Research Paper

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# Net Zero and Beyond
## What Role for Bioenergy with Carbon Capture and Storage?

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## Summary

- Current climate efforts are not progressing quickly enough to prevent the world from overshooting the global emissions targets set in the Paris Agreement; accordingly, attention is turning increasingly to options for removing carbon dioxide from the atmosphere – 'carbon dioxide removal' (CDR).
- Alongside afforestation and reforestation, the main option under discussion is bioenergy with carbon capture and storage (BECCS): processes through which the carbon emissions from burning biomass for energy are captured before release into the atmosphere and stored in underground reservoirs.
- This pre-eminent status is not, however, based on a comprehensive analysis of the feasibility and impacts of BECCS. In reality, BECCS has many drawbacks.
- Models generally assume that biomass for energy is inherently carbon-neutral (and thus that BECCS, by capturing and storing the emissions from combustion, is carbon-negative), but in reality this is not a valid assumption.
- On top of this, the deployment of BECCS at the scales assumed in most models would consume land on a scale comparable to half that currently taken up by global cropland, entailing massive land-use change, potentially endangering food security and biodiversity. There is also significant doubt about the likely energy output of BECCS solutions.
- BECCS may still have some role to play in strategies for CDR, depending mainly on the feedstock used; but it should be evaluated on the same basis as other CDR options, such as nature-based solutions or direct air carbon capture and storage (DACCS). Analysis should take full account of carbon balances over time, the requirements of each CDR option in terms of demand for land, water and other inputs, and the consequences of that demand.
- There is an urgent need for policymakers to engage with these debates. The danger at the moment is that policymakers are 'sleepwalking towards BECCS' simply because most models incorporate it – or, almost as bad, it may be that they are simply ignoring the need for any meaningful action on CDR as a whole.

## Introduction

In the context of seeking to reduce greenhouse gas emissions to net zero, policymakers are beginning to pay more attention to options for removing carbon dioxide from the atmosphere – a process referred to as CDR ('carbon dioxide removal'). Without the rapid scale-up of such measures, achieving Paris Agreement temperature targets will be increasingly challenging: current emissions abatement efforts are not progressing quickly enough to prevent the world from overshooting global emissions targets.

In theory, CDR measures may permit the total costs of a climate mitigation strategy to be reduced in absolute terms (or amortized over a longer period); enable ambitious targets (such as limiting global warming to 1.5°C) to become more feasible; or delay the point when peak emissions are reached, retroactively compensating for overshooting the cumulative carbon budget.

A wide range of potential CDR measures are currently being discussed.[1] Alongside afforestation and reforestation, the main option featuring in integrated assessment models (IAMs) is bioenergy with carbon capture and storage (BECCS). BECCS refers to a set of technologies and processes through which the carbon emissions from burning biomass for energy are captured before release into the atmosphere, and then stored in underground reservoirs. If this biomass energy is assumed to be carbon-neutral, BECCS should theoretically result in net negative emissions, as the accompanying carbon sequestered by biomass is permanently stored.

The prominence of BECCS in the models does not, however, represent a prescriptive judgment about its merits relative to other negative emissions options. Nor does it necessarily validate the current, highly constrained, development trajectory of BECCS technology. It is, rather, a reflection mainly of the fact that BECCS is based on well-understood biology, so it is easier to make assumptions about and model the impacts on emissions at various carbon prices. In contrast, evaluating the potential of newer and more speculative negative emissions technologies is more challenging.

In reality, there are many reasons to question the reliance on BECCS assumed in the models – including the carbon balances achievable,[2] the substantial demand for land, water and other inputs that is associated with BECCS solutions, and the underlying assumption that technically and economically viable carbon capture and storage (CCS) technologies will be available 'off the shelf' in the near term, which is not being borne out in practice.

This is not to argue that BECCS cannot play a role in CDR, but that, as with other options, it offers no silver bullet. Rather, all CDR approaches need to be evaluated on comparable terms against a range of sustainability and socio-political criteria. Such evaluations should inform the development of a portfolio of locally appropriate (and cumulatively globally significant) CDR solutions, including those that are nature-based, such as afforestation and reforestation. Alongside the acceleration of conventional abatement action, these portfolios of solutions will need to be deployed as rapidly

[1] For overviews, see European Academies Science Advisory Council (EASAC) (2018), *Negative Emission Technologies: What role in meeting Paris Agreement targets?*, Halle, Germany: EASAC; Royal Society (2018), *Greenhouse Gas Removal*, London: Royal Society and Royal Academy of Engineering; Morrow, D. R., Buck, H. J., Burns, W. C. G., Nicholson, S. and Turkaly, C. (2018), *Why Talk about Carbon Removal?*, Washington, DC: Institute for Carbon Removal Law and Policy, American University, doi:10.17606/M6H66H; National Academies of Sciences, Engineering, and Medicine (2019), *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda*, Washington, DC: The National Academies Press, doi:10.17226/25259; Fajardy, M., Köberle, A., Mac Dowell, N. and Fantuzzi, A. (2019), *BECCS Deployment: A Reality Check,* London: Imperial College, Grantham Institute Briefing Paper No. 28, https://www.imperial.ac.uk/media/imperial-college/grantham-institute/public/publications/briefing-papers/BECCS-deployment---a-reality-check.pdf; EASAC (2019), *Forest Bioenergy, Carbon Capture and Storage and Carbon Dioxide Removal: An Update*, https://easac.eu/publications/details/forest-bioenergy-carbon-capture-and-storage-and-carbon-dioxide-removal-an-update/.
[2] These are not always negative. The actual carbon balances achievable vary significantly, depending on a wide range of factors that include, crucially, the feedstocks used.

as possible. Delays in developing the requisite policy and regulatory frameworks will increase the risks of overshooting atmospheric carbon limits, in turn necessitating much larger and riskier negative emissions initiatives in the future.[3]

## What is BECCS?

As already indicated, the term 'BECCS' covers a number of different carbon capture technologies. The system most commonly referred to involves the capture of carbon dioxide emitted from the combustion of biomass for heat and power. Potential capture technologies are the same as those beginning to be deployed and under development for conventional fossil fuel plants, and include post-combustion, oxy-combustion (combustion in pure oxygen rather than air), and pre-combustion gasification (high-temperature non-combustive reactions between biomass and oxygen and/or steam to produce synthesis gas, which is a combustible fuel). An alternative approach captures carbon dioxide from fermentation processes, such as those used to produce ethanol from crops such as maize, wheat or sugarcane. This has the advantage of resulting in a purer stream of carbon dioxide that is easier to process. The carbon dioxide captured can then be transported to geological storage at sites such as saline aquifers or abandoned oil wells, just as with conventional CCS projects.

Another approach, depending on the feedstock and process conditions, is to produce a proportion of the carbon as 'biochar' (solid carbon). Biochar has various uses, mainly related to increasing agricultural productivity by improving soil conditions. Although questions remain about the long-term stability of biochar, its use in agricultural soils may reduce the need for fertilizer, since it absorbs and slowly releases nutrients such as phosphorus to plants, improves soil moisture retention (increasing the drought tolerance of crops), improves germination rates and reduces methane emissions from rice paddies. Despite various pilot projects, however, biochar has not yet been deployed at a commercial scale.

BECCS projects and models typically involve five main categories of feedstock:

- **Wood:** either from whole trees harvested specifically for bioenergy or from forestry wastes and residues, such as small branches, bark and thinnings left over from forestry operations.
- **Industrial wood wastes and residues from wood-processing industries (e.g. sawmills):** this includes black liquor, a waste product of chemical pulp and paper processes.
- **Energy crops:** crops grown specifically for energy supply, including fast-growing trees (e.g. willow, poplar and eucalyptus) and herbaceous crops such as miscanthus (elephant grass), switchgrass or energy cane (genetically modified sugarcane).
- **Agricultural residues:** including field residues (materials left in the field after a crop has been harvested, such as stalks, stubble or leaves) and process residues (leftover materials from the processing of crops for food or other products, including husks, seeds, bagasse,[4] molasses and roots).
- **Other organic wastes:** including post-consumer wood waste, the organic fraction of municipal solid waste, livestock manures, sewage sludge, tallow and used cooking oil.

[3] The increased scale would inherently result in increased resource demand and all the downside risks that this would entail, as well as the very real possibility that, once safe atmospheric concentrations of carbon had been exceeded, irreversible earth-system processes (such as the melting of ice caps) might be triggered that no amount of CDR could retroactively reverse.
[4] The dry pulpy residue that remains after sugarcane or sorghum stalks are crushed to extract their juice.

There is currently an extensive industry using modern technologies to convert energy from biomass without CCS into applications for heat, power or transport. The industry is particularly well developed in the EU, mainly as a result of member state renewable energy targets set out in the 2009 Renewable Energy Directive. Heat, power, liquid and gaseous fuel production processes are all amenable to the addition of CCS, though the capture potential is generally higher for heat and power.

Worldwide, the main biomass feedstock for heat and power is currently wood, though municipal wastes, agricultural residues, and palm oil and other vegetable oils are also used in various locations. Wood is more energy-dense (and slower-growing) than most other feedstocks, and tends to be easier to collect, process, store and transport, often as wood chips or pellets. Some types of residues, particularly bagasse from sugarcane processing and black liquor produced from the digestion of pulpwood into paper pulp, are harder to transport and generally used for power generation on site in sugar mills or paper mills.

