energy and agricultural markets. *Applied Economic Perspectives and Policy*, **30**(3), pp. 387-396.

Tyner, W., F. Taheripour, Q. Zhuang, D. Birur, and U. Baldos (2010). *Land Use Changes and Consequent CO_2 Emissions due to U.S. Corn Ethanol Production: A Comprehensive Analysis.* GTAP Resource 3288, Department of Agricultural Economics, Purdue University, West Lafayette, IN, USA, 90 pp.

UN-Water (2007). *Coping with Water Scarcity: Challenge of the Twenty-First Century.* Prepared for World Water Day 2007, United Nations, New York, NY, USA, 29 pp.

UNECE/FAO TIMBER Database (2011). Market Presentations at http: timber.unece.org/. United Nations Economic Commission for Europe and Food and Agricultural Organization.

UNEP (2008a). *UNEP Year Book 2008: an Overview of Our Changing Environment.* United Nations Environment Programme, Nairobi, Kenya.

UNEP (2008b). *The Potential Impacts of Biofuels on Biodiversity, Notes by the Executive Secretary.* UNEP/CBD/COP/9/26, United Nations Environment Programme, Bonn, Germany, 16 pp.

UNEP/SEFI/Bloomberg (2010). *Global Trends in Sustainable Energy Investment 2010.* DTI/1186/PA, Sustainable Energy Finance Initiative, United Nations Environment Programme and Bloomberg New Energy Finance, Geneva, Switzerland, 61 pp.

UK DfT (2003). *International Resource Costs of Biodiesel and Bioethanol.* AEAT/ENV/ED50273/R1, United Kingdom Department for Transport, Oxfordshire, UK, 51 pp.

University of Illinois (2011). *farmdoc: Historical Corn Prices.* University of Illinois, Urbana, Illinois, USA. Available at: www.farmdoc.illinois.edu/manage/pricehistory/price_history.htm.

US DOE (2009). *National Algal Biofuels Technology Roadmap.* U.S. Department of Energy Biomass Program, Washington, DC, USA, 214 pp.

US DOE (2011). *Biomass as Feedstock for a Bioenergy and Bioproducts Industry: An Update to the Billion-Ton Annual Supply.* R.D. Perlack and B.J. Stokes (Leads), ORNL/TM-2010/xx. U.S. Department of Energy, Oak Ridge National Laboratory, Oak Ridge, TN, USA, in press.

USDA (2006). *Oil Crops Yearbook/OCS-2006/Mar21.* Economic Research Service, US Department of Agriculture (USDA), Washington, DC, USA.

USDA (2007). *Wheat Data: Yearbook Tables.* Economic Research Service, US Department of Agriculture (USDA), Washington, DC, USA.

Uslu, A., A.P.C. Faaij, and P.C.A. Bergman (2008). Pre-treatment technologies, and their effect on international bioenergy supply chain logistics. Techno-economic evaluation of torrefaction, fast pyrolysis and pelletisation. *Energy*, **33**(8), pp. 1206-1223.

van Dam, J., M. Junginger, A. Faaij, I. Jürgens, G. Best, and U. Fritsche (2008). Overview of recent developments in sustainable biomass certification. *Biomass and Bioenergy*, **32**(8), pp. 749-780.

van Dam, J., A.P.C. Faaij, J. Hilbert, H. Petruzzi, and W.C. Turkenburg (2009a). Large-scale bioenergy production from soybeans and switchgrass in Argentina: Part A: Potential and economic feasibility for national and international markets. *Renewable and Sustainable Energy Reviews*, **13**(8), pp. 1710-1733.

van Dam, J., A.P.C. Faaij, J. Hilbert, H. Petruzzi, and W.C. Turkenburg (2009b). Large-scale bioenergy production from soybeans and switchgrass in Argentina: Part B. Environmental and socio-economic impacts on a regional level. *Renewable and Sustainable Energy Reviews*, **13**(8), pp. 1679-1709.

van Dam, J., A.P.C. Faaij, I. Lewandowski, and B. Van Zeebroeck (2009c). Options of biofuel trade from Central and Eastern to Western European countries. *Biomass and Bioenergy*, **33**(4), pp. 728-744.

