STRANDED ASSETS

PROGRAMME

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Stranded Carbon Assets and Negative Emissions Technologies

Working Paper

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About the Stranded Assets Programme

The Stranded Assets Programme at the University of Oxford's Smith School of Enterprise and the Environment was established in 2012 to understand environment-related risks driving asset stranding in different sectors and systemically. We research the materiality of environment-related risks over time, how different risks might be interrelated, and the potential impacts of stranded assets on investors, businesses, regulators, and policymakers. We also work with partners to develop strategies to manage the consequences of environment-related risks and stranded assets.

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Executive Summary

Negative Emissions Technologies (NETs)[1] have the potential to remove carbon dioxide (CO_2) from the atmosphere and this could reduce the impacts of ocean acidification and anthropogenic climate change. NETs are a family of technologies that encompass diverse options, including: Afforestation, Agricultural Soil Carbon Sequestration, Biochar, Bioenergy with Carbon Capture and Storage (BECCS), Direct Air Capture (DAC), Ocean Liming, Enhanced Weathering, and Ocean Fertilisation.

NETs may help to extend carbon budgets and therefore provide more time to reduce emissions. Carbon budgets represent our best estimates of the amount of CO_2 that may be released into the atmosphere before it becomes unlikely that the 2°C target can be avoided. Based on the latest IPCC work[2] the current carbon budgets are 900, 1050 and 1,200 $GtCO_2$ under 66%, 50% and 33% probabilities, respectively. In 2010, gross annual Greenhouse Gas (GHG) emissions totalled ~50 $GtCO_2$-equivalent. Ocean and land sinks absorb just over 50% of the emissions resulting in net atmospheric emissions increasing by around 22 $GtCO_2$ pa and therefore an average ~3 ppm increase of atmospheric CO_2 concentration per year, although the fraction absorbed by these sinks is falling.[3]

To see whether carbon budgets can be extended and if so, for how long, we use the methodology used by the Carbon Tracker Initiative when it assessed the role of Carbon Capture and Storage (CCS) technology development and deployment on carbon budgets. It used the IEA CCS Roadmap[4] to quantify the 'extra space' that would be created in carbon budgets and found that a total of 125 $GtCO_2$ could be sequestered by 2050; this is the equivalent of 2.5 years of present gross annual emissions.

We repeat this exercise for NETs, characterising possible NET deployment scenarios up to 2050 and 2100 based on the latest literature on technical potentials and limiting constraints on NET deployment. We find that between now and 2050, there may be the technical potential to attain negative emissions of the order of 120 $GtCO_2$ cumulatively (~15 ppm reduction), with the vast majority of this potential coming from afforestation, soil carbon improvements, and some biochar deployed in the near term[5].

This potential represents an extension of the 2050 carbon budget by 11-13% for a 50-80% probability of meeting a 2-degree warming target. More industrial technologies (DAC, Ocean Liming, and BECCS) that rely on CCS are likely to have very limited potential by 2050, largely due to limits imposed by CCS development and more significant technical and policy challenges. Their contribution to the pre-2050 potential is only around 20 $GtCO_2$ (2.5 ppm), or an extension of only ~2% of the 2050 carbon budget.

Cumulative negative emissions potential between now and 2100 is very poorly understood. The long-term performance, costs, feasibility, and impacts of large-scale deployment of the technologies that provide the bulk of post-2050 potential – BECCS, DAC, and Ocean Liming – are highly uncertain, and the wider social, political, environmental, and economic context in which they would be deployed are also well beyond our ability to predict accurately. In principle, over 1,000 $GtCO_2$ might be possible in the second half of the century, but reaching this depends on extreme rates of NET deployment after 2050. The cumulative technical potential of all NETs considered between now and 2100, in scenarios of maximum deployment, may be of the order of ~700-1350 $GtCO_2$, or 90-170 ppm. This represents an extension of the global carbon budget of 70-140% or more (for an 80% chance to remain below 2°C) or 45-90% or more (for a 50% chance). Reaching even the lower bound of this

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[1] Also referred to as Carbon Dioxide Removal (CDR) or Greenhouse Gas Removal (GGR).
[2] IPCC (2013) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press: Cambridge, United Kingdom and New York, NY, USA.
[3] Le Quéré, C., Raupach, M.R., Canadell, J.G., Marland, G., Bopp, L., Ciais, P., Conway, T.J., Doney, S.C., Feely, R. A., Foster, P., Friedlingstein, P., Gurney, K., Houghton, R. A., House, J.I., Huntingford, C., Levy, P.E., Lomas, M.R., Majkut, J., Metzl, N., Ometto, J.P., Peters, G.P., Prentice, I.C., Randerson, J.T., Running, S.W., Sarmiento, J.L., Schuster, U., Sitch, S., Takahashi, T., Viovy, N., van der Werf, G.R., Woodward, F.I. (2009) "Trends in the sources and sinks of carbon dioxide," *Nature Geoscience*, 2(12), 831–836.
[4] IEA, 2012. *Technology Roadmap: Carbon Capture and Storage*, International Energy Agency, Paris.
[5] Note that the lower bounds of the ranges given account for potential saturation of biological sinks and impermanence risks for carbon stored in forests, soils, and biochar.

range, however, would already require deployment of negative emissions and CO_2 storage infrastructure on an improbably massive global scale.

The availability and accessibility of geological storage for CO_2 is a key uncertainty. If ultimately realisable storage is towards the low end of current estimates due to physical, technological, or political factors, this could severely constrain the total negative emissions attainable through BECCS, DAC, and in some cases Ocean Liming in the 2050-2100 period.

Given these uncertainties and deployment challenges, it would be foolhardy for an owner or operator of carbon-intensive assets to assume that NETs will fundamentally alter the carbon budgets that they may face due to climate policy and regulation. This is particularly the case for point source emissions from power stations, as there are already a number of viable options to deal with these emissions. It would be hard to argue that resorting to highly uncertain NETs prior to undertaking a variety of mitigation options is an economically or socially desirable course of action.

Given the barriers it is extremely unlikely that a situation will be able to develop whereby a fossil fuel intensive sector could operate alongside a large-scale negative emissions sector. Even lower bound potentials would require a very significant scaling up of activity – essentially the creation of major, new global industries to capture and sequester carbon. Even if this was to occur successfully, the scale of potential deployment would still not negate the need for deep emission reductions. There must also remain a very clear preference for timely mitigation over negative emissions as there are significant dangers associated with tipping points. Once alternative earth system states have been realised, the system may not return to where it originally started even if CO_2 concentrations are then reduced.

In addition to these observations, there are several related recommendations that carbon-intensive sectors and policymakers should take into account when considering NETs:

First, 'no-regrets' NETs (NR NETs), which are characterised by low upfront capital costs, co-benefits (such as enhanced soil fertility), no CCS dependence, economic and environmental co-benefits, and fewer uncertainties, include afforestation, soil carbon improvements, and biochar. Even considering the potential for limited release of stored carbon in the future, they are the most promising NETs between now and 2050. To the extent that NR NETs create additional carbon budget, this should be reserved for the residual emissions (emissions after feasible mitigation actions) from important, but 'stubborn' non-point source emitters like agriculture and aviation. It is possible that NR NETs will have a niche role by 2050 offsetting these difficult to mitigate emissions sources. Policymakers and the owners and operators of assets in the relevant sectors should work together to maximise NR NETs deployment, minimise residual emissions from stubborn sectors, and develop plausible deployment pathways.

Secondly, the question of the cost of NETs and how those costs are shared is of profound importance for a range of issues, including the following: understanding how assets might be impacted by such costs; securing the cash flows and financing necessary for NETs deployment; and identifying implications for fairness and sustainable development. The challenge of commissioning and paying for conventional CCS demonstration plants highlights how difficult these issues are to resolve. International cooperation to address free riding and related issues is also required and this should be overlaid onto existing international processes and negotiations.

Thirdly, successful NETs deployment would not mean business as usual for carbon-intensive assets. Sectors (and consumers) will have to pay directly or indirectly for the cost of mitigation actions, and quite probably the cost of negative emissions deployment to address overshoot and stubborn emissions from non-point sources. NETs deployment addresses risk on the one hand (by extending carbon budgets), and creates it on the other (through new and uncertain costs). NETs should not be seen as a *deus ex machina* that will 'save the day'. Consequently, businesses and investors need to factor carbon asset risk into their business planning and strategic asset allocation processes. Scenario planning and regular assessments of how carbon budgets are being translated into policy and regulation will be important.[6] As is work to understand other environment-related risks that could strand assets.

Fourthly, CCS is a key bottleneck for post-2050 NETs and this should be addressed to keep the option open for significant future deployment of DAC, Ocean Liming, and BECCS. While this option is uncertain, it is of sufficiently high potential impact to merit investment, as long as a possible dilemma can be resolved: deploying conventional CCS today results in positive net emissions and uses finite geological storage that might constrain storage capacity in the future; but unless conventional CCS is deployed at scale, the technology for negative emissions CCS might never be developed. The trade-off between these options and to what extent conventional CCS needs to be deployed for DAC, Ocean Liming, and BECCS to be viable future options is an important area for future research.

Finally, it is clear that attaining negative emissions is in no sense an easier option than reducing current emissions. To remove CO_2 on a comparable scale to the rate it is being emitted inevitably requires effort and infrastructure on a comparable scale to global energy or agricultural systems. Combined with the potentially high costs and energy requirements of several technologies, and the global effort needed to approach the technical potentials discussed previously, it is clear that very large-scale negative emissions deployment, if it were possible, is not in any sense preferable to timely decarbonisation of the energy and agricultural systems.

[6] See: Caldecott, B. L., J. Tilbury and C. Carey (2014). Stranded Assets and Scenarios. Discussion Paper, Smith School of Enterprise and Environment, University of Oxford.

1. Introduction

Negative Emissions Technologies (NETs)[7] have the potential to remove carbon dioxide (CO_2) from the atmosphere and this could reduce the impacts of ocean acidification and anthropogenic climate change. NETs are a family of technologies that encompass diverse options including Afforestation, Agricultural Soil Carbon Sequestration, Biochar, Bioenergy with Carbon Capture and Storage (BECCS), Direct Air Capture (DAC), Ocean Liming, Enhanced Weathering, and Ocean Fertilisation (see Table 1 for further details).

Box 1: Carbon budgets
Carbon budgets represent our best estimates of the amount of CO_2 that may be released into the atmosphere before it becomes unlikely that the 2°C target can be avoided. Based on the latest IPCC work[8] the current cumulative carbon budgets are 900, 1050, and 1,200 $GtCO_2$ under 66%, 50%, and 33% probabilities, respectively. In 2010, gross annual Greenhouse Gas (GHG) emissions totalled ~50 $GtCO_2$-equivalent. Ocean and land sinks absorb just over 50% of the emissions resulting in net atmospheric emissions increasing by around 22 $GtCO_2$ pa and therefore an average ~3 ppm increase of atmospheric CO_2 concentration per year, although the fraction absorbed by these sinks is falling.[9]

For a given temperature target, different estimates of the carbon budget will vary depending on, for example, the assumed future trends in non-CO_2 greenhouse gases or aerosol forcings. For our calculations below, we use budgets modelled by the Carbon Tracker Initiative (CTI) since they provide both 2050 and 2100 budgets, while the IPCC provides only a cumulative budget. The CTI budgets are larger than those of the IPCC (Table B1.)

Table B1: Carbon budgets modelled by the Carbon Tracker Initiative[10]

Probability of not exceeding 2°C	2013-2050 carbon budget ($GtCO_2$)	2050-2100 carbon budget ($GtCO_2$)
50%	1075	475
80%	900	75

There are two technically possible, but as yet unrealised options to address the limited space for atmospheric CO_2 while allowing for the continued use of some fossil fuel resources: carbon capture and storage (CCS) and negative emissions technologies (NETs).

NETs could contribute to climate change mitigation efforts in a number of ways. First, early indications are that some NETs are potentially cost competitive with mitigation options. For example, based on our initial calculations from 2012[11], several options might be available at scale with abatement costs of US$60-160/$tCO_2$. For comparison, the latest IPCC figures estimate that most of the mitigation potential of industry emissions (such as fuel switching or CCS) will be available at $50-200/$tCO_2$, and that some mitigation options in the

[7] Also referred to as Carbon Dioxide Removal (CDR) or Greenhouse Gas Removal (GGR).
[8] IPCC (2013) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press: Cambridge, United Kingdom and New York, NY, USA.
[9] Le Quéré, C., Raupach, M.R., Canadell, J.G., Marland, G., Bopp, L., Ciais, P., Conway, T.J., Doney, S.C., Feely, R. A., Foster, P., Friedlingstein, P., Gurney, K., Houghton, R. A., House, J.I., Huntingford, C., Levy, P.E., Lomas, M.R., Majkut, J., Metzl, N., Ometto, J.P., Peters, G.P., Prentice, I.C., Randerson, J.T., Running, S.W., Sarmiento, J.L., Schuster, U., Sitch, S., Takahashi, T., Viovy, N., van der Werf, G.R., Woodward, F.I. (2009) "Trends in the sources and sinks of carbon dioxide," *Nature Geoscience*, 2(12), 831–836.
[10] Carbon Tracker Initiative, 2013. Unburnable Carbon 2013: Wasted Capital and Stranded Assets. http://www.carbontracker.org/wastedcapital
[11] McGlashan, N., Shah, N., Caldecott, B., Workman, M. 2012 "High-level techno-economic assessment of negative emissions technologies," *Process Safety and Environmental Protection*, 90(6), 501–510.

transport sector (especially HGVs and aviation) may have costs ranging from \$0-400/tCO_2[12]. NETs could therefore reduce the total cost of mitigation, and if it were possible for NETs to be generated at the 100s GtCO_2 scale there is the possibility that they could set a ceiling price for CO_2. Secondly, many NETs options remove the need for a physical link between the sources of emissions and mitigation of those emissions. This is especially useful for stubborn, non-point source emissions, such as those generated by transport and agriculture. NETs can allow these dispersed emissions to be offset by subsequent recapture. Thirdly, they provide an option to bring back concentrations of CO_2 towards less risky levels should total emissions overshoot. Fourthly, NETs may help to extend carbon budgets and therefore provide more time to reduce emissions.