The main feedstocks for liquid biofuels – which are usually used in transport applications, though sometimes for heat and power – are oil crops such as oil palm, soybean, rapeseed and sunflower (for biodiesel), and starch crops such as wheat, maize (corn), sugarbeet and sugarcane (for bioethanol). A range of other feedstocks, including wastes, agricultural residues and algae (a high-energy-density feedstock with the potential to significantly reduce land and water constraints), are under development or beginning to enter commercial production.

Biogas is less extensively used in modern energy systems, though production has increased in recent years (particularly in the EU), mainly through anaerobic digestion – a collection of processes by which micro-organisms break down biodegradable material in the absence of oxygen. Most existing installations process residual sludge from wastewater treatment plants or agricultural and food waste, though in principle almost any organic waste can be used. Biogas can be used directly for heat, power or transport, or injected into natural gas grids for heating.

## The growing role of BECCS in mitigation scenarios

The concept of BECCS first emerged in the late 1990s and early 2000s; the term itself was coined in 2003.[5] In 2007, for the first time, the Intergovernmental Panel on Climate Change (IPCC), in its Fourth Assessment Report, identified BECCS as a potential option for stabilizing greenhouse gas emissions or as a rapid-response prevention strategy for abrupt climate change. It offered the following caution, however:

> To date, detailed analysis of large-scale biomass conversion with $CO_2$ capture and storage is scarce … further research is necessary to characterise biomass's long-term mitigation potential … and opportunity costs … In particular, present studies are relatively poor in representing land competition with food supply and timber production, which has a significant influence on the economic potential of bio-energy crops.[6]

In 2011, the IPCC's special report on renewable energy contained only limited coverage of BECCS and no quantification of its potential. In the same year, the International Energy Agency (IEA) reviewed the potential of BECCS in different forms, including dedicated biomass stations with CCS,

[5] Hickman, L. (2016), 'Timeline: How BECCS became climate change's 'saviour' technology', Carbon Brief, 13 April 2016, https://www.carbonbrief.org/beccs-the-story-of-climate-changes-saviour-technology.
[6] IPCC (2007), *Climate Change 2007: Mitigation of Climate Change. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Metz, B., Davidson, O. R., Bosch, P. R., Dave, R. and Meyer, L. A. (eds)], Cambridge and New York: Cambridge University Press, p. 211, https://www.ipcc.ch/site/assets/uploads/2018/03/ar4_wg3_full_report-1.pdf.

co-firing with coal with CCS, and liquid biofuel production with CCS.[7] The IEA concluded that the potential technically existed for negative greenhouse gas emissions of up to 10 gigatonnes of carbon dioxide ($GtCO_2$) annually (a significant level; in comparison, total global emissions in 2017 were 53.5 $GtCO_2e$), with the largest reductions coming from dedicated biomass power generation with CCS. The report identified the immaturity of the technology, uncertainty over the availability of sustainable biomass supply and secure and permanent carbon dioxide storage, and negative public perceptions of CCS as important barriers, though it considered that the association of CCS with biomass, as a renewable energy technology, could possibly help overcome public resistance.

BECCS assumed a much more prominent role in the IPCC's Fifth Assessment Report. Across the 116 scenarios reviewed that were consistent with limiting global warming to 2°C, 101 involved some form of negative emissions, either through BECCS or afforestation and reforestation.

In 2014, BECCS assumed a much more prominent role in the IPCC's Fifth Assessment Report. Across the 116 scenarios reviewed that were consistent with limiting global warming to 2°C, 101 involved some form of negative emissions, either through BECCS or afforestation and reforestation. The average level of BECCS deployment by 2100 in these scenarios was 12.1 $GtCO_2$/year (full range: 0–22 $GtCO_2$/year).[8] Every scenario aiming to limit global warming to 1.5°C included BECCS.[9] The scenarios considered in the report required BECCS, in particular, to compensate for residual emissions from sectors where mitigation was more expensive, such as aviation or agriculture, or to return emissions to target levels after an overshoot resulting from a lack of near-term action. The synthesis report concluded: 'Many models could not limit *likely* warming to below 2°C … if … bioenergy, CCS, and their combination (BECCS) are limited (*high confidence*).'[10]

However, these scenarios did not evaluate the on-the-ground feasibility of such removals; they merely demonstrated the necessity of CDR given the emissions profiles in the scenarios. Important factors limiting the extent of BECCS included uncertain land availability, the likely difficulty of ensuring a sustainable supply of biomass and storage capacity, and possible competition for biomass from other uses of bioenergy. The IPCC cautioned: 'The use of BECCS faces large challenges in financing, and currently no such plants have been built and tested at scale.'[11]

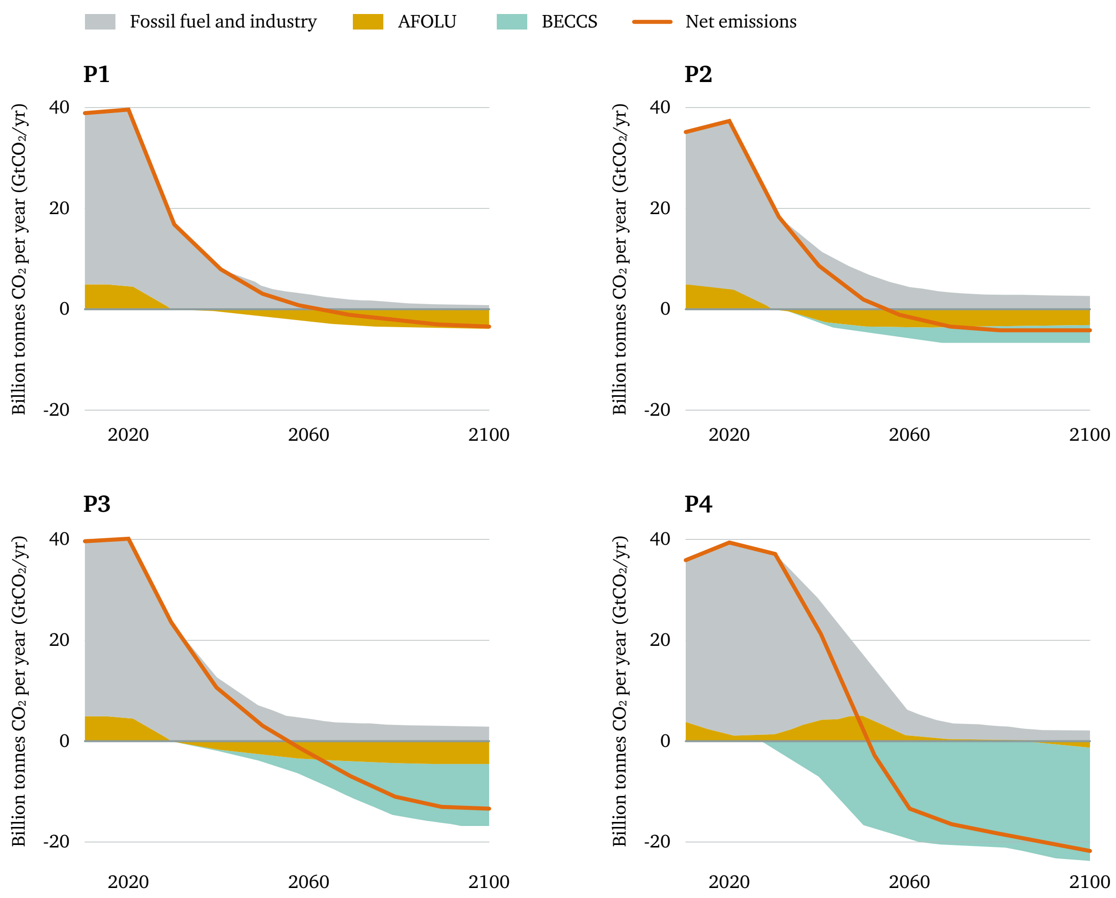
Despite such caveats, the increasing attention paid to BECCS has continued into the IPCC's Sixth Assessment cycle, including both the 2018 special report on *Global Warming of 1.5°C* (SR1.5)[12] and

[7] Ecofys (2011), *Potential for Biomass and Carbon Dioxide Capture and Storage,* Paris: IEA, http://www.eenews.net/assets/2011/08/04/document_cw_01.pdf.
[8] Smith, P. and Porter, J. R. (2018), 'Bioenergy in the IPCC assessments', *Global Change Biology Bioenergy,* pp. 428–31, doi: 10.1111/gcbb.12514.
[9] 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* [Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Farahani, E., Kadner, S., Seyboth, K., Adler, A., Baum, I., Brunner, S., Eickemeier, P., Kriemann, B., Savolainen, J., Schlömer, S., von Stechow, C., Zwickel, T. and Minx, J. C. (eds)], Cambridge and New York: Cambridge University Press, https://www.ipcc.ch/report/ar5/wg3/. Also see Fuss, S. (2016), 'The role of BECCS in climate change mitigation: potentials and limits', presentation to IEA BECCS Specialist Meeting, London, 23 June 2016.
[10] IPCC (2015), *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Core Writing Team, Pachauri, R. K. and Meyer, L. A. (eds)], Geneva: IPCC, p. 85, https://www.ipcc.ch/pdf/assessment-report/ar5/syr/SYR_AR5_FINAL_full_wcover.pdf.
[11] IPCC (2014), *Climate Change 2014: Mitigation of Climate Change*, p. 486.
[12] IPCC (2018), *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* [Masson-Delmotte, V., Zhai, P., Pörtner, H.-O., Roberts, D., Skea, J., Shukla, P. R., Pirani, A., Moufouma-Okia, W., Péan, C., Pidcock, R., Connors, S., Matthews, J. B. R., Chen, Y., Zhou, X., Gomis, M. I., Lonnoy, E., Maycock, T., Tignor, M. and Waterfield, T. (eds)], https://www.ipcc.ch/sr15/.