van Dam, J., M. Junginger, and A.P.C. Faaij (2010). From the global efforts on certification of bioenergy towards an integrated approach based on sustainable land use planning. *Renewable and Sustainable Energy Reviews*, **14**(9), pp. 2445-2472.

van den Wall Bake, J.D. (2006). *Cane as Key in Brazilian Ethanol Industry.* Master's Thesis, Copernicus Institute, Utrecht University, Utrecht, The Netherlands, 83 pp.

van den Wall Bake, J.D., M. Junginger, A. Faaij, T. Poot, and A. Walter (2009). Explaining the experience curve: Cost reductions of Brazilian ethanol from sugarcane. *Biomass and Bioenergy*, **33**(4), pp. 644-658.

van der Horst, D., and J. Evans (2010). Carbon claims and energy landscapes: Exploring the political ecology of biomass. *Landscape Research*, **35**(2), pp. 173-193.

van Iersel, S., L. Gamba, A. Rossi, S. Alberici, B. Dehue, J. van de Staaij, and A. Flammini (2009). *Algae-Based Biofuels: A Review of Challenges and Opportunities for Developing Countries.* Food and Agriculture Organization, Rome, Italy, 59 pp.

van Loo, S., and J. Koppejan (eds.) (2002). *Handbook of Biomass Combustion and Cofiring.* 1st ed. Twente University Press, Enschede, The Netherlands, 442 pp.

van Minnen, J.G., B.J. Strengers, B. Eickhout, R.J. Swart, and R. Leemans (2008). Quantifying the effectiveness of climate change mitigation through forest plantations and carbon sequestration with an integrated land-use model. *Carbon Balance and Management*, **3**(3), 20 pp.

van Vliet, O.P.R., A.P.C. Faaij, and W.C. Turkenburg (2009). Fischer-Tropsch diesel production in a well-to-wheel perspective: A carbon, energy flow and cost analysis. *Energy Conversion and Management*, **50**(4), pp. 855-876.

van Vuuren, D., M. den Elzen, P. Lucas, B. Eickhout, B. Strengers, B. van Ruijven, S. Wonink, and R. van Houdt (2007). Stabilizing greenhouse gas concentrations at low levels: an assessment of reduction strategies and costs. *Climatic Change*, **81**(2), pp. 119-159.

van Vuuren, D.P., J. van Vliet, and E. Stehfest (2009). Future bio-energy potential under various natural constraints. *Energy Policy*, **37**(11), pp. 4220-4230.

van Vuuren, D.P., E. Bellevrat, A. Kitous, and M. Isaac (2010). Bio-energy use and low stabilization scenarios. *The Energy Journal*, **31**(Special Issue), pp. 192-222.

van Zyl, W., L. Lynd, R. den Haan, and J. McBride (2007). Consolidated bioprocessing for bioethanol production using Saccharomyces cerevisiae. *Advanced Biochemical Engineering Biotechnology*, **108**, pp. 205-235.

Vandermeer, J., and I. Perfecto (2006). Response to comments on "A Keystone Mutualism Drives Pattern in a Power Function". *Science*, **313**(5794), pp. 1739.

Venkataraman, C., A.D. Sagar, G. Habib, N. Lam, and K.R. Smith (2010). The Indian National Initiative for Advanced Biomass Cookstoves: The benefits of clean combustion. *Energy for Sustainable Development*, **14**(2), pp. 63-72.

Venter, O., E. Meijaard, H. Possingham, R. Dennis, D. Sheil, S. Wich, L. Hovani, and K. Wilson (2009). Carbon payments as a safeguard for threatened tropical mammals. *Conservation Letters*, **2**(3), pp. 123-129.

Verhaeven, E., L. Pelkmans, L. Govaerts, R. Lamers, and F. Theunissen (2005). Results of demonstration and evaluation projects of biodiesel from rapeseed and used frying oil on light and heavy duty vehicles. In: *2005 SAE Brasil Fuels & Lubricants Meeting.* SAE International, Rio De Janeiro, Brasil, May 2005, 7 pp., doi:10.4271/2005-01-2201.