It is the fourth topic – NETs extending carbon budgets – which is the central focus of this paper. We examine whether NETs can extend carbon budgets[13] and if so, by how much and over what time horizons. We also investigate the possible implications for policymakers, investors, and firms and explore whether NETs, by potentially reducing the scale and pace of carbon constraints on fossil fuel industries, could reduce the risk of carbon intensive assets becoming 'stranded assets', which are assets that have suffered from unanticipated or premature write-downs, devaluations, or conversion to liabilities.[14]

To see whether carbon budgets can be extended and if so, for how long, we use the methodology used by the Carbon Tracker Initiative[15] when it assessed the role of Carbon Capture and Storage (CCS) technology development and deployment on carbon budgets. It used the IEA CCS Roadmap[16] to quantify the 'extra space' that would be created in carbon budgets and found that a total of 125 GtCO_2 could be sequestered; this is the equivalent of 2.5 years of present gross annual emissions. We repeat this exercise for NETs, characterising possible NET deployment scenarios up to 2050 and 2100 based on the latest literature on technical potentials and limiting constraints on NET deployment.

We start with a brief overview of NETs, reviewing their position within the suite of climate change options and the state of technology development. Section 3 sets out possible NET deployment scenarios up to 2050 and 2100 and estimates the size and timing of any impact on carbon budgets. Section 4 examines the possible implications for policymakers, investors, and firms, especially in terms of whether NETs change the stranded asset risks facing carbon intensive sectors. Section 5 concludes with recommendations and markers for further work.

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[12] IPCC, 2014. Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, NY, USA.

[13] For our calculations, we use figures from the Carbon Tracker Initiative (CTI), since they provide both 2050 and 2100 carbon budgets based on energy system modelling, while the IPCC provides only a cumulative budget. See Box 1.

[14] Caldecott, B.L., & McDaniels, J. (2014) *Financial dynamics of the environment: risks, impacts, and barriers to resilience. Working Paper for the UNEP Inquiry into the Design of a Sustainable Financial System*. Working Paper. Smith School of Enterprise and the Environment, University of Oxford (Oxford, UK).

[15] Carbon Tracker Initiative, 2013. Unburnable Carbon 2013: Wasted Capital and Stranded Assets. http://www.carbontracker.org/wastedcapital

[16] IEA, 2012. *Technology Roadmap: Carbon Capture and Storage*, International Energy Agency, Paris.

2. Negative Emissions Technologies

While mitigation options address the root cause of anthropogenic climate change by limiting cumulative GHG emissions, they may be insufficient to deliver the scale and pace of emission reductions required to keep atmospheric concentrations of GHGs within tolerable boundaries.[17] In the future it may be necessary to deploy NETs at scale so as to capture and sequester CO_2 from the atmosphere directly or indirectly.

Figure 1: Typology for the five responses to anthropogenic climate change[18]

AIM	AVOIDING CLIMATE CHANGE			Avoiding "dangerous" climate change	Responding to dangerous climate change
	Avoiding a given level of atmospheric GHG concentration		Avoiding global average temperature increases	Ensuring that rising temperatures do not impact upon core interests	Providing redress for injuries to core interests
STRATEGY	**Mitigation** Reducing GHG emissons	**CDR** Drawing GHGs out of the atmosphere	**SRM** Increasing albedo	**Adaptation** Improved irrigation, flood defences, protection against disease	**Rectification** Financial compensation, symbolic reparation

The above classification by Heyward[18,19] sets out the different possible responses to anthropogenic climate change. This review focuses on the suite of technologies known as NETs, which aim to remove GHGs from the atmosphere over their lifecycle and isolate them from the atmosphere for the long term. The approaches encompassed by this definition are diverse. Many 'technologies' rely on photosynthesis to achieve CO_2 removal, either storing it in original biomass (e.g. afforestation) or converting it to another form for more permanent storage (e.g. in geological reservoirs). Others, such as Direct Air Capture (DAC), use chemical sorbents, in industrial capture plants, to extract CO_2 directly. The range of proposed technologies is shown in Figure 2 below.

[17] UNEP, 2013. The Emissions Gap Report 2013 – A UNEP Synthesis Report. Nairobi, Kenya: UNEP.

[18] Heyward, C. 2013. Situating and Abandoning Geoengineering: A Typology of Five Responses to Dangerous Climate Change. Symposium: Climate Change Justice. *PS* January 2013, 23-27.

[19] As Heyward notes, the distinction between mitigation and CDR, or NETs, is not clear cut. The formal UNFCCC definition of mitigation includes 'sink enhancement' as well as emissions reduction, and a single technology may include both emissions reduction and negative emissions components.

Figure 2: Negative Emissions Technologies[20]

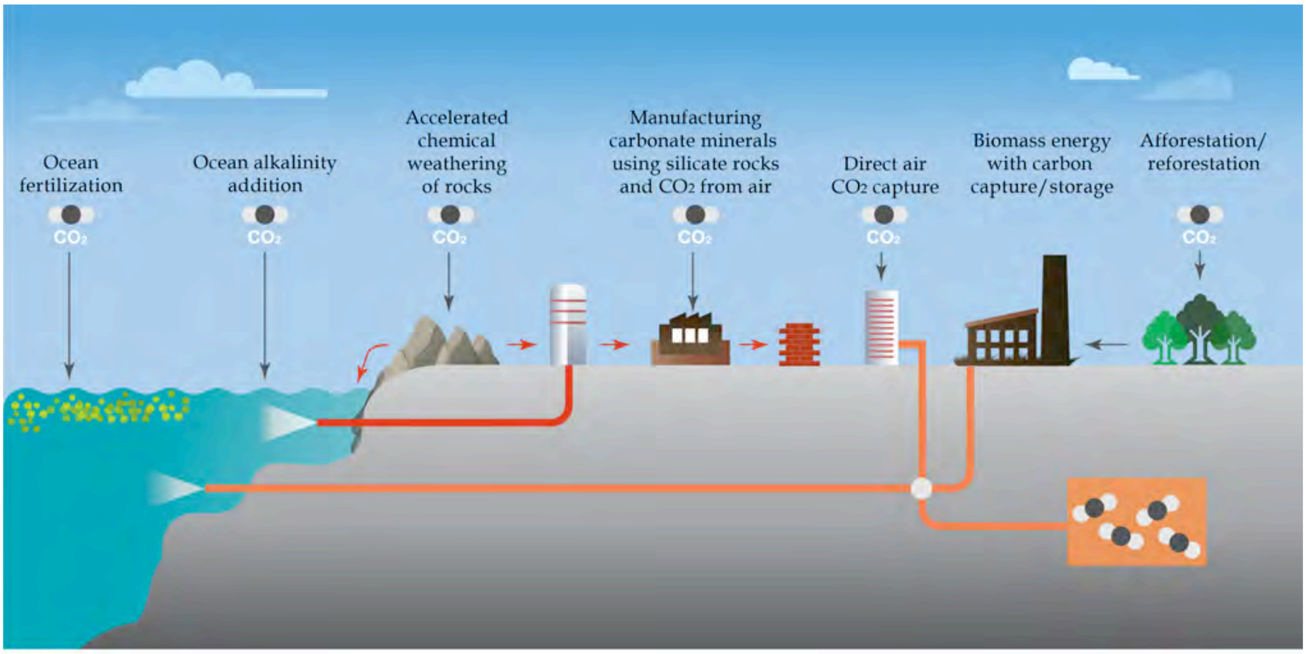


Table 1 below briefly describes six of the most widely discussed NETs. More detailed descriptions of the methods themselves can be found in several excellent recent reviews of this space.[21]

Table 1: Summary of six of the most widely discussed NETs

NET	Description	Storage Medium	Estimated Abatement Cost
Afforestation & Other Forestry	Planting or replanting forests on cleared or abandoned land; managing forests to enhance uptake	Biomass and soil organic carbon	\$20-100/tCO_2[22]
Agricultural Land Management	Changing land management practices to increase organic carbon levels in soils	Soil organic carbon	Cost-negative to \$100/tCO_2[23]
Biochar	Converting biomass through pyrolysis to a solid, stable 'char' product that can be added to soils	Stable char product in soils	\$0-135/tCO_2[24]
Bioenergy with Carbon Capture and Storage	Capturing CO_2 released during any biomass combustion or other conversion processes	Supercritical CO_2 in geological storage	\$45-250/tCO_2[25]

[20] Caldeira, K., Bala, G., Cao, L., 2013. The Science of Geoengineering. *Annu. Rev. Earth Planet. Sci*. 41, 231–256.
[21] McLaren, D., 2012. A comparative global assessment of potential negative emissions technologies. *Process Safety and Environmental Protection* **90**(6), 489–500.; McGlashan, N., Shah, N., Caldecott, B., Workman, M., 2012. High-level techno-economic assessment of negative emissions technologies. *Process Safety and Environmental Protection* **90**(6), 501–510.; Vaughan, N.E., Lenton, T.M., 2011. A review of climate geoengineering proposals. *Climatic Change* **109**(3-4), 745–790.; Royal Society, 2009. *Geoengineering the climate: Science, governance and uncertainty*. Royal Society, London.
[22] Canadell, J.G., Raupach, M.R., 2008. Managing forests for climate change mitigation. *Science* **320**, 1456–7.
[23] Smith, P., Martino, D., Cai, Z., Gwary, D., Janzen, H., Kumar, P., McCarl, B., Ogle, S., O'Mara, F., Rice, C., Scholes, B., Sirotenko, O., Howden, M., McAllister, T., Pan, G., Romanenkov, V., Schneider, U., Towprayoon, S., Wattenbach, M., Smith, J., 2008. Greenhouse gas mitigation in agriculture. *Philosophical transactions of the Royal Society of London. Series B, Biological sciences* **363**(1492), 789–813.
[24] Roberts, K.G., Gloy, B.A., Joseph, S., Scott, N.R., Lehmann, J., 2010. Life cycle assessment of biochar systems: estimating the energetic, economic, and climate change potential. *Environmental Science and Technology* **44**, 827–33; McGlashan, N., Shah, N., Caldecott, B., Workman, M. 2012 "High-level techno-economic assessment of negative emissions technologies," *Process Safety and Environmental Protection*, 90(6), 501–510.
[25] McLaren, D., 2012. A comparative global assessment of potential negative emissions technologies. *Process Safety and Environmental Protection* 90(6), 489–500;

(BECCS)	and storing it as a supercritical fluid in geological reservoirs		
Direct Air Capture (DAC)	Extracting a near-pure CO_2 stream directly from the air using sorbents and storing it as a supercritical fluid in geological reservoirs. Sorbents are then regenerated through heating or other treatment	Supercritical CO_2 in geological storage	\$40-600/tCO_2[25]
Ocean Liming (OL)	Adding lime (calcium oxide) produced from high-temperature calcination of limestone to the oceans, thereby enhancing their uptake of CO_2	Dissolved carbonate / bicarbonate in oceans	\$72-159/tCO_2[26]

As can be seen in Table 1, the NETs family represents a heterogeneous set of technologies that may be characterised as follows:

- There is a substantial variety of potential technologies making use of a wide range of removal pathways and forms of final carbon storage, and thus an equally diverse set of technical, economic, social and policy issues through their ongoing development is likely.
- Early estimates of levelised abatement costs range from cost-negative to several hundred dollars per tonne of CO_2 removed, with costs for some technologies overlapping with some conventional mitigation approaches. Capital requirements, in particular, vary widely.
- The technologies are at widely varying levels of technical readiness (for example, biochar is an ancient technology while artificial trees are at an early stage of demonstration).
- There are substantial research needs for all the technologies with the need to confirm abatement costs and negative emissions potentials at larger scales on a full life-cycle basis.