the 2019 special report on *Climate Change and Land* (SRCCL),[13] each of which contains critical appraisals of the feasibility, costs and benefits of extensive use of BECCS in meeting 1.5–2°C warming limitation targets. SR1.5 sets out four illustrative model pathways to limit warming to 1.5°C, three of which involve no or limited overshooting of cumulative emissions targets (see Figure 1). All four pathways include contributions from various means of CDR, mainly BECCS and afforestation and reforestation:

- P1 (focus on reducing energy demand): no contribution from BECCS.
- P2 (broad focus on sustainability): cumulative 151 $GtCO_2$ captured by BECCS to 2100.
- P3 (middle-of-the-road scenario, largely following historical patterns): cumulative 414 $GtCO_2$ captured by BECCS to 2100.
- P4 (resource- and energy-intensive overshoot scenario in which emissions reductions are mainly achieved through BECCS): cumulative 1,191 $GtCO_2$ captured by BECCS to 2100.

### Figure 1: Breakdown of contributions to global net $CO_2$ emissions in four illustrative model pathways




Source: IPCC (2018), *Global Warming of 1.5°C*, p. 14. Note: AFOLU = agriculture, forestry and other land use.

[13] IPCC (2019), *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems* [Shukla, P. R., Skea, J., Calvo Buendia, E., Masson-Delmotte, V., Pörtner, H.-O., Roberts, D. C., Zhai, P., Slade, R., Connors, S., van Diemen, R., Ferrat, M., Haughey, E., Luz, S., Neogi, S., Pathak, M., Petzold, J., Portugal Pereira, J., Vyas, P., Huntley, E., Kissick, K., Belkacemi, M. and Malley, J. (eds)], https://www.ipcc.ch/srccl/.

In all of these 1.5°C scenarios,[14] generation of negative emissions is required to begin in the first half of the century; the urgency and scale of the requirement depend on the degree of emissions abatement elsewhere in the economy. Under the most intransigent scenario (P4), the total area of land required for bioenergy crops for BECCS is 7.2 million km$^2$, more than double the area of India or equivalent to around half of the current extent of global croplands.[15]

The literature and models reviewed by SR1.5 exhibit huge variations in mitigation potential for BECCS, ranging from 1 $GtCO_2$/year to 85 $GtCO_2$/year by 2050. The report accepted, however, the more cautious assessment made in a recent systematic review of the literature on global negative emissions potentials, which concluded that the most likely scope for BECCS, taking into account other sustainability aims, was 0.5–5 $GtCO_2$/year, at costs of US$100–200/$tCO_2$.[16]

SR1.5 touched on the factors constraining the availability of BECCS feedstock and highlighted the associated demand for land and water:

> Large-scale deployment of BECCS and/or AR [afforestation and reforestation] would have a far-reaching land and water footprint (*high confidence*). Whether this footprint would result in adverse impacts, for example on biodiversity or food production, depends on the existence and effectiveness of measures to conserve land carbon stocks, measures to limit agricultural expansion in order to protect natural ecosystems, and the potential to increase agricultural productivity (*medium agreement*).[17]

This theme was taken up in greater detail in SRCCL, which reached similar conclusions. It also noted that:

> These impacts are context specific and depend on the scale of deployment, initial land use, land type, bioenergy feedstock, initial carbon stocks, climatic region and management regime, and other land-demanding response options can have a similar range of consequences (*high confidence*).[18]

Certainly, where feedstocks are sourced from high-carbon ecosystems (such as primary forests), this would result in large initial carbon losses and long payback periods, meaning that the protection of ecosystems would be a more optimal approach.[19]

SRCCL also clearly demonstrated that the risks from widespread BECCS deployment are closely linked to the overall sustainability of development trajectories. It considered various socioeconomic pathways, from sustainability-focused to resource-intensive, and the land-use implications of mitigation actions that would be compatible with limiting warming to 1.5°C under each pathway. At the more sustainable end (SSP1), with low populations, effective land-use regulation, food systems with low greenhouse gas emissions, and lower food losses and waste, the aggregate risks to food security, land quality and water supply in drylands only hit moderate levels when bioenergy or BECCS feedstocks occupy 1–4 million km$^2$ of land, largely because changes in food demand free up land for biomass. At the other end of the spectrum – pathways associated with high populations, low income and slow rates of technological change (such as SSP3) – moderate risks emerge when bioenergy feedstocks occupy a far more modest 0.1–1 million km$^2$.

[14] These pathways are something of an exception, as the majority of feasible 1.5°C and 2°C emissions pathways in IAMs are budget overshoot pathways with high discount rates.
[15] IPCC (2018), *Global Warming of 1.5°C,* 'Summary for Policymakers', p. 14.
[16] Fuss, S., Lamb, W. F., Callaghan, M. W., Hilaire, J., Creutzig, F., Amann, T., Beringer, T., de Oliveira Garcia, W., Hartmann, J., Khanna, T., Luderer, G., Nemet, G. F., Rogelj, J., Smith. P., Vicente, J. L. V., Wilcox, J., del Mar Zamora Dominguez, M. and Minx, J. C. (2018), 'Negative emissions—Part 2: Costs, potentials and side effects', *Environmental Research Letters*, 13(6), doi:10.1088/1748-9326/aabf9f.
[17] IPCC (2018), *Global Warming of 1.5°C*, p. 180.
[18] IPCC (2019), *Climate Change and Land*, 'Summary for Policymakers'.
[19] Ibid., Chapter 2.

Although other potential negative emissions technologies – such as direct air carbon capture and storage (DACCS) and enhanced weathering – are increasingly reviewed in the literature, and were considered in the AR6 special reports, they feature less frequently quantitatively in IAMs. Rather, BECCS has assumed almost a default role in many of these models because – as mentioned – its impacts on emissions are relatively straightforward to quantify at various carbon prices compared with those of other (even more nascent) negative emissions technologies:

> Technologies other than BECCS and afforestation have yet to be comprehensively assessed in integrated assessment approaches. No proposed technology is close to deployment at scale, and regulatory frameworks are not established. This limits how they can be realistically implemented within IAMs.[20]

## Development of CCS and BECCS technologies

Despite the greater amenability of BECCS to quantitative modelling than many other negative emissions technologies, it is still only a fledgling technology, unproven at scale (see Box 1). Its slow progress is part of a wider picture of sluggish development of CCS technology generally. By 2019, 18 large-scale CCS facilities were in commercial operation worldwide, capturing 40 million tonnes of carbon dioxide a year (though only around a tenth of this was in geological storage);[21] this was an increase from 15 facilities and 28 million tonnes three years earlier. A further five facilities were under construction and 20 were in various stages of development.[22] While significant, this is far from the trajectory needed to satisfy Paris Agreement-compatible capture rates under the IEA's Energy Technology Perspectives scenarios. Under the reference technology scenario, in which CCS expansion is consistent with 2017 growth rates (reflecting a continuing lack of investment incentives), total CCS deployment reaches 1.3 $GtCO_2$/year by 2060 (more than 30 times the total 2019 capacity). Under the 2°C scenario, deployment reaches 6.8 $GtCO_2$/year (of which BECCS accounts for 2.7 $GtCO_2$). Under the 'beyond 2°C' scenario, CCS deployment reaches 11.2 $GtCO_2$/year by 2060 (with BECCS accounting for 4.9 $GtCO_2$).[23]

### Box 1: The slow progress of BECCS projects

By 2019, worldwide, only one BECCS project was operating at commercial scale: the Illinois Industrial CCS facility at Decatur in the US.[24] Owned by the multinational agribusiness firm Archer Daniels Midland, the plant produces ethanol from corn, with the fermentation process generating an almost pure stream of carbon dioxide. The carbon dioxide is injected into local porous sandstone formations beneath three layers of dense shale. Co-funded by the US government, the plant has been capturing an estimated 1 million tonnes of carbon dioxide a year since 2017. Since the plant itself is largely powered by gas, however, it is still a net emitter overall. Furthermore, the ethanol is largely destined for use in road transport, thus ultimately producing carbon dioxide and rendering the lifecycle emissions of the bioenergy potentially net positive despite the significant CCS component.[25]

[20] IPCC (2018), *Global Warming of 1.5°C*, p. 158.
[21] Fajardy et al. (2019), *BECCS Deployment: A Reality Check*.
[22] Global CCS Institute (undated), 'Large Scale CCS Projects', http://www.globalccsinstitute.com/projects/large-scale-ccs-projects.
[23] IEA (2017), *Energy Technology Perspectives 2017*, Paris: IEA, https://webstore.iea.org/energy-technology-perspectives-2017.
[24] Consoli, C. (2019), *Bioenergy and Carbon Capture and Storage: 2019 Perspective*, Melbourne: Global CCS Institute, https://www.globalccsinstitute.com/wp-content/uploads/2019/03/BECCS-Perspective_FINAL_PDF.pdf.
[25] Yeo, S. and Pearce, R. (2016), 'Analysis: Negative emissions tested at world's first major BECCS facility', Carbon Brief, 31 May 2016, https://www.carbonbrief.org/analysis-negative-emissions-tested-worlds-first-major-beccs-facility.