Vinnerås, B., C. Schönning, and A. Nordin (2006). Identification of the microbiological community in biogas systems and evaluation of microbial risks from gas usage. *Science of the Total Environment*, **367**(2-3), pp. 606-615.

von Blottnitz, H., and M.A. Curran (2007). A review of assessments conducted on bio-ethanol as a transportation fuel from a net energy, greenhouse gas, and environmental life cycle perspective. *Journal of Cleaner Production*, **15**(7), pp. 607-619.

von Geibler, J., C. Liedtke, H. Wallbaum, and S. Schaller (2006). Accounting for the social dimension of sustainability: experiences from the biotechnology industry. *Business Strategy and the Environment*, **15**(5), pp. 334-346.

von Schirnding, Y., N. Bruce, K. Smith, G. Ballard-Treemer, M. Ezzati, and K. Lvovsky (2001). *Addressing the Impact of Household Energy and Indoor Air Pollution on the Health of the Poor - Implications for Policy Action and Intervention Measures.* WHO/HDE/HID/02.9, Commission on Macroeconomics and Health, World Health Organization, Geneva, Switzerland, 52 pp.

von Weyman, N. (2007). *Bioetanolia maatalouden selluloosavirroista (Bioethanol from agricultural lignocellulosic residues).* VTT Tiedotteita 2412, VTT Technical Research Centre of Finland, Espoo, Finland, 48 pp.

Walmsley, J.D., and D.L. Godbold (2010). Stump harvesting for bioenergy - A review of the environmental impacts. *Forestry*, **83**(1), pp. 17-38.

Walsh, M.E. (2008). *U.S. Cellulosic Biomass Feedstock Supplies and Distribution.* Ag Econ Search - Research in Agricultural and Applied Economics, University of Minnesota, St. Paul, Minnesota, 47 pp. Available at: ageconsearch.umn.edu/bitstream/7625/2/U.S.%20Biomass%20Supplies.pdf.

Walter, A., F. Rosillo-Calle, P. Dolzan, E. Piacente, and K. Borges da Cunha (2008). Perspectives on fuel ethanol consumption and trade. *Biomass and Bioenergy*, **32**(8), pp. 730-748.

Wang, M., C. Saricks, and D. Santini (1999). *Effects of fuel ethanol use on fuel-cycle energy and greenhouse gas emissions.* ANL/ESD-38, Argonne Energy Systems Division, Argonne National Laboratory, Argonne, IL, USA, 39 pp.

Wang, M., M. Wu, and H. Huo (2007). Life-cycle energy and greenhouse gas emission impacts of different corn ethanol plant types. *Environmental Research Letters*, **2**(2), 024001.

Wang, M., H. Huo, and S. Arora (2010). Methods of dealing with co-products of biofuels in life-cycle 3 analysis and consequent results within the U.S. context. *Energy Policy*, in press, doi:10.1016/j.enpol.2010.03.052.

Wang, M.Q., J. Han, Z. Haq, W.E. Tyner, M. Wu, and A. Elgowainy (2011). Energy and greenhouse gas emission effects of corn and cellulosic ethanol with technology improvements and land use changes. *Biomass and Bioenergy*, **35**(5), pp. 1885-1896.

Warwick, S.I., H.J. Beckie, and L.M. Hall (2009). Gene flow, invasiveness, and ecological impact of genetically modified crops. *Annals of the New York Academy of Sciences*, **1168**(1), pp. 72-99.

WBGU (2009). *World in Transition – Future Bioenergy and Sustainable Land Use.* German Advisory Council on Global Change (WBGU), Berlin, Germany, 393 pp. (ISBN 978-1-84407-841-7).

Weyer, K., D. Bush, A. Darzins, and B. Willson (2009). Theoretical maximum algal oil production. *BioEnergy Research*, **3**(2), pp. 204-213.

Wicke, B., V. Dornburg, M. Junginger, and A. Faaij (2008). Different palm oil production systems for energy purposes and their greenhouse gas implications. *Biomass and Bioenergy*, **32**(12), pp. 1322-1337.

Wicke, B., E. Smeets, A. Tabeau, J. Hilbert, and A. Faaij (2009). Macroeconomic impacts of bioenergy production on surplus agricultural land – A case study of Argentina. *Renewable and Sustainable Energy Reviews*, **13**(9), pp. 2463-2473.