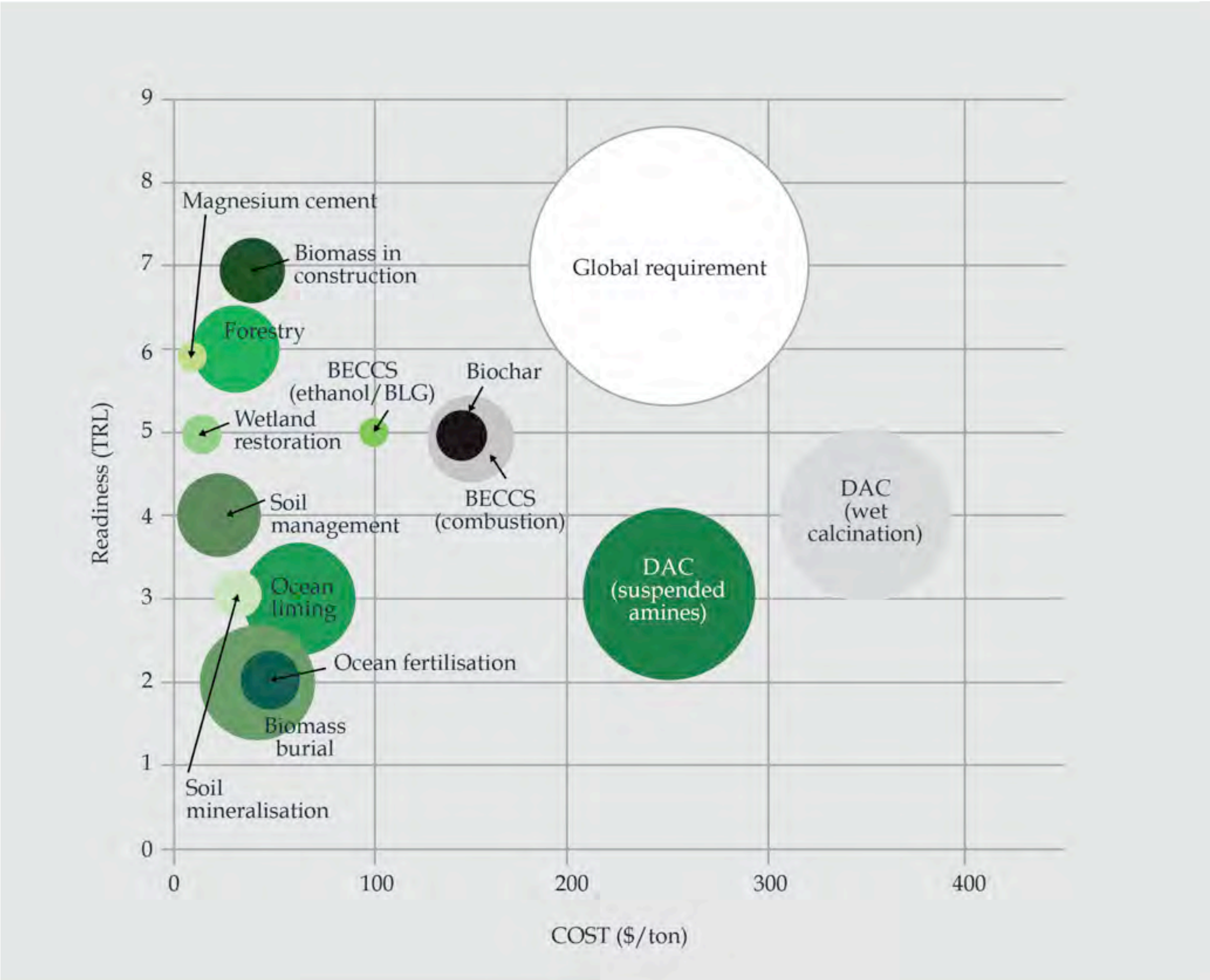
Such is the heterogeneity of negative emissions processes it is important to distinguish between different technologies to ensure that generalisations do not result in the tainting of promising technologies. It is also noteworthy that a substantial number also depend on the realisation of CCS technology to economically inject substantial proportions of CO_2 into geological storage sinks for the long term.[27]

A number of recent reviews of negative emissions options have identified several potential roles they could play in addressing climate change.[28] These include:

- **A supplement to mitigation** – Several NETs are potentially cost-competitive with some mitigation technologies and may therefore act to complement mitigation strategies – Figure 3. Indeed if negative emissions can be developed to a 10-100's of GtCO_2 scale then a ceiling price for CO_2 could be effectively set, potentially lowering the total cost of decarbonisation. If NETs can be deployed at significant scale and at comparable cost to mitigation technologies, this additional mitigation potential could make deeper cuts in net emissions (now or in the future) more feasible, or buy some extra time for energy system change to reduce total emissions to a given target.

[26] Renforth, P., Jenkins, B.G., Kruger, T., 2013. "Engineering challenges of ocean liming," *Energy* 60, 442–452; McGlashan, N., Shah, N., Caldecott, B., Workman, M. 2012 "High-level techno-economic assessment of negative emissions technologies," *Process Safety and Environmental Protection*, 90(6), 501–510.
[27] McGlashan, N., Shah, N., Caldecott, B., Workman, M. 2012 "High-level techno-economic assessment of negative emissions technologies," *Process Safety and Environmental Protection*, 90(6), 501–510.
[28] Keith, D.W. 2000. Geoengineering the Climate: History and Prospect. Annu. Rev. Energy Environ. 2000. 25:245–84;
Vaughan and Lenton, 2011. A review of climate geoengineering proposals. Climate Change (2011) 109: 745-790; Socolow, R., Desmond, M., Aines, R., Blackstock, J., Bolland, O., Kaarsberg, T., Lewis, N., Mazzotti, M., Pfeffer, A., Sawyer, K., Siirola, J., Smit, B., Wilcox, J. (2011) *Direct Air Capture of CO2 with Chemicals: A Technology Assessment for the APS Panel on Public Affairs*, College Park, Maryland; McGlashan, N., Shah, N., Caldecott, B., Workman, M. 2012 "High-level techno-economic assessment of negative emissions technologies," *Process Safety and Environmental Protection*, 90(6), 501–510; McLaren, D. 2012. *Negatonnes – An Initial Assessment of the Potential for Negative Emission Techniques to Contribute Safely and Fairly to Meeting Carbon Budgets in the 21st Century.* Friends of the Earth; Meadowcroft, J., 2013. Exploring negative territory: Carbon dioxide removal and climate policy initiatives. *Climatic Change* **118**(1), 137–149. Rayner S., Redgwell C., Savulescu J., Pidgeon N., Kruger T.' 2009. Memorandum on draft principles for the conduct of geoengineering research. Available at http://www.geoengineering.ox.ac.uk/oxford-principles/history/; Tavoni, M. and Socolow, R. 2013. Modelling meets science and technology: An introduction to a special issue on negative emissions. Climatic Change (2013) 118:1-14.

Figure 3: Indicative sequestration costs and technical readiness of different NETs from an early review of leading approaches.[29] The area of circles indicates their estimated achievable scale.



- **Dispersed and locked-in emissions** – NETs have the advantage of separating CO_2 sources from sinks allowing stranded sinks to be utilised. This allows them to be used to negate 'stubborn' emissions from sources where conventional mitigation measures are not yet technically or economically feasible. This essentially enables a limited amount of fossil fuel use from important non-point source emissions. Examples could be aviation and agriculture, and areas where conventional CCS pipelines and storage would not be available.

- **Correcting for an overshoot** – Lastly, if the large-scale deployment of NETs were possible, it could potentially allow for the capture of historic emissions and could be used as a technology of last resort should mitigation measures fall short. With the increasing likelihood of there being a carbon budget overshoot, such global 'net negative emissions' may be required to actively reduce atmospheric GHG concentrations to safer

[29] McLaren, D., 2012. *Negatonnes – An Initial Assessment of the Potential for Negative Emission Techniques to Contribute Safely and Fairly to Meeting Carbon Budgets in the 21st Century*. Friends of the Earth.

levels. However, while this type of large-scale removal of CO_2 may eventually be required, there are two reasons why hoping to reach emissions targets via such an overshoot trajectory is a dangerous alternative to timely mitigation. First, there are serious limitations to our ability to predict technological and societal development over subsequent decades, and thus the feasibility of large-scale removal in the future. Neglecting to reduce emissions now on the assumption that NETs can recapture emissions in future would be dangerous if NET deployment on the required scale could not then be realised.[30] There are also significant dangers of passing tipping points, such as the dieback of the Amazon Rainforest or the rapid collapse of the Greenland Ice sheet,[31] that increase as CO_2 levels rise. Once alternative earth system states have been realised, the system may not return to where it originally started if CO_2 concentrations are then reduced.

[30] Meadowcroft, J., 2013. Exploring negative territory: Carbon dioxide removal and climate policy initiatives. *Climatic Change* **118**(1), 137–149.
[31] Lenton, T.M. *et al.* 2008. Tipping Elements in the Earth's Climate System. *Proceedings of the National Academies of Sciences* **105** (6): 1786-1793.

3. Carbon budgets

Many NETs are at an early stage and face substantial technical challenges before they are ready for deployment, let alone deployment at scale. The development of appropriate governance and policy frameworks is also a necessary prerequisite for these technologies, and these are only starting to be discussed.[32] For example, many techniques will require protocols to verify and account for CO_2 removed from the atmosphere, including provision for impermanent reductions. Proposed approaches that interfere with natural earth system processes, or manipulate ocean chemistry, for example, may also require changes to international governance laws and institutions.

With the nascent state of the NETs evidence base in mind and the substantial uncertainties that are inherent when assessing the potential long-term development of a technology family, this paper does not seek to make detailed projections. Instead, we set out the presently available evidence as to the technical limits of some of the most promising technologies and the feasibility of achieving their potential, focusing on the key limiting factors and uncertainties. Technologies presented here are limited to those that have been relatively well-explored in the scientific literature, and were selected based on early indications that they may be able to attain substantial (>1 $GtCO_2$/year) sequestration rates globally without demonstrably unmanageable environmental side effects.[33] This allows us to characterise optimistic and conservative scenarios for possible NET deployment, relating the feasibility of each to the impact that they may have on global carbon budgets to 2050 and 2100.

The technologies considered here are Afforestation and Reforestation, Agricultural Land Management for soil carbon, Biochar, Bioenergy with Carbon Capture and Storage (BECCS), Direct Air Capture (DAC), and Ocean Liming (OL). Other proposed negative emissions technologies, notably Ocean Fertilisation and Enhanced Silicate Weathering, are not considered here, owing to particularly large scientific uncertainties over their feasibility, effectiveness, and environmental impacts, and early indications that any negative emissions they might provide would likely be modest.[33]

The unit of negative emissions used is a $GtCO_2$, or a gigatonne (one billion tonnes) of CO_2 removed from the atmosphere. For illustrative purposes, key figures are also expressed in terms of the change in atmospheric CO_2 concentration (in parts per million, ppm) they would entail, with a 1 ppm change equivalent to 7.81 $GtCO_2$ removed from the atmosphere. However, carbon cycle feedbacks between the atmosphere and other carbon reservoirs, especially equilibration with the ocean inorganic carbon pool, mean that sequestration of 7.81 $GtCO_2$ is likely to lead to a true reduction of somewhat less than 1 ppm, depending on the method used.[34]

Outlook to 2050

There appears to be significant negative emissions potential in the period to 2050, particularly through those NETs that rely on natural biological systems. These may also have lower capital requirements and fewer technical barriers than other NETs options. This section reviews the likely constraints on the scale that each of the six technologies chosen could achieve by 2050.

[32] Royal Society, 2009. *Geoengineering the climate: Science, governance and uncertainty*. The Royal Society, London.
[33] McLaren, D., 2012. A comparative global assessment of potential negative emissions technologies. *Process Safety and Environmental Protection* **90**(6), 489–500.; Williamson, P., Wallace, D.W.R., Law, C.S., Boyd, P.W., Collos, Y., Croot, P., Denman, K., Riebesell, U., Takeda, S., Vivian, C., 2012. Ocean fertilization for geoengineering: A review of effectiveness, environmental impacts and emerging governance. *Process Safety and Environmental Protection* **90**(6), 475–488. Hartmann, J., West, A.J., Renforth, P., Köhler, P., De La Rocha, C.L., Wolf-Gladrow, D.A., Dürr, H.H., Scheffran, J., 2013. Enhanced chemical weathering as a geoengineering strategy to reduce atmospheric carbon dioxide, supply nutrients, and mitigate ocean acidification. *Reviews of Geophysics* **51**(2), 113–149.
[34] Vichi, M., Navarra, A., Fogli, P.G., 2013. Adjustment of the natural ocean carbon cycle to negative emission rates. *Climatic Change* **118**(1), 105–118.

Afforestation and **Agricultural Soil Carbon** enhancement are both negative emissions 'technologies' with relatively low capital requirements and costs, sometimes paying for themselves in co-benefits and improved productivity, and are both already practised widely for various reasons. The key factors limiting their technical potential by 2050 are the area of land that will be available for these methods and the per-hectare rate of carbon sequestration they can attain.

Agricultural techniques improving soil organic carbon levels typically achieve lower average per-hectare rates of sequestration than afforestation, since they do not achieve the permanent build-up of large above ground stocks of carbon that forest biomass achieves. However, they have the advantage that they do not remove land from food or energy production, and often improve yields and soil health.[35] A comprehensive review of agricultural methods for the IPCC identified global biophysical potential (i.e. with no economic or social constraints) of 1.4-3.9 $GtCO_2$ per year net carbon sequestration through agriculture and soil restoration by 2030.[36]

Afforestation and reforestation can sequester carbon relatively rapidly at well over a tonne of carbon (3.7 tonnes of CO_2) per hectare per year.[37] The key uncertainty in estimates is the area of land that will be available and suitable for afforestation, since this depends on future trends in agriculture and food demand, as well as land area dedicated to non-forest energy crops. The IPCC 4AR gave a range of 1.3-4.2 $GtCO_2$ per year mitigation potential through all forestry by 2030 at <\$100/tCO_2, although around half of this represents avoided emissions (associated with reduced deforestation and forest degradation) rather than true negative emissions.[38]

The review of estimates by Lenton (2010) reports a similar range of 2050 technical potential of 0.75-5.5 $GtCO_2$ per year through afforestation alone depending on the area of degraded, marginal, and abandoned land expected to become available.[37] Global availability of land for afforestation is very difficult to predict, and depends on many uncertain quantities including global population, diet, trends in the efficiency and intensity of the food system, and the strength of ecological restrictions preventing conversion of natural ecosystems, as well as competition for land due to rising demand for bioenergy.[37,38] While the upper ends of given ranges may well be plausible for more optimistic scenarios, they are less robust to assumed trends in these key variables, and also assume that none of this land is required for energy crops. Here, therefore, we take a conservative estimate in this range of 1-3 $GtCO_2$ per year of negative emissions in 2030. Since the available land area is the key limiting factor, we assume that these potentials remain constant to 2050, with any further 'spare' land that does become available being used for bioenergy, discussed below, rather than further afforestation.