Other ethanol production plants have the ability to capture carbon dioxide for use in enhanced oil recovery; in 2019 the Global CCS Institute identified three such plants in the US and one in Canada.[26] A large proportion (estimated at 90–95 per cent) of the carbon dioxide thus used is likely to be stored permanently.[27] Another six facilities were operating or had recently operated to capture carbon dioxide for other uses, mainly crop cultivation in greenhouses; in these cases the carbon dioxide is vented into the atmosphere and not stored. Five of these facilities – four in Europe, one in the US – are ethanol plants, and the sixth is a very small waste-to-energy plant in Japan.

Three additional BECCS projects are at earlier stages, and others are being proposed or planned.[28] In Omuta in Japan, construction is under way to install CCS equipment in Toshiba's Mikawa power plant, which was converted from coal to biomass (palm kernel shells) in 2017.[29] Following a pilot phase, which started in 2009 and captured 10 tonnes of carbon dioxide a day, the new equipment is designed to capture more than 500 tonnes per day, about 50 per cent of the plant's emissions, with the aim of evaluating the performance of the carbon dioxide absorption technology (which uses ammonia-derived solvents to wash carbon dioxide out of mixed flue gases) under various operating conditions. Work to identify secure offshore storage is under way.

In February 2019, a BECCS demonstration project began capturing carbon dioxide at Drax in the UK, currently the largest biomass-burning power station (mainly burning wood pellets) in the world.[30] The project was designed to capture 1 tonne of carbon dioxide a day over a period of six months to test a proprietary solvent developed by the company C-Capture, with the aim of scaling up the process in due course. What will happen to the captured carbon dioxide is not clear. News reports have suggested that the company has been in discussion with the British Beer and Pub Association over use of the carbon dioxide in brewing, and that in the longer term its use is being contemplated in the manufacture of synthetic fuels. Such a process, although potentially carbon-reducing relative to fossil fuels, would not achieve the negative emissions potentials of long-term carbon storage (due to carbon being re-released at the point of synfuel combustion).[31] In May 2019, Drax signed a memorandum of understanding with Equinor and National Grid Ventures, committing the parties to work together to explore how a large-scale carbon capture, usage and storage network and a hydrogen production facility could be constructed in the mid-2020s.[32]

Finally, design work is under way on Norway's full-chain CCS demonstration project.[33] The intention is for an estimated 400,000 tonnes of carbon dioxide a year to be captured from each of two facilities: the Klemetsrud waste-to-energy plant and the Norcem cement plant (which currently co-fires up to 30 per cent biomass). In each case, the carbon dioxide captured will be stored on site until it can be transported by ship for injection into a sub-sea reservoir off the Norwegian coast in the North Sea. The final investment decision is intended to be taken in 2020/21, with the project beginning operation in 2023/24.

In general, CCS technology has proved more expensive and less effective than originally expected. As in other areas, the falling prices of renewable energy technologies, particularly solar photovoltaic (PV) and wind, have undercut the appeal of CCS as a low-carbon option. This has accelerated the phase-out of coal, thus partially removing one of the sources of fossil fuels that CCS was intended for. CCS equipment can be fitted to gas-fired power plants and industrial processes, but the reductions

[26] Consoli (2019), *Bioenergy and Carbon Capture and Storage: 2019 Perspective*.
[27] Núñez-López, V. and Moskal, E. (2019), 'Potential of $CO_2$-EOR for Near-Term Decarbonization', Front. Clim., 27 September 2019, doi:10.3389/fclim.2019.00005.
[28] Ibid.
[29] Kitamura, H. (2019), 'Toshiba's Activity in Ministry of the Environment Sustainable CCS Project', presentation to Japan CCS Forum, 12 June 2019, https://www.globalccsinstitute.com/wp-content/uploads/2019/06/HO_SS4a_ToshibaES.pdf.
[30] Drax (2019), 'Carbon dioxide now being captured in first of its kind BECCS pilot', press release, 7 February 2019, https://www.drax.com/press_release/world-first-CO2-beccs-ccus/.
[31] Holder, M. (2019) '"World-first": Drax BECCS pilot begins capturing carbon emissions', *Business Green*, 7 February 2019, https://www.businessgreen.com/bg/news/3070608/world-first-drax-beccs-pilot-begins-capturing-carbon-emissions.
[32] Drax (2019), 'Leading energy companies announce new zero-carbon UK partnership', press release, 27 May 2019, https://www.drax.com/press_release/energy-companies-announce-new-zero-carbon-uk-partnership-ccus-hydrogen-beccs-humber-equinor-national-grid/.
[33] Simon, F. (2018), 'Norway's latest CCS revival attempt meets lukewarm EU response', EURACTIV.com, 12 October 2018, https://www.euractiv.com/section/energy/news/norways-latest-ccs-revival-attempt-meets-lukewarm-eu-response/.

in carbon emissions are lower than for coal, and therefore the cost per tonne of carbon captured is higher. This is not to negate the importance of CCS for industrial uses, but the case for energy-related CCS is beginning to be eroded.

The steady adoption of national net zero greenhouse gas emissions targets can be expected to accelerate progress, however, particularly in the development of CCS for hard-to-treat sources such as industrial process emissions. Some countries are beginning to put support policies in place. But as the IPCC observed in SR1.5, CCS is largely absent from countries' Nationally Determined Contributions (NDCs) under the Paris Agreement and generally ranks low in investment priorities.[34] CCS was only identified as a priority in three of the Intended NDCs submitted in the run-up to the 2015 Paris conference, and BECCS was absent from all of them.[35] This clearly places a constraint on the rapid deployment of BECCS projects.

## Is BECCS carbon-negative?

The vast majority of papers discussing BECCS take as their starting point the assumption that biomass energy is by definition carbon-neutral: i.e., that the emissions from consuming the biomass are part of a natural cycle in which, over time, tree or plant growth balances the carbon emitted on combustion (as long as the trees or crops are regrown after harvesting). Hence, the reasoning goes, if even a proportion of those combustive emissions are captured, BECCS will result in net negative emissions. The assumption of carbon neutrality is very widely held, underlying, for example, all the models of the potential for BECCS reviewed by the IPCC in its Fifth Assessment Report. Although recent studies,[36] including some reviewed in SR1.5,[37] have increasingly recognized that this central assumption is invalid,[38] understanding of the potential limitations of BECCS is not yet widespread. For example, although ways to account for the impact of bioenergy production on soil degradation are actively being developed in IAMs, such impact was not comprehensively accounted for in SR1.5.[39]

> In reality, the net impact on the atmosphere is a combination of all these variables, along with the emission/capture volumes at the point of combustion and counterfactual factors – i.e. what would have happened to the biomass if it had not been burnt for energy?

A full carbon lifecycle analysis must take into account a wide range of factors that affect the balance between carbon in biomass and in the atmosphere. These factors include: the impacts of any initial land clearance to grow trees or crops; any indirect land-use effects (e.g. from the clearance of forests to grow agricultural crops displaced by energy crops); any losses of soil carbon during harvesting (which are generally significant); supply-chain emissions from the energy consumed in harvesting,

[34] IPCC (2018), *Global Warming of 1.5°C*, p. 346.
[35] Fuss, S., Jones, C. D., Kraxner, F., Peters, G. P., Smith, P., Tavoni, M., van Vuuren, D. P., Canadell, J. G., Jackson, R. B., Milne, J., Moreira, J. R., Nakicenovic, N., Sharifi, A. and Yamagata, Y. (2016), 'Research priorities for negative emissions', *Environmental Research Letters*, 11(11), p. 115007, doi: 10.1088/1748-9326/11/11/115007; 'Paris Reality Check - pledged climate futures', https://www.pik-potsdam.de/paris-reality-check/indcs-carbon-capture-and-storage/.
[36] Fuss et al. (2016), 'Research priorities for negative emissions'.
[37] IPCC (2018), *Global Warming of 1.5°C*, Chapter 2, 'Supplementary Material'.
[38] For a longer discussion of this topic, see Brack, D. (2017), *Woody Biomass for Power and Heat: Impacts on the Global Climate*, London: Royal Institute of International Affairs, https://www.chathamhouse.org/publication/woody-biomass-power-and-heat-impacts-global-climate; and EASAC (2017), *Multi-functionality and sustainability in the European Union's forests*, Halle, Germany: EASAC, https://easac.eu/fileadmin/PDF_s/reports_statements/Forests/EASAC_Forests_web_complete.pdf.
[39] IPCC (2018), *Global Warming of 1.5°C,* Chapter 2.

processing and transporting biomass; and – particularly for trees – the time delay until replacement trees are large enough to absorb carbon at the same rate as the harvested trees. In reality, the net impact on the atmosphere is a combination of all these variables, along with the emission/capture volumes at the point of combustion and counterfactual factors – i.e. what would have happened to the biomass if it had not been burnt for energy?

Left to themselves, trees continue to grow and sequester carbon. If trees or energy crops are harvested specifically for energy, not only is the stored biomass converted into carbon dioxide but the future carbon sequestration potential of that vegetation is lost.