Wilhelm, W.W., J.M.F. Johnson, J.L. Hatfield, W.B. Voorhees, and D.R. Linden (2004). Crop and soil productivity response to corn residue removal: A literature review. *Agronomy Journal*, **96**(1), pp. 1-17.

Wilhelm, W.W., J.M.E. Johnson, D.L. Karlen, and D.T. Lightle (2007). Corn stover to sustain soil organic carbon further constrains biomass supply. *Agronomy Journal*, **99**, pp. 1665-1667.

Wilkie, A.C., and J.M. Evans (2010). Aquatic plants: an opportunity feedstock in the age of bioenergy. *Biofuels*, **1**(2), pp. 311-321.

Wilkie, A.C., K.J. Riedesel, and J.M. Owens (2000). Stillage characterization and anaerobic treatment of ethanol stillage from conventional and cellulosic feedstocks. *Biomass and Bioenergy*, **19**(2), pp. 63-102.

Wilkinson, P., K.R. Smith, M. Davies, H. Adair, B.G. Armstrong, M. Barrett, N. Bruce, A. Haines, I. Hamilton, T. Oreszczyn, I. Ridley, C. Tonne, and Z. Chalabi (2009). Public health benefits of strategies to reduce greenhouse-gas emissions: household energy. *The Lancet*, **374**(9705), pp. 1917-1929.

Williams, R.H., E.D. Larson, G. Liu, and T.G. Kreutz (2009). Fischer-Tropsch fuels from coal and biomass: Strategic advantages of once-through ("polygeneration") configurations. *Energy Procedia*, **1**(1), pp. 4379-4386.

Wirsenius, S. (2003). Efficiencies and biomass appropriation of food commodities on global and regional levels. *Agricultural Systems*, **77**(3), pp. 219-255.

Wirsenius, S., C. Azar, and G. Berndes (2010). How much land is needed for global food production under scenarios of dietary changes and livestock productivity increases in 2030? *Agricultural Systems*, **103**(9), pp. 621-638.

Wise, M., K. Calvin, A. Thomson, L. Clarke, B. Bond-Lamberty, R. Sands, S.J. Smith, A. Janetos, and J. Edmonds (2009). Implications of limiting CO_2 concentrations for land use and energy. *Science*, **324**(5931), pp. 1183-1186.

Wiskerke, W.T., V. Dornburg, C.D.K. Rubanza, R.E. Malimbwi, and A.P.C. Faaij (2010). Cost/benefit analysis of biomass energy supply options for rural smallholders in the semi-arid eastern part of Shinyanga Region in Tanzania. *Renewable and Sustainable Energy Reviews*, **14**(1), pp. 148-165.

Wolf, J., P.S. Bindraban, J.C. Luijten, and L.M. Vleeshouwers (2003). Exploratory study on the land area required for global food supply and the potential global production of bioenergy. *Agricultural Systems*, **76**, pp. 841-861.

Wooley, R., M. Ruth, D. Glassner, and J. Sheehan (1999). Process design and costing of bioethanol technology: A tool for determining the status and direction of research and development. *Biotechnology Progress*, **15**(5), pp. 794-803.

Woolf, D., J.E. Amonette, F.A. Street-Perrott, J. Lehmann, and S. Joseph (2010). Sustainable biochar to mitigate global climate change. *Nature Communications*, **1**(56), pp. 1-9.

World Bank (2009). *The World Bank - Global Economic Prospects - Commodities at the Crossroad.* The World Bank, The International Bank for Reconstruction and Development, Washington, DC, USA, 196 pp. (see page 73).

World Bank (2010). *Improved Cookstoves and Better Health in Bangladesh: Lessons from Household Energy and Sanitation Programs.* The World Bank, The International Bank for Reconstruction and Development, Washington, DC, USA, 136 pp.

Wright, B. (2009). *International Gain Reserves and Other Instruments to Address Volatility in Grain Market.* Policy Research Working Paper 5028, World Bank Group, Washington, DC, USA, 61 pp.

Wright, D.H. (1990). Human impacts on energy flow through natural ecosystems, and implications for species endangerment. *AMBIO: A Journal of the Human Environment*, **19**(4), pp. 189-194.