Biochar and **Bioenergy with Carbon Capture and Storage** (BECCS) also rely on photosynthesis as the initial capture CO_2, but aim to convert the resulting biomass to a more stable, secure form of storage (solid char or CO_2 stored in geological reservoirs), extracting useful energy, and other co-benefits at the same time. Like afforestation and agricultural soil methods, these approaches will also be constrained by land area and biological productivity, this time through the availability and mobilisation of sustainable biomass. In storage terms, BECCS is also ultimately constrained by the availability of geological storage sites and the extent to which those sites are successfully developed; biochar is ultimately constrained by the area of land where it can be applied, and the maximum safe biochar holding capacity of soils.[37]

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[35] Victoria, R., Banwart, S., Black, H., Ingram, J., Joosten, H., Milne, E., Noellemeyer, E., 2012. The Benefits of Soil Carbon: Managing soils for multiple economic, societal and environmental benefits. *UNEP Year Book 2012. Nairobi, Kenya: UNEP.*

[36] Smith, P., Martino, D., Cai, Z., Gwary, D., Janzen, H., Kumar, P., McCarl, B., Ogle, S., O'Mara, F., Rice, C., Scholes, B., Sirotenko, O., Howden, M., McAllister, T., Pan, G., Romanenkov, V., Schneider, U., Towprayoon, S., Wattenbach, M., Smith, J., 2008. Greenhouse gas mitigation in agriculture. *Philosophical Transactions of the Royal Society of London. Series B, Biological sciences* **363**(1492), 789–813.

[37] Lenton, T.M., 2010. The potential for land-based biological CO2 removal to lower future atmospheric CO2 concentration. *Carbon Management* **1**(1), 145–160.

[38] Nabuurs, G.J., Masera, O., Andrasko, K., Benitez-Ponce, P., Boer, R., Dutschke, M., Elsiddig, E., Ford-Robertson, J., Frumhoff, P., Karjalainen, T., Krankina, O., Kurz, W.A., Matsumoto, M., Oyhantcabal, W., Ravindranath, N.H., Sanchez, M.J.S., Zhang, X., 2007. "Forestry", in: Metz, B., Davidson, O.R., Bosch, P.R., Dave, R., Meyer, L.A. (Eds.), *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, UK and New York, NY, USA.

There have been many attempts to estimate the amount of biomass that can be sustainably mobilised for bioenergy, and estimates range over orders of magnitude from near-zero to well above current world energy supply.[39] The resource is typically divided into wastes and agricultural or forestry residues for bioenergy, which can be realised simply through better use of existing biomass flows, and energy crops such as willow or energy grasses, which require land to be dedicated to bioenergy.

Most estimates for residue and waste potential are between 20 and 100 EJ (exajoules) per year by 2050, with 50-60 EJ per year an average figure.[39] Assuming an average energy density of dry biomass of about 18 GJ/tonne, this corresponds to around 3 Gt biomass per year, or 1.5 Gt carbon.[37,39,40] Energy crop estimates are much more variable, since they are sensitive to both energy crop yield and land available, and the latter itself depends on highly uncertain global population, diet, food crop yields, and food system efficiency.[39,40] In the worst case, almost no energy crops are possible in 2050 without impacting global food security or converting natural ecosystems, but other studies identify areas of more marginal land of 100-400 million hectares that conservatively could yield energy crops of the order of a further 60-120 EJ per year, ~3-6 Gt biomass per year.

The same biomass resource clearly cannot be used for biochar and BECCS. Following Lenton[37] and Powell & Lenton[40], we assume that dispersed and variable residues and wastes (~60 EJ optimistically) are more suited to conversion to biochar via pyrolysis, and energy crops are fed into efficient BECCS systems that attain higher rates of negative emissions. Both of these scenarios are upper bounds, as in reality any biomass resources that are developed will likely be in demand for a wide range of different end uses.

Biochar can be produced from a range of feedstocks through pyrolysis, the thermal decomposition of biomass when heated to several hundred degrees in the absence of oxygen. One form of the process, slow pyrolysis, can convert of the order of 50% of the carbon in biomass into stable carbon-dense char, with the remainder converted to various gases and bio-oils that can be used for energy.[41] 60 EJ per year, 3 Gt per year biomass resource would yield a negative emissions potential from biochar in 2050 of approximately 0.75 GtC per year, or 2.75 $GtCO_2$ per year.[42] However, there is some uncertainty around the long-term stability of char in soil under different conditions, with some risk of partial decomposition over century timescales.[43] We therefore follow Roberts et al. in conservatively assuming only 80% of stored carbon (2.2 $GtCO_2$/yr) is permanently stored.[44] Based on maximum application rates of 140 tonnes per hectare, Lenton estimates a global soil capacity for biochar of over 200 GtC in cropland soils alone.[37] The capacity of soil sinks, therefore, is unlikely to limit biochar potential to 2050.

CO_2 capture processes proposed for BECCS may capture 90% or more of the CO_2 released through biomass combustion.[45] The net life-cycle removal, however, depends on emissions associated with supply, processing and transport of biomass, and on any emissions associated with direct or indirect land use change, which is highly dependent on the particular feedstock, supply chain, and wider factors such as policy safeguards.[46] Estimates of production emissions range from around 2-30% of total carbon present in the biomass.[45] Land use change emissions are harder to constrain, but risks can be reduced by sustainability standards and an emphasis on residues, forestry, and energy crops rather than food crop feedstocks.[46] Most estimates for the technical

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[39] Slade, R., Saunders, R., Gross, R., Bauen, A., 2011. *Energy from biomass: the size of the global resource*. Imperial College Centre for Energy Policy and Technology and UK Energy Research Centre, London.
[40] Powell, T.W.R., Lenton, T.M., 2012. Future carbon dioxide removal via biomass energy constrained by agricultural efficiency and dietary trends. *Energy & Environmental Science* **5**(8), 8116.
[41] Sohi, S., Lopez-Capel, E., Krull, E., Bol, R., *Biochar, climate change and soil: A review to guide future research*. CSIRO Land and Water Science Report 05/09.
[42] 3/11 (27.3%) of the mass of a molecule of carbon dioxide consists of carbon, with the remainder the mass of the oxygen atoms. 1 gigatonne of carbon (GtC) is therefore equivalent to 3.7 gigatonnes of CO_2 ($GtCO_2$) in the atmosphere.
[43] Lehmann, J., Czimczik, C., Laird, D., Sohi, S., 2009. Stability of Biochar in Soil, in: Lehmann, J., Joseph, S. (Eds.), *Biochar for Environmental Management*. Earthscan, London.
[44] Roberts, K.G., Gloy, B.A., Joseph, S., Scott, N.R., Lehmann, J., 2010. Life cycle assessment of biochar systems: estimating the energetic, economic, and climate change potential. *Environ. Sci. Technol.* **44**(2), 827–33.
[45] Koornneef, J., van Breevoort, P., Hamelinck, C., Hendriks, C., Hoogwijk, M., Koop, K., Koper, M., Dixon, T., Camps, A., 2012. Global potential for biomass and carbon dioxide capture, transport and storage up to 2050. *International Journal of Greenhouse Gas Control* **11**, 117–132.
[46] IEA Bioenergy, 2011. *Bioenergy, Land Use Change and Climate Change Mitigation*. IEA Bioenergy.

potential of biomass supply from energy crops account for sustainability constraints and exclude land currently used for food production. However, higher estimates of eventual potential (>100 EJ per year) entail higher risks of conflict with agriculture, forests, and other ecosystems, and thus significantly higher risks of land use change emissions.[47]

Studies have assumed different figures for the net storage 'efficiency' of BECCS, the percentage of total biomass carbon removed from the atmosphere on a life-cycle basis, ranging from 50-90%.[45,48] We cautiously assume an average figure of 70%, with the caveat that this figure is likely to decrease for increasing scales of biomass supply. Converting 60-120 EJ of energy crop resource using BECCS would therefore yield negative emissions of the order of 1.1-2.3 GtC per year or 4.2-8.4 $GtCO_2$ per year. More detailed modelling by Koornneef et al.[45] conservatively assuming 61 EJ residues and wastes and 65 EJ energy crops can all be used for BECCS, reach a comparable upper estimate of 10.4 $GtCO_2$ per year by 2050, leaving approximately half that from energy crops alone.

However, rollout of the CCS element, and integration of CCS with biomass conversion technologies, appear likely to constrain BECCS more strongly in 2050 than biomass availability. The latest IEA CCS Roadmap[49] anticipates a total of 7 $GtCO_2$ per year to be stored in 2050, of which only around 1.5 $GtCO_2$ per year is associated with bioenergy. The larger potential negative emissions flows implied by anticipated biomass supply are therefore unlikely to be realised until the second half of the century.

The final NETs considered here, **Direct Air Capture** (DAC) and **Ocean Liming** (OL) rely on chemical processes to draw down CO_2 from the air. They are thus not limited in the same way by available land area or biological productivity, but instead by capital requirements, industrial plant and infrastructure rollout, and energy use.[50,51]

Direct Air Capture refers to any system that uses chemical sorbents to extract CO_2 directly from the atmosphere, and then releases it as a concentrated stream through the regeneration of this sorbent. Leading designs aim to use strong alkaline solutions or amine-based resins as the key sorbent. Like Bioenergy with CCS, DAC produces a stream of concentrated CO_2 gas or liquid rather than a stable form of carbon such as biomass, carbon, or dissolved carbonate. It is therefore also entirely dependent on successful development of downstream technologies for geological or mineral CO_2 storage, and like BECCS it may be ultimately limited by geological storage space.

Ocean Liming refers to the process of adding benign soluble alkalis, typically calcium oxide (lime) or hydroxide, to the oceans. This addition alters ocean carbonate chemistry, converting dissolved CO_2 to bicarbonate and carbonate ions and driving increased uptake of CO_2 into the oceans. The principle method for producing the calcium oxide required is calcination, or thermal decomposition, of limestone, a process widely practised in industry to produce lime for cement production, among other uses.

In principle, since the main effect is increased uptake of CO_2 in the oceans, Ocean Liming can achieve negative emissions without downstream CO_2 storage. However, calcination of limestone itself releases CO_2, and the high-temperature heat required for this process today is derived from fossil fuel combustion, also a CO_2 source. In this context, Ocean Liming can only yield good life-cycle sequestration with current technologies if most of this CO_2 is captured and put into geological storage.[52] The situation may be improved in future through the use of solar calcination kilns (reducing emissions associated with fossil fuels) and through new processes that use

[47] Slade, R., Saunders, R., Gross, R., Bauen, A., 2011. *Energy from biomass: the size of the global resource*. Imperial College Centre for Energy Policy and Technology and UK Energy Research Centre, London.
[48] Smith, L.J., Torn, M.S., 2013. Ecological limits to terrestrial biological carbon dioxide removal. *Climatic Change* **118**(1), 89–103.
[49] IEA, 2013. *Technology Roadmap: Carbon Capture and Storage*. International Energy Agency, Paris.
[50] McGlashan, N., Shah, N., Caldecott, B., Workman, M., 2012. High-level techno-economic assessment of negative emissions technologies. *Process Safety and Environmental Protection* **90**(6), 501–510.; McLaren, D., 2012. A comparative global assessment of potential negative emissions technologies. *Process Safety and Environmental Protection* **90**(6), 489–500.
[51] Keith, D., Ha-Duong, M., Stolaroff, J., 2006. Climate strategy with CO_2 capture from air. *Climatic Change* **74**, 17-45.
[52] Renforth, P., Jenkins, B.G., Kruger, T., 2013. Engineering challenges of ocean liming. *Energy* **60**, 442–452.

silicates, rather than limestone, as a feedstock (reducing emissions from the calcination itself), both of which would reduce its reliance on CO_2 storage.[52]

Both DAC and OL are therefore constrained by similar factors in the near term. Both have relatively high capital costs and expected total abatement costs, both require working CO_2 transport and storage infrastructure, and both are at a relatively early stage of demonstration as NETs relative to conventional CCS.