Left to themselves, trees continue to grow and sequester carbon. If trees or energy crops are harvested specifically for energy, not only is the stored biomass converted into carbon dioxide (which may or may not be captured) but the future carbon sequestration potential of that vegetation – i.e. the carbon that would have been absorbed during the remainder of the tree or plant's lifetime – is lost. This foregone sequestration can be replaced if replanting occurs after harvesting, but the initial rate of absorption may be slower; this is particularly true for trees, since although young trees grow faster than mature specimens, their much lower leaf cover means they absorb much less carbon from the atmosphere.[40] As a 2014 study concluded:

> For most species mass growth rate increases continuously with tree size. Thus, large, old trees do not act simply as senescent carbon reservoirs but actively fix large amounts of carbon compared to smaller trees; at the extreme, a single big tree can add the same amount of carbon to the forest within a year as is contained in an entire mid-sized tree.[41]

There is a difference between the carbon sequestration rates of individual trees and entire forests, however; older forests tend to contain fewer trees, as an increasing number succumb to pests or disease. Nevertheless, a 2008 study concluded that 'in forests between 15 and 800 years of age, net ecosystem productivity (the net carbon balance of the forest including soils) is usually positive'.[42] Older trees and forests also store higher volumes of carbon than their younger counterparts, though there is a risk that – unlike geological carbon repositories that are more or less permanent – vegetative stores of carbon can rapidly be transformed from carbon sinks into carbon sources if unsustainably felled or lost to wildfires; they are therefore vulnerable to social, political, economic and environmental changes, and need safeguarding against dangerous positive-feedback cycles.

[40] See, for example, Luyssaert, S., Schulze, E.-D., Börner, A., Knohl, A., Hessenmöller, D., Law, B. E., Ciais, P. and Grace, J. (2008), 'Old-growth forests as global carbon sinks', *Nature,* 455, doi: 10.1038/nature07276; Lewis, S., Lopez-Gonzalez, G., Sonké, B., Affum-Baffoe, K., Baker, T. R., Ojo, L. O., Phillips, O. L., Reitsma, J. M., White, L., Comiskey, J. A., Djuikouo K, M.-N., Ewango, C. E. N., Feldpausch, T. R., Hamilton, A. C., Gloor, M., Hart, T., Hladik, A., Lloyd, J., Lovett, J. C., Makana, J.-R., Malhi, Y., Mbago, F. M., Ndangalasi, H. J., Peacock, J., Peh, K. S.-H., Sheil, D., Sunderland, T., Swaine, M. D., Taplin, J., Taylor, D., Thomas, S. C., Votere, R. and Wöll, H. (2009), 'Increasing carbon storage in intact African tropical forests', *Nature,* 457, https://www.nature.com/articles/nature07771; Bellassen, V. and Luyssaert, S. (2014), 'Carbon sequestration: Managing forests in uncertain times', *Nature,* 506, https://www.nature.com/news/carbon-sequestration-managing-forests-in-uncertain-times-1.14687; Stephenson, N. L., Das, A. J., Condit, R., Russo, S. E., Baker, P. J., Beckman, N. G., Coomes, D. A., Lines, E. R., Morris, W. K., Rüger, N., Álvarez, E., Blundo, C., Bunyavejchewin, S., Chuyong, G., Davies, S. J., Duque, Á., Ewango, C. N., Flores. O., Franklin, J. F., Grau, H. R., Hao, Z., Harmon, M. E., Hubbell, S. P., Kenfack, D., Lin, Y., Makana, J.-R., Malizia, A., Malizia, L. R., Pabst, R. J., Pongpattananurak, N., Su, S.-H., Sun, I.-F., Tan, S., Thomas, D., van Mantgem, P. J., Wang, X., Wiser, S. K. and Zavala, M. A. (2014), 'Rate of tree carbon accumulation increases continuously with tree size', *Nature*, 507, doi: 10.1038/nature12914; and Craggs, G. (2016), *The Role of Old-Growth Forests in Carbon Sequestration*, Future Directions International. Over 60 studies showing the same phenomenon are summarized in *$CO_2$ Science* (2014), 'Forests (Growth Rates of Old vs. Young Trees) – Summary'.
[41] Stephenson et al. (2014), 'Rate of tree carbon accumulation increases continuously with tree size'.
[42] Luyssaert et al. (2008), 'Old-growth forests as global carbon sinks', pp. 213–15.

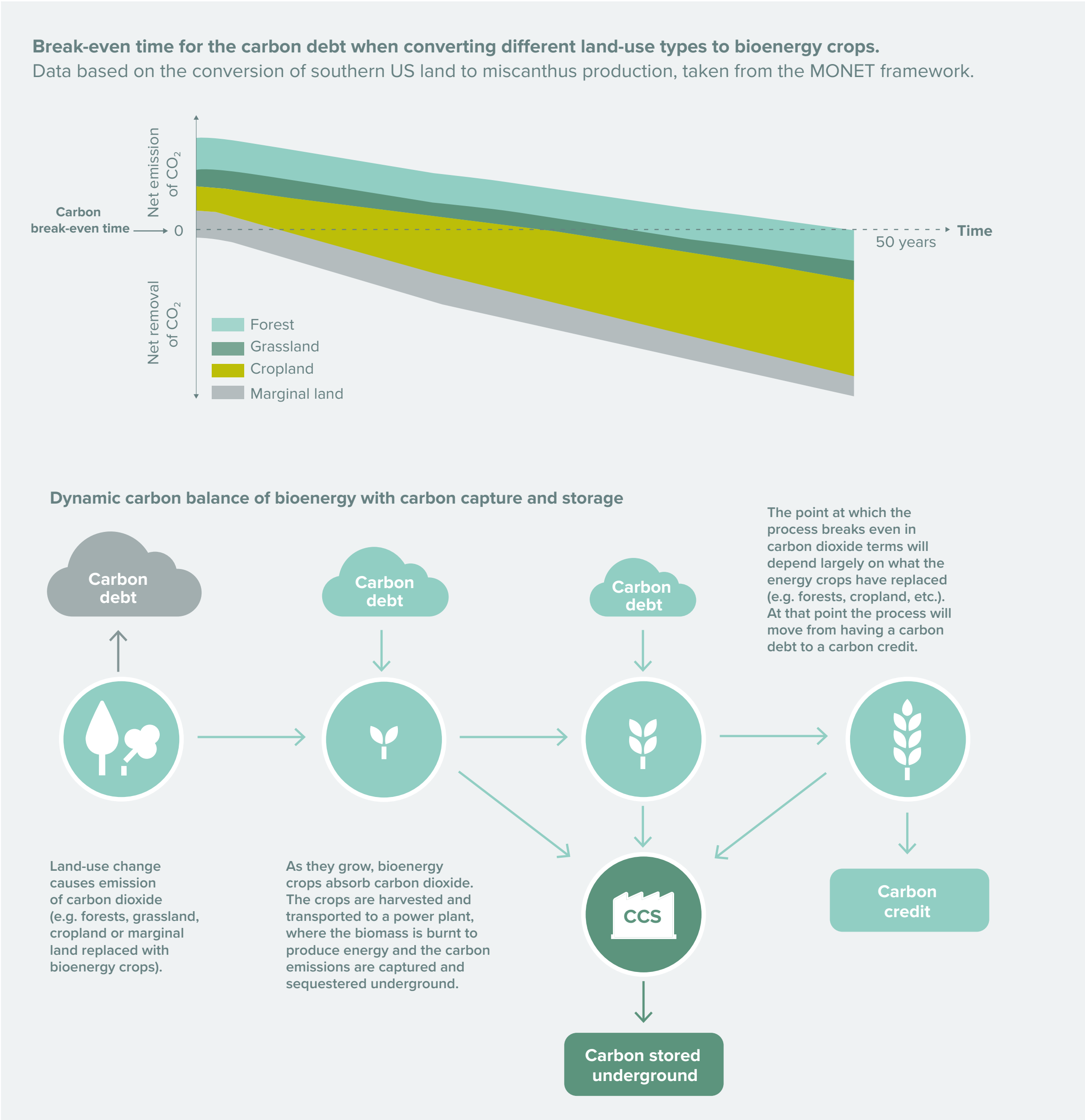
The balance is different for faster-growing coppices, where the difference in carbon sequestration rates between young and mature plants is much smaller. Even in these cases, however, it is important to measure the climate impacts of regular planting and harvesting. Tree plantations are much poorer at storing carbon than are natural forests, which develop with little or no disturbance from humans. The regular harvesting and clearing of plantations – which would be necessary to guarantee a regular supply of BECCS feedstock (if wood were the main feedstock) – releases stored carbon dioxide back into the atmosphere every 10–20 years. In practice, as a 2019 study concluded, 'plantations hold little more carbon, on average, than the land cleared to plant them'.[43] By contrast, natural forests continue to sequester carbon for many decades or even centuries, implying that stopping deforestation and promoting natural forest restoration, if and where possible, are likely to be better CDR options than using forests as BECCS feedstock sources. These options will not provide energy co-benefits, but the energy balance of BECCS is in any case contestable (see next section).

> Although the potential deployment rates for carbon-negative biomass are frequently lower than suggested by IAMs, the possibilities that its use presents are nonetheless substantial and could be exploited in appropriate circumstances.