Wu, M., Y. Wu, and M. Wang (2005). *Mobility Chains Analysis of Technologies for Passenger Cars and Light Duty Vehicles Fueled with Biofuels: Application of the Greet Model to Project the Role of Biomass in America's Energy Future (RBAEF) project.* ANL/ESD/07-11, Argonne National Laboratory, Argonne, IL, USA, 84 pp.

Wu, M., M. Wang, J. Liu, and H. Huo (2008). Assessment of potential life-cycle energy and greenhouse gas emission effects from using corn-based butanol as a transportation fuel. *Biotechnology Progress*, **24**(6), pp. 1204-1214.

Wu, M., M. Mintz, M. Wang, and S. Arora (2009). Water consumption in the production of ethanol and petroleum gasoline. *Environmental Management*, **44**(5), pp. 981-997.

WWI (2006). *Biofuels for Transportation – Global Potential and Implications for Sustainable Agriculture and Energy in the 21st Century.* World Watch Institute, Washington, DC, USA, 417 pp.

Wydra, S. (2009). *Production and Employment Impacts of New Technologies – Analysis for Biotechnology.* Discussion Paper 08-2009, Forschungszentrum Innovation und Dienstleistung, Universität Hohenheim, Stuttgart, Germany, 31 pp.

Wyman, C.E., B.E. Dale, R.T. Elander, M. Holtzapple, M.R. Ladisch, and Y.Y. Lee (2005). Coordinated development of leading biomass pretreatment technologies. *Bioresource Technology*, **96**(18), pp. 1959-1966.

Yamashita, K., and L. Barreto (2004). *Biomass Gasification for the Co-production of Fischer-Tropsch Liquids and Electricity.* Interim Report IR-04-047, International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria, 50 pp.

Yanowitz, J., and R.L. McCormick (2009). Effect of biodiesel blends on North American heavy-duty diesel engine emissions. *European Journal of Lipid Science and Technology*, **111**(8), pp. 763-772.

Yazdani, S.S., and R. Gonzalez (2007). Anaerobic fermentation of glycerol: a path to economic viability for the biofuels industry. *Current Opinion in Biotechnology*, **18**(3), pp. 213-219.

Yeh, S., S.M. Jordaan, A.R. Brandt, M.R. Turetsky, S. Spatari, and D.W. Keith (2010). Land use greenhouse gas emissions from conventional oil production and oil sands. *Environmental Science & Technology*, **44**(22), pp. 8766-8772.

Yokoyama, S., and Y. Matsumura (eds.) (2008). *The Asian Biomass Handbook: A Guide for Biomass Production and Utilization.* The Japan Institute of Energy, Tokyo, Japan, 326 pp.

Zabowski, D., D. Chambreau, N. Rotramel, and W.G. Thies (2008). Long-term effects of stump removal to control root rot on forest soil bulk density, soil carbon and nitrogen content. *Forest Ecology and Management*, **255**(3-4), pp. 720-727.

Zemke-White, L., and M. Ohno (1999). World seaweed utilisation: An end-of-century summary. *Journal of Applied Phycology*, **11**(4), pp. 369-376.

Zezza, A., B. Davis, C. Azzarri, K. Covarrubias, L. Tasciotti, and G. Anriquez (2008). *The Impact of Rising Food Prices on the Poor.* ESA Working Paper No. 08-07, Agricultural Development Economics Division, Food and Agriculture Organization, Rome, Italy, 37 pp.

Zhang, X., R.C. Izaurralde, D. Manowitz, T.O. West, W.M. Post, A.M. Thomson, V.P. Bandaru, J. Nichols, and J.R. Williams (2010). An integrative modeling framework to evaluate the productivity and sustainability of biofuel crop production systems. *Global Change Biology Bioenergy*, **2**(5), pp. 258-277.

Zomer, R.J., A. Trabucco, O. van Straaten, and D.A. Bossio (2006). *Carbon, Land and Water: A Global Analysis of the Hydrologic Dimensions of Climate Change Mitigation through Afforestation/Reforestation.* IWMI Research Report 101, International Water Management Institute, Colombo, Sri Lanka, 48 pp.