Box 2: Carbon Capture and Storage (CCS) and NETs

While some NETs sequester atmospheric carbon by converting it directly to more stable forms (such as biochar or dissolved carbonate), several approaches involve production of a concentrated stream of gaseous or liquid CO_2 that must then be stored or immobilised. The concept of Carbon Capture and Storage has been developed to capture CO_2 from large point sources such as fossil-fired power plants in order to greatly reduce the net emissions associated with such activities. CCS from point sources can be considered as two distinct stages: CO_2 capture and CO_2 transport and storage.[53]

CO_2 Capture and NETs

With the exception of certain industrial sources, such as cement plants, that produce concentrated streams, most CCS is targeted at large-scale fossil fuel combustion that ordinarily produces a dilute flue gas (<15% CO_2) not directly suitable for storage. Several technologies are under development to convert this to a near-pure CO_2 stream that can be efficiently transported and stored. The leading families of capture approaches are:

- **Post-combustion capture** – CO_2 is stripped directly from the dilute flue gas, typically with a chemical sorbent that can then be regenerated on heating to yield pure CO_2. The technology used here is often related to that used in DAC.
- **Pre-combustion capture** – fossil fuels are reacted with oxygen and/or steam in a series of steps to yield a mixture of hydrogen gas (the fuel) and CO_2. CO_2 can then be separated at higher concentrations before combustion.
- **Oxy-fuel combustion** – fuels are combusted in pure oxygen rather than air, ultimately producing a near-pure CO_2 stream rather than one diluted with atmospheric nitrogen.

In terms of NETs, successful development of such combustion-based technologies is required for BECCS, as well as OL where fuel combustion with CCS is used as a heat source. DAC approaches make use of similar principles to post-combustion capture, but the particular technologies used are different, and are optimised for air capture.

CO_2 Transport and Storage and NETs

- **Geological Storage**

The vast majority of CCS research and demonstration projects involve compression and liquefaction of the CO_2, transport by pipeline to suitable sites and then long-term storage by injection into suitably deep, secure, and permeable geological formations. Promising sites for such storage are depleted reservoir formations for oil and gas, since the infrastructure and geological surveys are already largely complete, and the storage integrity has been proven over geological timescales. Deep saline aquifers are another major alternative, potentially with much larger global capacity, but are typically much less well characterised geologically. Technology for both pipeline transport and subsurface injection of CO_2 is already used widely within the oil and gas industry, as are many subsurface exploration and monitoring tools. However, the ultimate integrity of CO_2 storage in such locations, as well as the total cost once ongoing monitoring and leakage liability is considered, are still uncertain.

- **Mineral Carbonation**

An alternative to geological storage is the reaction of CO_2 with naturally occurring magnesium and calcium-containing minerals (typically silicates) in industrial reaction vessels, producing mineral carbonates that are non-toxic, and chemically stable on geological timescales. While more secure than geological storage, and so without the extensive surveying and monitoring required of geological storage sites, mineral carbonation is still only at pilot scale today. It currently faces much higher estimated costs than geological storage, owing to the large energy requirements that current technologies entail to accelerate the carbonation reaction. Both DAC and BECCS produce a pure stream of CO_2 for subsequent storage, so the success of both at scale is utterly dependent on the development of technology, infrastructure, and governance systems for long-term CO_2 transport and storage.

[53] IPCC, 2005. *IPCC Special Report on Carbon Dioxide Capture and Storage*. Prepared by Working Group III of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Given these considerations, it is unlikely that either approach will reach more than a small fraction of the total CCS capacity projected by the IEA CCS Roadmap in 2050 (optimistically, of the order of 500 $MtCO_2$ per year between them, if DAC is able to leverage early EOR markets, and existing lime waste flows from cement production are used for Ocean Liming).[54]

The 2050 estimates described above are summarised in Table 2 below.

Table 2: Estimates of chosen technologies' potential to sequester CO_2 in 2050

NET	2050 Potential (per year)	Key constraints	Notes
Afforestation and Other Forestry	1-3 $GtCO_2$, 0.13-0.38 ppm	Conservative estimates of available land area and carbon yields	Higher estimates for afforestation may conflict with land used for food production or energy crops
Agricultural Soil Carbon	1.4-3.9 $GtCO_2$, 0.18-0.50 ppm	Suitable land areas and attainable annual sequestration rates	Fewer trade-offs with other land uses; saturation and risk of impermanence limit cumulative potential
Biochar	~2.2 $GtCO_2$, ~0.28 ppm	Pyrolysis of 60 EJ per year (3 Gt per year) bioenergy residues and wastes	May conflict with other demands for residues and wastes; assumes 80% stability over century timescales
BECCS	~1.5 $GtCO_2$, ~0.19 ppm	Constrained by CCS roll-out and integration with bioenergy, using IEA projections for 2050	Bioenergy supply is a less limiting constraint than CCS development to 2050.
Direct Air Capture	~0.25 $GtCO_2$, ~0.03 ppm	This figure assumes use for EOR at a scale equivalent to the current US market	High costs give it very little role pre-2050 in 'optimal' mitigation models
Ocean Liming	~0.25 $GtCO_2$, ~0.03 ppm	This figure assumes all existing lime wastes from cement production are used for carbon capture	No detailed projections / models available, but similar challenges to DAC
TOTAL	6.6-11.1 $GtCO_2$, 0.85-1.42 ppm		

Outlook to 2100

The large uncertainties present in assessing 2050 technical potentials become far larger when considering the deployment of these technologies, many of which do not yet even exist at commercial scale, in the second half of this century. This is particularly true for DAC and OL, which are the least technically developed systems and, unlike biological approaches, are not fundamentally constrained by biological productivity and land area. This section therefore develops an illustrative high and low 2100 scenario for each NET, using generous and conservative assumptions respectively. For DAC and OL, there is no clear physical quantity providing an absolute limit on the annual sequestration. For these technologies, we therefore try to give some sense of the level of global effort and infrastructure required to attain a given level of negative emissions by relating it to the scale of comparable existing industries. The question of absolute limits on cumulative storage is then discussed in Section 4.4.

[54] McLaren, D., 2012. A comparative global assessment of potential negative emissions technologies. *Process Safety and Environmental Protection* **90**(6), 489–500.; Renforth, P., Washbourne, C.-L., Taylder, J., Manning, D. A. C., 2011. Silicate production and availability for mineral carbonation. *Environmental science & technology* **45**(6), 2035–41.

Forestry and **Agricultural Soil Carbon** enhancement have high near-term potential, but their long-term cumulative value may be limited by both saturation of the carbon sinks and the risk of re-emission of stored carbon.[55]

'Saturation' refers to the fall in net sequestration rate over time in forests or other ecosystems as they reach an equilibrium between net growth and net decay of organic matter over several decades. Maintaining a continuous global negative emissions flow through forestry or agriculture would require continuing expansion of forested or managed agricultural area, or periodic removal of mature trees to prevent saturation. Such harvested biomass would need to be converted to stably-stored carbon elsewhere (e.g. through biochar or BECCS) to provide true negative emissions. Global cumulative limits arising from saturation are discussed below.

A second limitation is the vulnerability of carbon stocks sequestered in biomass and soils. The carbon pool is in constant exchange with the atmosphere and so is vulnerable to re-release if conditions change. Climate change, natural disturbances such as wildfires, or future changes in land management may all lead to release, potentially reducing the security of stored carbon and the future sink capacity.

For the purposes of negative emissions potentials, we therefore consider a saturation scenario, in which flows decrease linearly to zero 30-50 years after they begin, and a continued flow scenario, where estimated 2050 flows are maintained at constant levels until 2100.

Biochar in principle entails lower risks of re-release than biomass and soil storage. Early results suggest a substantial fraction of the stored carbon can be stable in the soil on timescales of decades to centuries. As discussed previously, there are still uncertainties over the long-term stability of biochar in different conditions,[56] but our conservative estimate assumes only 80% stability over the long term. In both scenarios, we therefore assume a constant stream of waste and residue feedstocks is converted to a constant flow of carbon sequestered in biochar (2.2 GtCO_2 per year). Since biochar produces a smaller negative emissions flow per unit of biomass than BECCS, any expansion of biochar at the expense of BECCS would reduce the technical potential for sequestration.

Towards 2100, **Bioenergy with CCS** potential would almost certainly be limited by the available biomass resource. The total biomass supply available in 2100 is, of course, even more uncertain than that in 2050: estimates for energy crop and forestry biomass resource range from less than 60 EJ per year to more than 400 EJ per year, equivalent to a BECCS negative emissions potential of anything from less than 5 GtCO_2 per year to over 30 GtCO_2 per year, depending on future developments in food demand, energy, and food crop yields; the extent to which different areas of natural or semi-natural grasslands or forests are converted or taken under management; and the extent to which we are prepared to accept negative side-effects of bioenergy supply. Social and political factors will also affect whether a large-scale global biomass supply for energy use can be realised. Demand for biomass for other uses of bioenergy, and potentially other forms of BECCS with lower efficiency of capture, will reduce the potential further. The higher the estimates of 2100 BECCS potential, the more optimistic these assumptions must be.

Integrated assessment modelling that has implied a significant role for BECCS in changing the optimal emissions pathway, or allowing global net negative emissions in late century, has tended to settle on total

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[55] Lenton, T.M., 2010. The potential for land-based biological CO2 removal to lower future atmospheric CO2 concentration. *Carbon Management* **1**(1), 145–160.; Smith, P., Martino, D., Cai, Z., Gwary, D., Janzen, H., Kumar, P., McCarl, B., Ogle, S., O'Mara, F., Rice, C., Scholes, B., Sirotenko, O., Howden, M., McAllister, T., Pan, G., Romanenkov, V., Schneider, U., Towprayoon, S., Wattenbach, M., Smith, J., 2008. Greenhouse gas mitigation in agriculture. *Philosophical transactions of the Royal Society of London. Series B, Biological sciences* **363**(1492), 789–813.; Canadell, J.G., Raupach, M.R., 2008. Managing forests for climate change mitigation. *Science* **320**(5882), 1456–7.

[56] Lehmann, J., Czimczik, C., Laird, D., Sohi, S., 2009. Stability of Biochar in Soil, in: Lehmann, J., Joseph, S. (Eds.), *Biochar for Environmental Management*. Earthscan, London.

bioenergy demand of 200-400 EJ per year.[57] The low and high deployment scenarios chosen here represent 60 EJ per year and 200 EJ per year bioenergy supply used for power sector BECCS, respectively, representing approximately 5 $GtCO_2$ per year and 16 $GtCO_2$ per year negative emissions in 2100.

It is even more difficult to make any meaningful prediction of what scale either **Direct Air Capture** or **Ocean Liming** might achieve post-2050, since there is so little firm information on performance and cost of commercial-scale systems and they are not constrained by any single quantity such as land area. To complicate matters further, there are a range of different routes to apply the general concept, each with different resource requirements and scale-up models. There may be no physical limits preventing tens of gigatonnes of negative emissions through these methods, while 'softer' financial, political, or social factors may make this unlikely – for example, McLaren has suggested that, considering the difficulty already evident in transforming and extending the global energy system, the significant energy requirements of DAC and OL systems at the required scale may constrain their expansion through competition for this limited resource.[58] It is not, therefore, possible to define an ultimate 'technical potential' for either technology at this stage.

Here we attempt to give a sense of the plausible scale through comparisons to key global industries in existence today, and putting into context the resources needed to achieve a certain negative emissions flow by each method.

For the case of **Direct Air Capture**, the current oil extraction industry provides a natural scale benchmark for an industry that aims to sequester billions of tonnes of pressurised fluid in geological formations. Global oil production in 2011 was approximately 4.1 billion tonnes.[59] Equivalent Direct Air Capture and storage infrastructure might sequester a similar amount of CO_2. In reality, some proposed DAC approaches are likely to require high temperature heat produced from fossil fuel combustion, so the net sequestration would be reduced by the storage of emissions from this combustion.[60] An oil extraction-sized DAC industry might therefore remove on the order of 3.7 $GtCO_2$ per year, or 1 GtC per year. Use of other storage systems such as mineral carbonation would make DAC less directly comparable, but the global industrial scale would be comparably vast.

Based on early assessments of DAC systems, such an industry might require around 5-7 EJ per year of electricity.[61] If the more technically mature, but more energy-intensive, lime-soda process is used, the high temperature heat required may be 20-30 EJ per year.[61] For context, global electricity supply is around 80 EJ per year, and global natural gas production equates to ~117 EJ per year.[43]

A DAC industry on this scale would require a very significant global scale-up effort, but would not be unreasonably large relative to world energy use and the projected scale of CCS, so we take it as our conservative DAC deployment potential. It is not obvious what an 'upper limit' DAC scenario might look like. In principle, the technology could extract tens of gigatonnes of CO_2 per year, but reaching such a scale would entail an

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[57] Azar, C., Lindgren, K., Obersteiner, M., Riahi, K., Vuuren, D.P., Elzen, K.M.G.J., Möllersten, K., Larson, E.D., 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), 195–202.; Edmonds, J., Luckow, P., Calvin, K., Wise, M., Dooley, J., Kyle, P., Kim, S.H., Patel, P., Clarke, L., 2013. Can radiative forcing be limited to 2.6 Wm−2 without negative emissions from bioenergy AND CO_2 capture and storage? *Climatic Change* **118**(1), 29–43.; Kriegler, E., Edenhofer, O., Reuster, L., Luderer, G., Klein, D., 2013. Is atmospheric carbon dioxide removal a game changer for climate change mitigation? *Climatic Change* **118**(1), 45–57.; Van Vuuren, D.P., Deetman, S., van Vliet, J., van den Berg, M., van Ruijven, B.J., Koelbl, B., 2013. The role of negative CO_2 emissions for reaching 2 °C—insights from integrated assessment modelling. *Climatic Change* **118**(1), 15–27.

[58] McLaren, D. 2014. Capturing the Imagination: Prospects for Direct Air Capture as a Climate Measure (Case Study). Geoengineering Our Climate? Working Paper and Opinion Article Series. Available at: http://wp.me/p2zsRk-9Z

[59] IEA, 2013. *Key World Energy Statistics 2013*. International Energy Agency, Paris.