Dedicated energy crops grow much more rapidly than trees, and harvesting therefore has a smaller impact on carbon sequestration rates; the main impact on the carbon break-even time – i.e. the time needed until the net carbon balance is zero – derives from the nature of the land-use conversion to establish the crop in the first place. If energy crops are planted on lands with a high carbon stock (e.g. as is the case when established forests are converted to such crops), then it can take anything from decades to over a century to compensate for the carbon losses from the initial land-use change.[44] Conversely, establishing energy crops on marginal lands can result in much faster carbon neutrality and much deeper carbon dioxide removals over time (see Figure 2). There is also the potential for positive, synergistic outcomes – such as management of dryland salinity, enhancement of biodiversity and reduced eutrophication – if perennial bioenergy crops are strategically and appropriately integrated with conventional crops.[45] Thus, although the potential deployment rates for carbon-negative biomass are frequently lower than suggested by IAMs, the possibilities that its use presents are nonetheless substantial and could be exploited in appropriate circumstances.

[43] Lewis, S. L., Wheeler, C., Mitchard, E. T. A. and Koch, A. (2019), 'Regenerate natural forests to store carbon', *Nature*, 568, pp: 25–28, doi: 10.1038/d41586-019-01026-8.
[44] IPCC (2019), *Climate Change and Land*, Chapter 6, cross-chapter box 7.
[45] Ibid.

### Figure 2: Impacts of land-use change on BECCS carbon break-even times




Source: Fajardy et al. (2019), *BECCS Deployment: A Reality Check*.

If agricultural or forest wastes or residues are used, clearly the impacts on forest or soil carbon stocks are much lower, since these do not involve harvesting (and consequent loss of future sequestration). Calculating the overall carbon impact is particularly complicated, however, due to the varying consequences of counterfactual uses. Sawmill residues can be used for engineered wood products, locking the carbon in the built environment, as well as for energy. If forest and agricultural residues that would otherwise have been left to rot and fertilize soils in situ are removed, this may have significant negative impacts in terms of soil degradation[46] and associated declines in levels of soil carbon and rates of tree growth.

[46] Ibid.

A further important component of carbon lifecycle balances in BECCS systems concerns the question of how much carbon is captured and stored during the combustion process. In SR1.5, the IPCC reported assumed capture rates of about 90 per cent of the carbon dioxide emitted from electricity and hydrogen production, and rates of about 40–50 per cent from liquid fuel production.[47] More complex models including supply-chain emissions suggested lower capture rates, of about 50 per cent and 25 per cent respectively.[48]

The net effect on carbon balances between living biomass, soil carbon, the atmosphere and carbon captured are not the only impacts of BECCS processes on climate change.[49] Biomass and biofuel production and combustion can lead to emissions of largely uncapturable 'black carbon', a short-lived climate forcer; of nitrous oxide from fertilizer use; and of methane from combustion and biomass decomposition in anaerobic conditions. Land-cover changes or land-use disturbances, including forest harvesting or conversion of natural lands to energy crops, can also lead to changes in albedo, surface roughness and evapotranspiration, with negative impacts on the climate system.

Thus, there are many circumstances under which BECCS may not result in net negative emissions – or could even increase carbon dioxide concentrations in the atmosphere by eroding forest carbon sinks. The carbon removal potential and time required for BECCS to become carbon-negative vary greatly depending on the feedstocks, supply-chain emissions, direct and indirect land-use changes, and whether the system is optimized for negative emissions or for power or heat production. Fully accounting for all these net changes is difficult, as some of the factors are highly species- and location-specific, but doing so is crucial in calculating the net effect of BECCS on the atmosphere and in stress-testing the efficiencies assumed by some IAMs.

While some of these factors – supply-chain and direct (though not usually indirect) land-use change emissions in particular – may be taken into account in models and policy frameworks, losses of soil carbon and changes in forest carbon stock over time are generally ignored in both models and policy frameworks, even though these are crucial to the net impact on the atmosphere. A 2019 review of 100 widely cited lifecycle assessments of bioenergy found that 71 of them assumed that 'biogenic carbon dioxide does not impact climate change'.[50] This casts serious doubts over the potential for BECCS assumed in many of the models. If BECCS involves replacing high-carbon-content ecosystems with energy crops, it is likely to be ineffectual in reducing atmospheric carbon dioxide for a sustained period; leaving the ecosystem intact is thus likely to be a better option.[51]

## Is BECCS energy-supply-positive?

Many of the IAMs reviewed by the IPCC in successive reports project a significant reliance on BECCS not just for carbon removal but also for energy supply – with projected annual contributions of 150–300 exajoules (EJ), or 14–20 per cent of global primary energy supply, by 2100, alongside

[47] IPCC (2018), *Global Warming of 1.5°C*, p. 124.
[48] Fajardy et al. (2019), *BECCS Deployment: A Reality Check*.
[49] National Academies of Sciences, Engineering, and Medicine (2019), *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda*.
[50] Agostini, A., Giuntoli, J., Marelli, L. and Amaducci, S. (2019), 'Flaws in the interpretation phase of bioenergy LCA fuel the debate and mislead policymakers', *The International Journal of Life Cycle Assessment*, doi:10.1007/s11367-019-01654-2.
[51] See, for example, IPCC (2019), *Climate Change and Land*; and Harper, A., Powell, T., Cox, P., House, J., Huntingford, C., Lenton, T. M., Sitch, S., Burke, E., Chadburn, S. E., Collins, W. J., Comyn-Platt, E., Daioglou, V., Doelman, J. C., Hayman, G., Robertson, E., van Vuuren, D., Wiltshire, A., Webber, C. P., Bastos, A., Boysen, L., Ciais, P., Devaraju, N., Jain, A. K., Krause, A., Poulter, B. and Shu, S. (2018), 'Land-use emissions play a critical role in land-based mitigation for Paris climate targets', *Nature Communications*, 9(1), https://www.nature.com/articles/s41467-018-05340-z.

8–16.5 $GtCO_2$/year of atmospheric carbon dioxide removal. Implicit in these scenarios is the assumption that BECCS is an efficient energy vector (in the sense of converting stored biomass into power, heat or transport fuels). Even in the absence of CCS, the quantity of bioenergy feedstocks used in these IAMs (and the assumed land requirement) is generally unchanged, or even increases, compared with IAMs that include BECCS, due to bioenergy's assumed potential to displace fossil fuels for power, heat or transport.[52, 53]

Biomass feedstocks inherently deliver less energy per unit of mass than do fossil fuels; biomass, whether from wood or herbaceous crops, is less dense and contains more moisture. Energy is also used in growing, harvesting, collecting, processing (including drying, pelletizing, etc.) and transporting the feedstock; the energy needed for collection is probably highest for diffuse residues such as those from harvests or forests, and lowest for processing residues such as sawmill or sugar mill waste. BECCS imposes no additional energy demand on these processes relative to bioenergy without CCS, but the energy efficiency of the supply chain does have a bearing on the energy and carbon break-even points. The CCS process itself imposes a 'parasitic' load on the biomass plant (i.e. as additional energy is required to power the CCS equipment), and energy is also needed to condense the captured carbon dioxide and move it to storage sites, whether by pipeline or surface transport.

Calculations of the overall energy balance suggest that BECCS projects may in fact deliver relatively little net energy as usable heat, power or fuel: indeed far less than the models project, once the energy requirements of full bioenergy supply chains are accounted for. A 2018 study concluded that energy output was strongly case-specific, with the energy return on investment (EROI) varying between a ratio of 0.5 (i.e. implying that more energy was consumed than produced) and 5.7 (roughly comparable to solar PV and, possibly, coal with CCS).[54] The main energy leakages stemmed from biomass conversion into combustible fuel sources and from the parasitic load of CCS, followed by road transport, drying and farming (including inputs). While improving power plant efficiency reduced energy leakages, it also reduced the amount of carbon sequestered, in effect creating a trade-off between carbon capture and energy delivery. In general, biofuel fermentation captures less carbon but delivers more usable energy per unit of feedstock.

> Exploring other ways of sequestering carbon from biomass that avoid the need to build potentially expensive or possibly unnecessary biomass plants should be a priority.

On top of this, the rapidly falling costs of other renewable technologies, notably wind and solar PV, are making BECCS – along with biomass-based electricity, liquid fuel, biogas and hydrogen production more generally – less competitive. IAMs place increasing value on the capture (i.e. 'CCS') component of BECCS rather than the bioenergy ('BE') component, as rising carbon prices are assumed to make carbon sequestration increasingly valuable over the course of the century. Thus, to the extent that BECCS plays a role in future climate mitigation pathways, it might be better seen primarily as a means of capturing carbon rather than as a useful energy vector relative to other carbon-neutral renewable energy alternatives. It should be compared – particularly in terms of cost, feasibility at different

[52] Bauer, N., Rose, S. K., Fujimori, S., van Vuuren, D. P., Weyant, J., Wise, M., Cui, Y., Daioglou, V., Gidden, M. J., Kato, E., Kitous, A., Leblanc, F., Sands, R., Sano, F., Strefler, J., Tsutsui, J., Bibas, R., Fricko, O., Hasegawa, T., Klein, D., Kurosawa, A., Mima, S. and Muratori, M. (2018), 'Global energy sector emission reductions and bioenergy use: Overview of the bioenergy demand phase of the EMF-33 model comparison', *Climatic Change*, doi: 10.1007/s10584-018-2226-y.
[53] IPCC (2019), *Climate Change and Land,* Chapter 6, cross-chapter box 7.
[54] Fajardy, M. and Mac Dowell, N. (2018), 'The energy return on investment of BECCS: is BECCS a threat to energy security?', *Energy and Environmental Science*, 2018, 11, p. 1581, doi: 10.1039/C7EE03610H.

carbon prices and other impacts – with other carbon-capturing (but not energy-delivering) approaches such as DACCS, nature-based climate solutions (forest ecosystem restoration, reducing deforestation, etc.), and alternative uses for biomass that keep carbon out of the atmosphere, such as using wood for construction. Thus, given ongoing power-sector transformations, exploring other ways of sequestering carbon from biomass that avoid the need to build potentially expensive or possibly unnecessary biomass plants should be a priority.