[60] McLaren, D., 2012. A comparative global assessment of potential negative emissions technologies. *Process Safety and Environmental Protection* **90**(6), 489–500.

[61] Lackner, K.S., 2009. Capture of carbon dioxide from ambient air. *The European Physical Journal Special Topics* **176**(1), 93–106.; Socolow, R., Desmond, M., Aines, R., Blackstock, J., Bolland, O., Kaarsberg, T., Lewis, N., Mazzotti, M., Pfeffer, A., Sawyer, K., Siirola, J., Smit, B., Wilcox, J., 2011. *Direct Air Capture of CO2 with Chemicals: A Technology Assessment for the APS Panel on Public Affairs*. College Park, Maryland; Baciocchi, R., Storti, G., Mazzotti, M., 2006. Process design and energy requirements for the capture of carbon dioxide from air. *Chemical Engineering and Processing: Process Intensification* **45**(12), 1047–1058.

industry many times the scale of the oil industry today, and would require a substantial fraction of global electricity and perhaps fuel supply. The required capital investment and roll-out rate of such an industry and accompanying energy infrastructure would need to be very high relative to historic precedents.

There is even less literature exploring the potential of large-scale **Ocean Liming** to remove large quantities of CO_2 from the atmosphere post-2050. We take a parallel approach to that described above, this time using the current global cement industry as a benchmark.

Global cement production is 3.4 Gt per year. Lime produced at this scale and distributed in the oceans would lead to approximately 0.75 GtC per year drawdown (2.75 $GtCO_2$ per year).[62] Such an industry would require approximately 5 Gt limestone per year, and 8-14 EJ of high temperature heat, depending on the technology (7-12% of current natural gas supply). If fossil fuels were used to provide this heat, and CO_2 released captured, around 2 $GtCO_2$ per year would also need to be stored, although this could be reduced or eliminated significantly through different technologies such as solar-heated lime kilns or integrated silicate carbonation.[46,58] Finally, shipping capacity would be required to disperse lime over the oceans. Renforth et al. suggest that up to 3.7 $GtCO_2$ (1 GtC) net removal per year might be accommodated with spare capacity on existing freight fleets, but larger industries may need a substantial dedicated fleet.[62] Based on the calculations of Renforth et al., however, each further 3.7 $GtCO_2$ per year would require a fleet with total capacity of around 30 million tonnes, less than the average annual growth in bulk cargo shipping capacity in 2006-2010.[63]

As with DAC, we take the cement-industry scale (2.75 $GtCO_2$ per year) as a conservative potential estimate, albeit one that would still require a very significant international deployment push. Rapid Chinese expansion of lime production reached 0.25 Gt per year capacity per year in 2000-2006, implying a potential scale-up time of the order of 15 years for such an industry.[64] Again, industries several times this scale, removing more than 10 $GtCO_2$ per year, are in principle possible, but again would require extremely high rates of scale-up, development of dedicated shipping capacity and energy use making up a significant fraction of world supply.

The high and low estimates for 2100 negative emissions technical potential through each route are summarised in Table 3.

Table 3: High and Low Scenarios of chosen technologies' technical potential to sequester CO_2 in 2100

NET	2100 TP – Low (per year)	Low Scenario Assumptions	2100 TP – High (per year)	High Scenario Assumptions
Afforestation & Other Forestry	0 $GtCO_2$, (0 ppm)	Saturation of new forests; new land used for bioenergy	1-3 $GtCO_2$, 0.13-0.38 ppm	Continued forest expansion
Agricultural Soil Carbon	0 $GtCO_2$, 0 ppm	Saturation of soil sinks	1.3-3.9 $GtCO_2$, 0.17-0.50 ppm	Continued increases in soil carbon e.g. through wider restoration
Biochar	2.2 $GtCO_2$, 0.28 ppm	As 2050; extra biomass goes to bioenergy / BECCS	2.2 $GtCO_2$, 0.28 ppm	As 2050
BECCS	5 $GtCO_2$, 0.64 ppm	60 EJ per year to BECCS at 80% efficiency	>16 $GtCO_2$, >2.0 ppm	>200 EJ per year to BECCS at 80% efficiency
Direct Air Capture	3.7 $GtCO_2$, 0.47 ppm	An oil industry-sized DAC system	>10 $GtCO_2$, >1.3 ppm	No obvious fundamental limit; 10 $GtCO_2$ per year represents ~2.5x oil industry
Ocean Liming	2.75 $GtCO_2$,	A cement industry-sized	>10 $GtCO_2$,	No obvious fundamental limit;

[62] Renforth, P., Jenkins, B.G., Kruger, T., 2013. Engineering challenges of ocean liming. *Energy* **60**, 442–452.
[63] ISL, 2012. *ISL Shipping Statistics and Market Review Volume 56*. Institute of Shipping Economics and Logistics, Bremen.
[64] McGlashan, N., Shah, N., Caldecott, B., Workman, M., 2012. High-level techno-economic assessment of negative emissions technologies. *Process Safety and Environmental Protection* **90**(6), 501–510.

	0.35 ppm	Ocean Liming system	>1.3 ppm	10 $GtCO_2$ per year represents ~3.5x cement industry
TOTAL	13.7 $GtCO_2$, 1.75 ppm		>40 $GtCO_2$ >5 ppm	

Cumulative potential and limits

Based on the above discussion, we now estimate the potential magnitude and timing of cumulative negative emissions available through this century using different methods. For the period 2050-2100, where uncertainty is highest and the technical potentials are least well-constrained, we develop a low-deployment and a high-deployment case for each technology. Table 4 reviews the assumed deployment patterns used for each scenario, also shown graphically in Figures 5 and 6. It must be emphasised again that such deployment patterns are speculative and intended to demonstrate only the timing and order of magnitude of carbon removals that may be possible.

For the cases of biochar, afforestation, and agricultural soil carbon methods, where the technology development and infrastructure is not as significant a constraint in the near-term, we assume linear scale-up of annual removals beginning in 2020 to the technical potential in 2050. For afforestation and agricultural methods, since this potential is so dependent on uncertain factors of the rate of soil carbon uptake and the land area available, the potential is given as a range. For this estimate, we take the mid-point of the given range as illustrative of 2050 potential (2 $GtCO_2$ and 2.6 $GtCO_2$ per year, respectively), but the uncertainty in this value must be recognised.

As discussed above, biochar is assumed to have constant capacity from 2050, making use of a constant stream of wastes and residues. The afforestation and soil carbon high scenarios also assume a constant negative emissions flow is maintained to 2100. In the low scenarios, the flow is assumed to fall to zero linearly from 2050-2100.

Post-2050 scenarios described for BECCS, DAC, and Ocean Liming assume linear scale-up from the 2050 value to the 2100 value associated with each scenario. This may not be realistic, and is not the pattern produced by economic models of future NET deployment. However, given the enormous uncertainty associated with these timescales, such simplified scenarios are sufficient to illustrate the order of magnitude of CO_2 removal that might be achievable globally.

Table 4: Assumed patterns of scale-up over time used for cumulative totals

NET	Deployment pre-2050	Post-2050 – Low Potential	Post-2050 – High Potential
Afforestation & Other Forestry	Linear scale-up to 2 $GtCO_2$ per year 2020-2050	Linear fall to zero 2050-2100	Constant flow of 2 $GtCO_2$ per year to 2100
Agricultural Soil Carbon	Linear scale-up to 2.6 $GtCO_2$ per year 2020-2050	Linear fall to zero 2050-2100	Constant flow of 2.5 $GtCO_2$ per year to 2100
Biochar	Linear scale up to 2.2 $GtCO_2$ per year 2020-2050	Constant flow of 2.2 $GtCO_2$ per year to 2100	Constant flow of 2.2 $GtCO_2$ per year to 2100
BECCS	Linear scale up to 1.5 $GtCO_2$ per year 2030-2050	Linear scale-up to 5 $GtCO_2$ per year in 2100	Linear scale-up to 16 $GtCO_2$ per year in 2100
Direct Air Capture	Linear scale up to 0.5 $GtCO_2$ per year from 2040	Linear scale-up to 3.7 $GtCO_2$ per year in 2100	Linear scale-up to >10 $GtCO_2$ per year in 2100
Ocean Liming	Linear scale up to 0.5 $GtCO_2$ per year from 2040	Linear scale-up to 2.75 $GtCO_2$ per year in 2100	Linear scale-up to >10 $GtCO_2$ in 2100

Figure 4: Assumed pattern of NET deployment over the century – Low Scenario

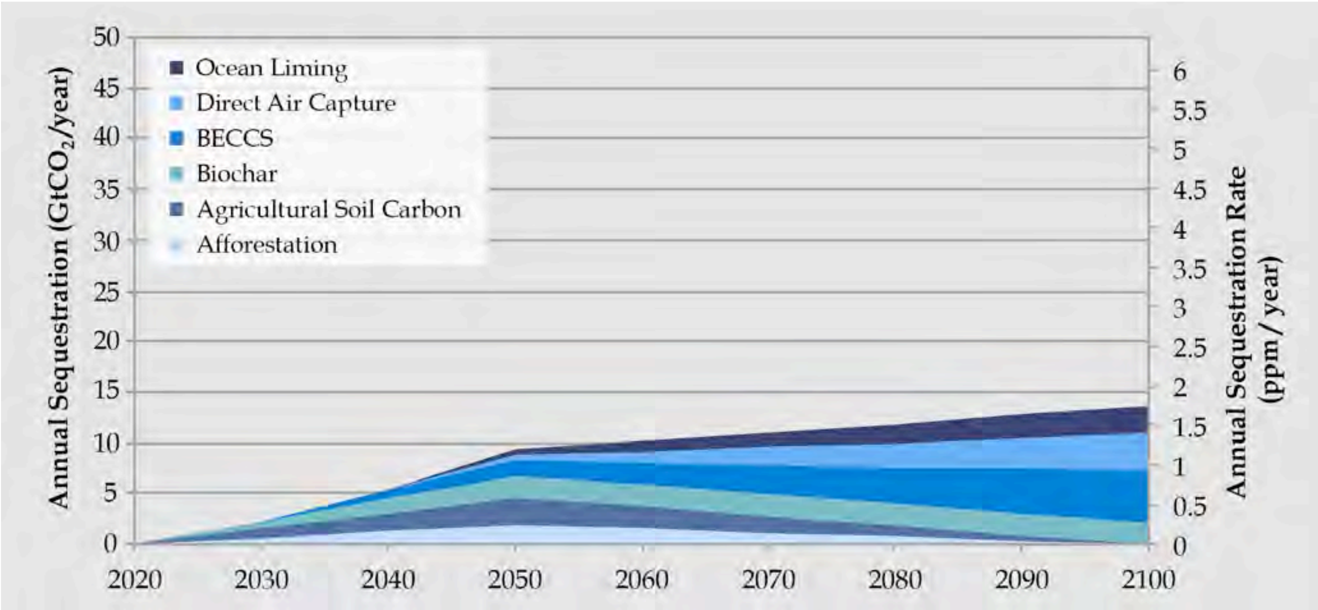


Figure 5: Assumed pattern of NET deployment over the century – High Scenario

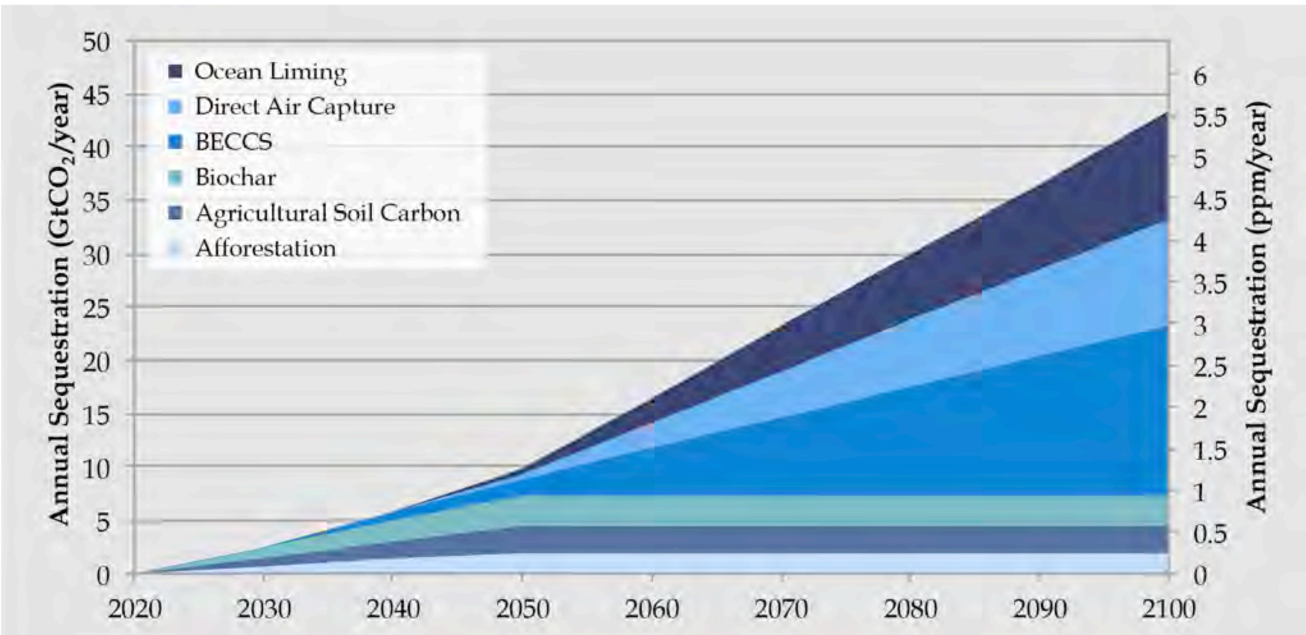


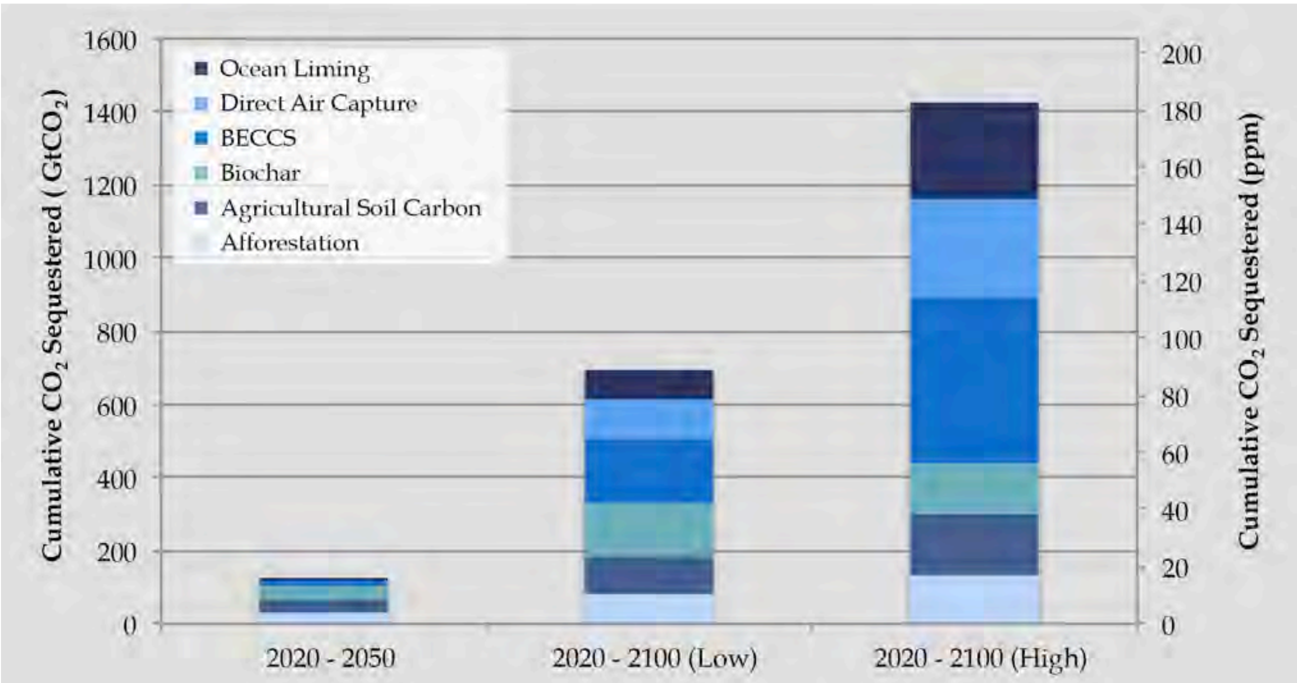
Table 5 and Figure 6 summarise the cumulative figures reached through this illustrative assessment. Again, the orders of magnitude are more significant than the figures themselves, so the totals are rounded to reflect this. Note that in both the table and figure, post-2050 cumulative figures include pre-2050 potential.

Table 5: Summary of order of magnitude cumulative potential sequestration for different technologies and scenarios for 2020-2050 and 2020-2100

NET	2020-2050 Potential	2020-2100 – Low Potential	2020-2100 – High Potential
Afforestation & Other Forestry	30 $GtCO_2$	80 $GtCO_2$	100 $GtCO_2$
Agricultural Soil Carbon	39 $GtCO_2$	104 $GtCO_2$	130 $GtCO_2$
Biochar	33 $GtCO_2$	143 $GtCO_2$	143 $GtCO_2$
BECCS	15 $GtCO_2$	178 $GtCO_2$	453 $GtCO_2$
Direct Air Capture	2.5 $GtCO_2$	108 $GtCO_2$	>260$GtCO_2$
Ocean Liming	2.5 $GtCO_2$	84 $GtCO_2$	>260$GtCO_2$
TOTAL ($GtCO_2$)	~120 $GtCO_2$	~700 $GtCO_2$	>~1,300 $GtCO_2$
TOTAL (ppm)	~15 ppm	~90 ppm	>~165 ppm

A few conclusions are apparent from Figures 5-7. First, the bulk of the cumulative sequestration potential for all NETs under our assumptions occurs in the period after 2050, owing to the timescales of scale-up, delays before deployment of some techniques and simply the longer time period over which techniques could act. This long-term potential is also dominated by those technologies that are the least developed (BECCS, DAC and Ocean Liming). Both of these elements mean the majority of the ultimate potential is subject to the largest uncertainties.

Figure 6: Illustrative cumulative sequestration potential of different NETs to 2050 and 2100



Second, the role of afforestation, soil carbon methods and biochar could nevertheless be cumulatively very significant. As more readily deployable technologies, they will likely dominate the total 2050 potential. But if they can be scaled up in the near term, this 'head start' may also give them a larger share of cumulative 2100 potential relative to more 'scalable' options (BECCS, DAC and OL) than the figures for annual potential would suggest: they form around 50% of total potential for the low scenario and 33% of the high scenario.

Finally, we briefly review limits on cumulative storage capacity of the key carbon reservoirs used by negative emissions technologies to determine the extent to which total capacity might constrain the cumulative negative emissions potential. Table 6 summarises various estimates of cumulative sink capacity, and is broadly adapted from Lenton.[66]

Table 6: Estimated limits on cumulative storage capacity of the key carbon sinks used by NETs

Form of Carbon	Location	Storage Capacity $GtCO_2$	Assumptions	Implications for Negative Emissions Potential Scenarios
Biomass	Permanent new forests	550[65]	Historic deforestation losses	Could constrain total in worst case
		60-540[66]	2100 range reported by Lenton	
Soil Organic Matter	Agricultural, grassland and peatland soils	240-330[67]	Historic soil carbon losses	No constraint, but similar order of magnitude
Biochar in Soils	Cropland only	820[66]	1.6 Gha, 140 tC/ha	No constraint this century
	All potential land	~1,800[66]	1.25 Gha, 140 tC/ha	
Pressurised CO_2	Oil and gas fields	675-900[66]	Based on IPCC estimates	If only the better characterised storage in abandoned oil and gas fields is considered, this may constrain total potential; there is no constraint if deep saline formation capacity is available
	Unmineable coal seams	15-200[66]		
	Deep saline formations	1,000-10,000[66]		
	All storage	400-2,000[68]	'Cautious' assessment (see text)	Lower estimates could severely constrain total potential for DAC, BECCS and perhaps Ocean Liming
Dissolved carbonate & bicarbonate	Oceans	1,400[69]	1% increase in ocean carbon pool	No constraint this century, but will require further research on environmental impacts and appropriate international agreements

Geological storage of pressurised CO_2 merits a more detailed discussion, since it is a key storage medium for DAC, BECCS, and Ocean Liming, and must also accommodate CO_2 captured from conventional fossil and industrial CCS. It potentially offers extremely large storage capacity, but our geological and operational knowledge are such that the ultimately accessible capacity is still highly uncertain. In a major IPCC study of CCS, 200 $GtCO_2$ of capacity was deemed virtually certain, 2,000 $GtCO_2$ likely to be available, and 11,000 $GtCO_2$

[65] Canadell, J.G., Raupach, M.R., 2008. Managing forests for climate change mitigation. *Science* **320**(5882), 1456–7.
[66] Lenton, T.M., 2010. The potential for land-based biological CO2 removal to lower future atmospheric CO2 concentration. *Carbon Management* **1**(1), 145–160.
[67] Lal, R., 2004. Soil carbon sequestration to mitigate climate change. *Geoderma* **123**(1-2), 1–22.
[68] McLaren, D., 2012. A comparative global assessment of potential negative emissions technologies. *Process Safety and Environmental Protection* **90**(6), 489–500.
[69] IPCC (2007) *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press: Cambridge, United Kingdom and New York, NY, USA.

possibly available.[70] Storage in depleted oil and gas fields makes up much of the 'likely available' category, since there is comparatively high confidence in their geology and storage integrity. However, the bulk of the total potential depends on deep saline aquifers, the behaviour of which is less well constrained. McLaren suggests that until the behaviour and accessibility of geological reservoirs is better understood, a cautious range of 400-2,000 GtCO_2 cumulative space should be assumed available.

How this translates into negative emissions capacity is complicated by the multiple technologies competing for this space (including conventional CCS), and the different life-cycle atmospheric removal each attains per tonne of CO_2 stored. While all the CO_2 stored by DAC systems powered by renewable energy may represent true atmospheric removal, systems where fossil fuels are combusted to provide heat may require 1.5-2 tonnes of CO_2 to be stored per tonne of CO_2 removed from the atmosphere. For BECCS, the figure may be 1.25-1.5 tonnes stored per tonne removed, or up to 5 tonnes for low-level co-firing.[71] Conventional fossil fuel CCS, with no net transfer of CO_2 from the atmosphere to storage, represents a waste of storage space from this perspective, and proposed deployment would likely reduce storage space available to NETs by hundreds of gigatonnes.

A detailed assessment of the implications of storage on various technology combinations is not attempted here, but it is notable that lower estimates on the order of 500 GtCO_2 would severely constrain the combined DAC, BECCS, and Ocean Liming potentials over 2050-2100 described above, especially if conventional CCS on the order of >200 GtCO_2 cumulative storage is assumed.

The constraint of geological storage capacity could be removed entirely, however, through the development of effective and economical mineral carbonation technology.[70,72] There are known to be sufficient magnesium and calcium silicate resources worldwide to fix in excess of 10,000 GtCO_2 in stable mineral form, in principle negating the need for storage and much of the associated infrastructure. However, overcoming the slow kinetics of the carbonation reaction currently entails a large energy input and high associated costs, and the reaction stoichiometry would require new extractive industries processing a mass of rock of around double the mass of CO_2 to be stored,[72] with the infrastructure and environmental challenges that would entail. Mineral carbonation is a promising prospect, but provides no easy solution to the problem of CO_2 storage.

[70] IPCC, 2005. *IPCC Special Report on Carbon Dioxide Capture and Storage*. Prepared by Working Group III of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
[71] McLaren, D., 2012. A comparative global assessment of potential negative emissions technologies. *Process Safety and Environmental Protection* **90**(6), 489–500.
[72] Olajire, A., 2013. A review of mineral carbonation technology in sequestration of CO_2. *Journal of Petroleum Science and Engineering* **109**, 364–392.

4. Stranded assets

'Stranded assets' are assets that have suffered from unanticipated or premature write-downs, devaluations, or conversion to liabilities.[73] They are a regular feature of economic systems and a phenomenon inherent in the 'creative destruction'[74] of economic growth. Recent developments illustrate that environment-related risks are increasingly responsible for stranding assets today, and these are likely to grow in significance over time.[75] Caldecott et al. (2013) propose a typology for the different environment-related risks that could cause stranded assets, which are set out below.[76] These risk factors could have a significant impact on the ability of different asset classes to generate value in the future, including physical, financial, natural, and intangible assets.[77] The prospect of stranded assets as a result has recently emerged as an area of concern and this has been flagged by academic institutions, financial institutions, and advocacy organisations.[78]

Table 7: Typology of environment-related risk[79]

SET	SUBSET
Environmental change	Climate change; natural capital depletion and degradation; biodiversity loss and decreasing species richness; air, land, and water contamination; habitat loss; and freshwater availability.
Resource landscapes	Price and availability of different resources such as oil, gas, coal and other minerals and metals; e.g. shale gas revolution, phosphate availability, and rare earth metals.
Government regulations	Carbon pricing (via taxes and trading schemes); subsidy regimes (e.g. for fossil fuels and renewables); air pollution regulation; voluntary and compulsory disclosure requirements; changing liability regimes and stricter licence conditions for operation; the 'carbon bubble' and international climate policy.
Technological change	Falling clean technology costs (e.g. solar PV, onshore wind); disruptive technologies; GMO; and electric vehicles.
Social norms and consumer behaviour	Fossil fuel divestment campaign; product labelling and certification schemes; and changing consumer preferences.
Litigation and statutory interpretations	Carbon liability; litigation; damages; and changes in the way existing laws are applied or interpreted.