## Availability of land

As noted by the IPCC and others, the availability of land for bioenergy is a limiting factor in the deployment of BECCS. The models reviewed in the IPCC's Fifth Assessment Report assumed the removal of 15–18 $GtCO_2$/year, with energy delivery of 200–400 EJ/year.[55] The latter figure included 80–100 EJ/year from the by-products of agriculture and forest industries, but the majority came from dedicated energy crops, which require considerable land for their production; a supply of 100 EJ/year could require up to 500 million ha of land (assuming an average annual biomass yield of 10 tonnes of dry biomass per hectare).[56] Assuming that agricultural and forestry by-products require no additional land and are residues from existing land use, producing 300 EJ/year from energy crops would require 1.5 billion ha – an area roughly equal to the total global land area currently planted with agricultural crops.[57] Scenarios like this also tend to assume radical changes in consumer behaviour, including a major shift away from eating meat (which theoretically would release much of the land currently used for pasture, or about 3.4 billion ha), together with rapid increases in food yields – in some cases higher than historical rates – sufficient to meet global food demand.

Although the assessment of the potential contribution of BECCS was more cautious in the IPCC's SR1.5 relative to earlier assessments, the anticipated demand for land remained substantial. One study cited estimated that 25–46 per cent of the world's arable and permanent crop area would be needed by 2100 to deliver 12 $GtCO_2$/year from BECCS.[58] SR1.5 presented three pathways that incorporated BECCS (see Figure 1). Overall, these required land areas of 93 million ha (pathway P2), 283 million ha (P3) and 724 million ha (P4) respectively by 2050. The IPCC report observed:

> In general, the literature shows low agreement on the availability of land … Productivity, food production and competition with other ecosystem services and land use by local communities are important factors for designing regulation. These potentials and trade-offs are not homogenously distributed across regions.[59]

As discussed above, any calculations of the impacts of BECCS must take land-use changes into account, whether these are direct (e.g. conversion of grassland or forest to energy crops) or indirect (e.g. conversion of agricultural areas to energy crops, and subsequent conversion of grassland or forest to agriculture). These impacts can be significant: for example, for switchgrass grown on marginal land with no net emissions from land-use change, the BECCS carbon efficiency is 62 per cent (i.e. 62 per cent

[55] US National Research Council (2015), *Climate Intervention: Carbon Dioxide Removal and Reliable Sequestration,* Washington, DC: National Academies Press, p. 64, doi:10.17226/18805.
[56] Azar, C., Lindgren, K., Obersteiner, M., Riahi, K., van Vuuren, D. P., den Elzen, K. M. G. J., Möllersten, K. and Larson, E. D. (2010), 'The feasibility of low CO2 concentration targets and the role of bio-energy with carbon capture and storage (BECCS)', *Climatic Change*, 100(1), pp. 195–202, doi:10.1007/s10584-010-9832-7.
[57] Food and Agriculture Organization of the United Nations (FAO) (2016), *State of the World's Forests 2016: Forests and agriculture: land-use challenges and opportunities,* Rome: FAO, http://www.fao.org/3/a-i5588e.pdf.
[58] Smith, P., House, J. I., Bustamante, M., Sobocká, J., Harper, R., Pan, G., West, P. C., Clark, J. M., Adhya, T., Rumpel, C., Paustian, K., Kuikman, P., Cotrufo, M. F., Elliott. J. A., McDowell, R., Griffiths, R. I., Asakawa, S., Bondeau, A., Jain. A. K., Meersmans, J. and Pugh, T. A. M. (2016), 'Global change pressures on soils from land use and management', *Global Change Biology*, 22(3), pp. 1008–1028, doi:10.1111/gcb.13068.
[59] IPCC (2018), *Global Warming of 1.5°C*, p. 343.

of carbon sequestered by biomass is permanently geologically stored), but this falls to 46 per cent when grassland is converted.[60] The geographical location of the land used is also important: in general, the governance and enforcement of land-use planning in poor countries tends to be worse than in more prosperous ones (see Box 2), increasing the likelihood of conflicts over competing demands for land use.

> In general, the governance and enforcement of land-use planning in poor countries tends to be worse than in more prosperous ones, increasing the likelihood of conflicts over competing demands for land use.

Where feedstock production sites are far from carbon dioxide storage facilities, this increases the requirement for transport either of the feedstock or of the carbon dioxide, with accompanying increases in energy consumption and greenhouse gas emissions. It is estimated that collecting and transporting bioenergy, its feedstocks and/or carbon dioxide on the scale envisioned could entail energy use equivalent to up to half of current total global primary energy consumption.[61] The logistics involved may also require construction of a pipeline network (between capture and storage sites) similar in size to the current global natural gas network.[62]

### Box 2: Where on Earth could BECCS go?

Given the scale of potential BECCS deployment and the land required for feedstocks (380–700 million ha by 2100), a key question is where these feedstocks could be sited. Beringer et al.[63] consider this question in terms of the availability of land for bioenergy plantations (both with and without CCS, and excluding any consideration of CCS requirements such as geological storage sites). Excluding land that is currently agricultural, severely degraded, in conservation areas, wetlands, or forested where carbon losses from land-use change would not be compensated for within 10 years, the authors consider four scenarios with and without food cropland expansion, and with higher and lower levels of nature conservation.

They find that, on average, South America (26 per cent), sub-Saharan Africa (17 per cent), Europe (14 per cent), North America (11 per cent) and China (7 per cent) collectively provide three-quarters of potential 2050 global biomass yields. Approximately a quarter of the potential comes from woody plantations (coppiced every eight years), including temperate deciduous trees (e.g. poplars and willows) and tropical evergreens (e.g. eucalyptus); the remainder comes from fast-growing grasses (e.g. miscanthus and switchgrass).

These estimates imply 142–454 million ha of new biomass plantations replacing natural vegetation, with about 40 per cent of such plantations replacing natural grasslands and shrublands, 10 per cent replacing semi-natural vegetation proximal to existing agricultural areas, and about 30 per cent being introduced on currently forested areas. In aggregate this would expand the world's existing cropland area by 10–30 per cent. Despite the sustainability constraints assumed in the model, the ecological, economic and social consequences of converting much of this land to energy crops would still present significant risks.[64] Further, given that much of the potential is in poorer countries with chequered histories of land-use planning, it is questionable whether regulatory constraints would be observed in reality. This would potentially jeopardize carbon- and biodiversity-rich natural forests, especially in tropical regions. Alternative, high-energy-density marine sources of biomass such as algae could potentially alleviate some of these spatial and capacity constraints.

[60] Fajardy, M. and Mac Dowell, N. (2017), 'Can BECCS deliver sustainable and resource efficient negative emissions?', *Energy and Environmental Science*, 10, pp. 1389–1426. See also correction in Ibid., 10(10), p. 2267.
[61] Anderson, K. and Peters, G. (2016), 'The trouble with negative emissions', *Science*, 354(6309), pp. 182–83, doi: 10.1126/science.aah4567.
[62] Fuss et al. (2016) 'Research priorities for negative emissions'.
[63] Beringer, T., Lucht, W. and Schaphoff, S. (2011), 'Bioenergy production potential of global biomass plantations under environmental and agricultural constraints', *Global Change Biology Bioenergy,* 3, pp. 299–312, doi: 10.1111/j.1757-1707.2010.01088.x.
[64] Ibid.

## Availability of inputs

Land is not the only factor of production needed by BECCS deployment: the cultivation of new energy crops is likely to lead to increased agricultural demand for water and nitrogen fertilizer. A study of the use of switchgrass for BECCS feedstock estimated that 200 million ha (about half the total cropland in the US) would be needed to remove 3.7 $GtCO_2$/year; the process would consume 20 per cent of global fertilizer production, itself a major source of emissions, and require 4 trillion $m^3$/year of water, an amount equal to current total global water withdrawals for irrigation.[65] Furthermore, CCS itself requires the use of water; one estimate suggested that the amount of water required to sequester 12 $GtCO_2$/year would be equivalent to approximately 3 per cent of total water consumption currently associated with human activities – though some water could be recycled from storage operations.[66]

In fact, estimates of the total water footprint of BECCS vary widely, and are highly dependent on the biomass type and region of production. Three different studies estimated, respectively, water demand of 0.72 trillion $m^3$, 3.6–9.7 trillion $m^3$ and 5.3–24.4 trillion $m^3$ to sequester 12 $GtCO_2$/year.[67] Excessive water withdrawals for BECCS feedstock production could also lead to freshwater ecosystem degradation and aquatic biodiversity loss; even if withdrawals are lower, water pollution from fertilizer use is likely.