From the late 1980s and accelerating rapidly from 2000, individuals and organisations working on sustainability issues began to acknowledge the possibility that climate policy and regulation could negatively the influence value or profitability of fossil fuel companies to the point that their assets could become impaired.[80] With the

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[73] Caldecott, B.L. and McDaniels, J., (2014). *Financial dynamics of the environment: risks, impacts, and barriers to resilience*. Working Paper Series, Smith School of Enterprise and Environment, University of Oxford.
[74] A term popularised by Schumpeter, see:
Reinert, H. and E. Reinert (2006). Creative Destruction in Economics: Nietzsche, Sombart, Schumpeter. Friedrich Nietzsche (1844–1900). J. Backhaus and W. Drechsler, Springer US. **3:** 55-85.
[75] Caldecott, B. L., J. Tilbury and C. Carey (2014). Stranded Assets and Scenarios. Discussion Paper, Smith School of Enterprise and Environment, University of Oxford.
[76] Caldecott, B., Howarth, N. and McSharry, P. (2013). *Stranded Assets in Agriculture: Protecting Value from Environment-Related Risks.* Stranded Asset Programme, Smith School of Enterprise and the Environment, Oxford University; Caldecott, B.L. and McDaniels, J. (2014) *Financial dynamics of the environment: risks, impacts, and barriers to resilience*. Working Paper Series, Smith School of Enterprise and Environment, University of Oxford.
[77] Ibid.
[78] Caldecott, B. L. (2012). Review of UK exposure to high carbon investments B. o. E. s. F. P. Commitee. London, UK, Climate Change Capital.
[79] Caldecott, B., Howarth, N. and McSharry, P. (2013). *Stranded Assets in Agriculture: Protecting Value from Environment-Related Risks.* Stranded Asset Programme, Smith School of Enterprise and the Environment, Oxford University; Caldecott, B.L. and McDaniels, J. (2014) *Financial dynamics of the environment: risks, impacts, and barriers to resilience*. Working Paper Series, Smith School of Enterprise and Environment, University of Oxford.
[80] IPCC (2001). IPCC Third Assessement Report - Climate Change 2001. Geneva, Switzerland, Intergovernmental Panel on Climate Change. IPCC, 2001; IEA (2008). World Energy Outlook 2008. Paris, France, International Energy Agency

concept of a global 'carbon budget'[81] – the cumulative atmospheric CO_2 emissions allowable for 2 degrees of global warming – there was one way of anticipating when 'stranded carbon assets' might occur. When the amount of fossil fuels combusted, plus the amount of carbon accounted for in reserves yet to be burned, exceeded the carbon budget, either carbon targets or the value of fossil fuel assets would have to give.

This issue has risen up the investment and policy agenda, particularly following the 2011 publication of *Unburnable Carbon*, the findings of which were popularised by the environmentalist Bill McKibben.[82] The concept of 'unburnable carbon'[83] – the proportion of fossil-fuel reserves that must remain in the ground in order to stay within the carbon budget – quantified the disconnect between the value of the listed equity of global energy firms and their potential commercialisation under a strict carbon constraint introduced by climate policy.

This paper has examined how NETs could help to extend carbon budgets and provide more time to reduce emissions, thereby potentially altering the risk profile of carbon assets that could become stranded. In the previous section we found that, between now and 2050, there may be the technical potential to attain negative emissions of the order of 120 $GtCO_2$ cumulatively (~15 ppm reduction), with most of this potential coming from afforestation, soil carbon improvements, and some biochar deployed in the near term. These options tend to have lower capital requirements, greater technical maturity and potential for significant co-benefits, but forestry and soil carbon carry higher risks of impermanence.

This potential represents an extension of the 2050 carbon budget by 11-13% for a 50-80% probability of meeting a 2-degree warming target.[84] More industrial technologies (DAC, Ocean Liming, and BECCS) that rely on CCS are likely to have very limited potential by 2050, largely due to limits imposed by CCS development and more significant technical and policy challenges. Their contribution to the pre-2050 potential is estimated at only around 20 $GtCO_2$ (2.5 ppm), or an extension of only ~2% of the 2050 carbon budget.

Cumulative negative emissions potential between now and 2100 is difficult to estimate. The long-term performance, costs, feasibility and impacts of large-scale deployment of the technologies that provide the bulk of post-2050 potential – BECCS, DAC, and Ocean Liming – are highly uncertain, and the wider social, political, environmental, and economic context in which they would be deployed are also well beyond our ability to predict accurately. In principle, over 1,000 $GtCO_2$ might be possible in the second half of the century, but reaching this depends on extreme rates of NET deployment after 2050. The cumulative technical potential of all NETs considered between now and 2100, in scenarios of maximum deployment, may be of the order of ~700-1350 $GtCO_2$, or 90-170 ppm. This represents an extension of the global carbon budget of 70-140% or more (for an 80% chance to remain below 2°C) or 45-90% or more (for a 50% chance). Reaching even the lower bound of this range, however, would already require deployment of negative emissions and CO_2 storage infrastructure on an improbably massive global scale.

The availability and accessibility of geological storage for CO_2 is a key uncertainty. If ultimately realisable storage is towards the low end of current estimates due to physical, technological, or political factors, this could severely constrain the total negative emissions attainable through BECCS, DAC, and in some cases Ocean Liming in the 2050-2100 period.

Given these significant uncertainties and deployment challenges, it would be foolhardy for an owner or operator of carbon-intensive assets to assume that NETs will fundamentally alter the carbon budgets that they may face due to climate policy and regulation. This is particularly the case for point source emissions from power stations and the like, as there are already a number of viable options to deal with these emissions. It would be hard to argue that resorting to highly uncertain NETs prior to undertaking a variety of mitigation options would be an economically or socially desirable course of action. Considering the technological, socio-political, and economic

[81] Krause, F., W. Backh and J. Koomey (1989). *From Warming Fate to Warming Limit: Benchmarks to a Global Climate Convention*. El Cerrito, CA, International Project for Sustainable Energy Paths.
[82] McKibben, B. (2011). Global Warming's Terrifying New Math. *Rolling Stone*.
[83] CTI (2011). Unburnable Carbon: Are the world's financial markets carrying a carbon bubble?, Carbon Tracker Initiative.
[84] CTI (2013). Unburnable Carbon 2013: Wasted Capital and Stranded Assets, Carbon Tracker Initiative.

barriers facing the more scalable negative emissions technologies, it is extremely unlikely that a situation will be able to develop whereby a fossil fuel intensive sector could operate alongside a large-scale negative emissions sector.

Sectors with non-point source emissions where technical and economic barriers to mitigation are particularly acute would have the most to gain from NETs deployment – aviation and agriculture being two prominent examples. Biological processes in agriculture mean that a certain amount of carbon emissions are unavoidable. In aviation, emissions can only be reduced so far given the dependency on the jet engine and associated high-energy density liquid fuels.[85]

In the absence of technical solutions, it could make sense for policymakers concerned with emissions from these activities to develop NETs in order to cover the 'residual' emissions generated after feasible mitigation actions are taken. These negative emissions might also be 'no-regrets' if the NETs developed were afforestation, soil carbon improvements, and biochar, which have co-benefits (such as enhanced soil fertility), but no CCS dependency and few downside risks. They also have lower upfront capital costs and far fewer uncertainties than other NETs. Matching the development of these No-Regrets NETs (NR NETs) with the scale of residual emissions from stubborn non-point source emitters like agriculture and aviation, if feasible, would create a target deployment rate that could be supported by governments and industry alike. More work would need to be done to design and test the feasibility of such deployment pathways.

Businesses operating in these sectors have an obvious interest in ensuring that NETs, particularly of the no-regrets variety, are developed quickly and at the lowest possible cost. Afforestation, soil carbon improvements, and biochar appear to have the lowest costs and the most potential between now and 2050, and would make a logical area for policymakers and the private sector to focus attention and resources on. CCS technology is key for post-2050 NETs potential and ensuring that this is available for DAC, Ocean Liming, and BECCS after 2050 is critical if globally significant deployment potential for these technologies is to be available. This should be another priority area for public-private collaboration.

Extending carbon budgets through NETs may buy time for owners and operators of assets at risk to exit their investments or put in place ways to manage their risk exposure. This paper has found that the technical potential for NETs by 2050 is in the order of 120 $GtCO_2$ cumulatively, which is approximately 2.5 years of current global greenhouse gas emissions. While this may provide some time, there are several important caveats: i) carbon budgets and the policies applied to implement them are not in 'sync', so a slightly larger carbon budget is unlikely to perfectly translate into commensurately 'softer' policies and regulations; ii) technical potentials are often much higher than ultimately realised potentials (an issue emphasised throughout this paper); iii) policymakers might not 'bank' a projected and uncertain carbon budget extension in the near term, but decide to wait until NETs deployment is successful. Due to the effects of discounting, this would then have little impact on firm or investor decision-making today.

The geographical and sectoral distribution of costs and benefits associated with NETs are highly uncertain. The spatial distribution of NETs development, production, deployment depends on the nature of the technology in question and will vary considerably between them. The benefits of successful deployment accrue to everyone and so there are significant free-rider issues. To what extent NETs might affect competition between coal, gas, and oil and influence the distribution of carbon budgets between fossil fuel basins is uncertain, but could be factored into existing scenario analysis.[86] This would help us to understand the winners and losers from NETs – for example would oil benefit the most, due to its role in producing transport-related non-point source emissions? These and related questions would be productive areas for further research.

[85] Caldecott, B. L. and S. Tooze (2009). Green skies thinking: promoting the development and commercialisation of sustainable bio-jet fuels. London, UK, Policy Exchange.
[86] For example: McGlade, C. and P. Ekins (2015). "The geographical distribution of fossil fuels unused when limiting global warming to 2 [deg]C." Nature **517**(7533): 187-190.

But the fact remains, that even if NETs were deployed successfully at sufficient scale to increase carbon budgets for sectors like agriculture and aviation, it would not protect business as usual. The extent to which sectors might benefit from NETs deployment depends on the cost of NETs and who bears these costs – variables exposed to significant uncertainty. If the sectors that benefit pay a proportion of development and deployment costs, which given the polluter pays principle might reasonably be expected to happen, business models would still be affected. So even sectors that might be 'bullish' or optimistic about NETs and their implications for future business, might be wise to temper this optimism. Either way, carbon budgets if implemented in some form, with or without NETs, will impact their activities and in ways that are difficult to predict.

5. Conclusions and recommendations

The uncertainties and challenges associated with NETs deployment are significant. While NETs are capable of making a contribution to tackling climate change, particularly for 'stubborn' non-point source emissions, they are very unlikely to alter the sheer scale of mitigation required between now and 2050. While it is conceivable that there is significant technical potential beyond 2050, this is extremely uncertain.

Nevertheless, it makes sense to continue investing in the development of 'low probability, high impact' post-2050 options in the hope that viable, large-scale NETs might be available in the unfortunate (but increasingly likely) event that they are required. The nature of these investments will vary by technology, but one thing is certain – without viable CCS large-scale post-2050 NETs will not be available.

In addition to these observations, there are several related recommendations that carbon-intensive sectors and policymakers should take into account when considering NETs:

First, 'no-regrets' NETs (NR NETs), which are characterised by low upfront capital costs, co-benefits (such as enhanced soil fertility), no CCS dependence, economic and environmental co-benefits, and fewer uncertainties, include afforestation, soil carbon improvements, and biochar. Even considering the potential for limited release of stored carbon in the future, they are the most promising NETs between now and 2050. To the extent that NR NETs create additional carbon budget, this should be reserved for the residual emissions (emissions after feasible mitigation actions) from important, but 'stubborn' non-point source emitters like agriculture and aviation. It is possible that NR NETs will have a niche role by 2050 offsetting these difficult to mitigate emissions sources. Policymakers and the owners and operators of assets in the relevant sectors should work together to maximise NR NETs deployment, minimise residual emissions from stubborn sectors, and develop plausible deployment pathways.

Secondly, the question of the cost of NETs and how those costs are shared is of profound importance for a range of issues, including the following: understanding how assets might be impacted by such costs; securing the cash flows and financing necessary for NETs deployment; and identifying implications for fairness and sustainable development. The challenge of commissioning and paying for conventional CCS demonstration plants highlights how difficult these issues are to resolve. International cooperation to address free riding and related issues is also required and this should be overlaid on to existing international processes and negotiations.

Thirdly, successful NETs deployment would not mean business as usual for carbon-intensive assets. Sectors (and consumers) will have to pay directly or indirectly for the cost of mitigation actions, and quite probably the cost of negative emissions deployment, to address overshoot and stubborn emissions from non-point sources. NETs deployment addresses risk on the one hand (by extending carbon budgets), and creates it on the other (through new and uncertain costs). NETs should not be seen as a *deus ex machina* that will 'save the day'. Consequently, businesses and investors need to factor carbon asset risk into their business planning and strategic asset allocation processes. Scenario planning and regular assessments of how carbon budgets are being translated into policy and regulation will be important,[87] as is work to understand other environment-related risks that could strand assets.

Fourthly, CCS is a key bottleneck for post-2050 NETs and this should be addressed to keep the option open for significant future deployment of DAC, Ocean Liming, and BECCS. While this option is uncertain, it is of sufficiently high potential impact to merit investment, as long as a possible dilemma can be resolved: deploying conventional CCS today results in positive net emissions and uses finite geological storage that might constrain storage capacity in the future; but unless conventional CCS is deployed at scale, the technology for negative emissions CCS might never be developed. The trade-off between these options and to what extent conventional

[87] See: Caldecott, B. L., J. Tilbury and C. Carey (2014). Stranded Assets and Scenarios. Discussion Paper, Smith School of Enterprise and Environment, University of Oxford.

CCS needs to be deployed for DAC, Ocean Liming, and BECCS to be viable future options is an important area for future research.

Finally, it is clear that attaining negative emissions is in no sense an easier option than reducing current emissions. To remove CO_2 on a comparable scale to the rate it is being emitted inevitably requires effort and infrastructure on a comparable scale to global energy or agricultural systems. Combined with the potentially high costs and energy requirements of several technologies, and the global effort needed to approach the technical potentials discussed previously, it is clear that very large-scale negative emissions deployment, if it were possible, is not in any sense preferable to timely decarbonisation of the energy and agricultural systems.

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