## Conclusions

Formidable challenges are associated with the use of carbon dioxide removal (CDR) approaches, including BECCS, to limit global warming to 1.5–2°C. On the one hand, as clearly evidenced by the latest IPCC assessments, it is becoming increasingly difficult to foresee the Paris Agreement targets being achieved without rapid scale-up in deployment of CDR solutions; emission abatement efforts are not progressing anywhere near rapidly enough to engender confidence that these alone will avoid global overshooting of emissions targets. On the other hand, as the IPCC's SR1.5 report cautioned, 'CDR deployed at scale is unproven, and reliance on such technology is a major risk in the ability to limit warming to 1.5°C'.[68]

BECCS is the main option assumed by integrated assessment models (IAMs), but, as we have argued, its prevalence in the models is not based on a comprehensive analysis of its feasibility and impacts, and often rests on the erroneous assumption that biomass for energy is inherently carbon-neutral. To the contrary, there are many reasons to conclude that BECCS cannot be deployed at the scales assumed in the majority of Paris-compliant emissions pathways. It would consume land on a scale comparable to half the current cropland, entailing massive land-use change, particularly in tropical regions with weak governance, high biodiversity and high terrestrial carbon stock. Competition for agricultural

[65] Reviewed in US National Research Council (2015), *Climate Intervention.*
[66] Smith, P., Davis, S. J., Creutzig, F., Fuss, S., Minx, J., Gabrielle, B., Kato, E., Jackson, R. B., Cowie, A., Kriegler, E., van Vuuren, D. P., Rogelj, J., Ciais, P., Milne, J., Canadell, J. G., McCollum, D., Peters, G., Andrew, R., Krey, V., Shrestha, G., Friedlingstein, P., Gasser, T., Grübler, A., Heidug, W. K., Jonas, M., Jones, C. D., Kraxner, F., Littleton, E., Lowe, J., Moreira, J. R., Nakicenovic, N., Obersteiner, M., Patwardhan. A., Rogner, M., Rubin, E., Sharifi. A., Torvanger, A., Yamagata. Y., Edmonds, J. and Yongsung, C. (2016), 'Biophysical and economic limits to negative $CO_2$ emissions', *Nature Climate Change*, 6(1), pp. 42–50, doi: 10.1038/Nclimate2870.
[67] Fajardy et al. (2019), *BECCS Deployment: A Reality Check*.
[68] IPCC (2018), *Global Warming of 1.5°C*, p. 34.

land would threaten food production and endanger food security.[69] And, depending on the feedstock, BECCS might not even deliver significant volumes of negative emissions over a timescale compatible with the Paris targets – or any negative emissions at all.

This is not to argue that BECCS cannot play a role, but its scope will depend primarily on the type of feedstock used. Agricultural and forestry residues, and industrial and municipal wastes, generally have the lowest impact on land-use change and – depending on the residue type and collection method – soil and forest carbon stocks. But they are also limited in availability and harder to collect, and can have other uses, including the manufacture of wood products and the maintenance of soil carbon and nutrient levels. Afforestation and reforestation initiatives that expand forest cover would increase the supply of forest residues, though their subsequent availability as a feedstock depends partly on whether wood-based industries also expand; in many countries there is likely potential for more extensive use of harvested wood products in climate-mitigating roles, for example in construction.

> The use of additional planted forests for feedstocks carries the largest risks to achieving meaningfully negative carbon balances, and is likely to have the most deleterious consequences from extensive use of land, water and other inputs such as fertilizers.

The use of additional planted forests for feedstocks carries the largest risks to achieving meaningfully negative carbon balances, and is likely to have the most deleterious consequences from extensive use of land, water and other inputs such as fertilizers. Dedicated energy crops have greater potential, particularly if sustainably integrated with the existing ecology, where they could bring additional benefits, particularly if appropriately integrated with conventional crops or grown on land not in demand for alternative uses.

The key is to ensure that all such options – and CDR technologies more broadly – are evaluated on a comparable basis. This means, above all, that the assumption that biomass feedstock is inherently carbon-neutral be abandoned. A full lifecycle analysis of carbon balances over time, including carbon stocks in standing forests or crops and the soil, must be part of the analysis of any given BECCS pathway and all other CDR options. Only then can we be sure that CDR solutions are actually removing carbon dioxide over policy-relevant time periods.

Other measures required to guarantee effective and sustainable removals include comprehensive analysis of likely demand for land, water and other inputs, and the consequences of their use; and rigorous assessment of the competing demands and requirements in terms of land and biodiversity/habitat preservation. Such analysis must be fully cognizant of, and make provisions for, weaknesses in land-use governance and law enforcement. Idealized assumptions about effective land management should be avoided. By and large, current IAMs do not contain sophisticated analysis of these issues, with the result that they may lead policymakers to the wrong conclusions.[70]

[69] Bailey, R. and King, R. (2018), 'Betting on BECCS? Exploring Land-Based Negative Emissions Technologies', Hoffmann Centre for Sustainable Resource Economy, 17 May 2018, https://hoffmanncentre.chathamhouse.org/article/betting-on-beccs-exploring-land-based-negative-emissions-technologies/.
[70] IPCC (2018), *Global Warming of 1.5°C*, Chapter 2.

This suggests three broad priorities for future climate strategies:

First, **accelerate conventional abatement action** as rapidly as possible (including, crucially, in the land-use sector, and by changing consumption patterns) to minimize the volume of additional negative emissions required.

Second, **rather than assuming that BECCS is the pre-eminent carbon removal solution due to its de facto use in IAMs, consider it alongside all other negative emissions solutions** such as nature-based solutions (afforestation, forest ecosystem restoration, etc.), DACCS and enhanced weathering. These evaluations need to be carried out on the basis of full lifecycle emission balances, as well as other local-to-global ecosystem and sustainability co-benefits and trade-offs that will vary by deployment (see Table 1 for an indicative global overview). In the case of BECCS, important factors include the types and locations of the feedstock, land-use changes, harvesting, processing, combustion, transportation and storage impacts – and the extent to which BECCS and nature-based solutions compete with each other for land. Where they do so, there is a strong likelihood that nature-based solutions will, in many cases, provide more effective removals in the near term (i.e. one to two decades). None of these negative emissions options will be a silver bullet, and a portfolio of locally appropriate but globally significant solutions will need to be developed.

Third, **take urgent action to rapidly scale up the development and deployment of sustainable approaches to negative emissions**. These need to start achieving meaningful levels of CDR in the next decade or so to prevent the overshooting of emissions targets and the potentially calamitous earth-system positive feedbacks this could catalyse, as well as to reduce the scale of negative emissions solutions needed by the end of the century. For land- and forest-based solutions, almost immediate implementation (planting or ensuring natural regeneration) is required, due to the time taken for these natural solutions to realize their full sequestration potential. For technological solutions, a step-change in research and development is required, along with the iteration and deployment of promising options. Both approaches require significant investment and financial mechanisms, and the concomitant development of broadly supportive governance arrangements and safeguards. These are required to ensure that the most appropriate options materialize, both by fostering an enabling environment through the right incentives and by ensuring that rapid progress still adheres to the precautionary principle.[71]

There is an urgent need for policymakers to be cognizant of, and engaged in, these kinds of debates, so that they can draw informed conclusions and chart a path forwards. Delaying decisions will increase the risk of missing climate goals and will also increase the scale of negative emissions needed in the future. The danger at the moment is that policymakers are 'sleepwalking towards BECCS' simply because most models incorporate it – or, almost as bad, it may be that policymakers are simply ignoring the need for any meaningful action on CDR as a whole.[72]

[71] See Brack, D. and King, R. (2020, forthcoming), 'Managing land-based CDR: BECCS, forests and carbon sequestration', *Global Policy*.
[72] Bailey and King (2018), 'Betting on BECCS? Exploring Land-Based Negative Emissions Technologies'.

### Table 1: Indicative global CDR abatement costs, deployment potentials and key side effects

| | Land-based | | | | | |
|---|---|---|---|---|---|---|
| | Saturable | | | | | |
| | **Afforestation/ reforestation** | **Biochar** | **Soil carbon sequestration** | **BECCS** | **DACCS** | **Enhanced weathering** |
| **Sequestration potential** | | | | | | |
| Potential sequestration rate by 2050 ($GtCO_2/y$)[a] | 0.5–3.6 | 0.5–2 | 2–5 | 0.5–5 | 0.5–5 | 2–4 |
| Potential rate by 2100 ($GtCO_2/y$) | 0.5–7 | 1–35 | 0.5–11 | 1–20+ | 1–20+ | 1–27 |
| Cumulative potential by 2100 ($GtCO_2$) | 80–260 | 78–477 | 104–130 | 100–1,170 | 100–1,000+ | 100–367 |
| Required 2100 annual removals in 2°C scenarios ($GtCO_2/y$)[b] | 4 [12] | – | – | 12 | 12 | 1 [4] |
| Saturation and permanence[a] | Saturation of forests; vulnerable to disturbance; post-AR forest management essential | Mean residence times: decades to centuries depending on soil type, management and environmental conditions | Soil sinks saturate and can reverse if poor management practices were to resume | Long-term governance of storage; limits on rates of bioenergy production and carbon sequestration | Long-term governance of storage | Saturation of soil; residence time from months to geological time scales |
| **Costs** | | | | | | |
| 2050 cost (2011$ per $tCO_2$)[a], author judgments [full range] | 5–50 [0–240] | 30–120 [10–345] | 0–100 [-45–100] | 100–200 [15–400] | 100–300 [25–1,000] | 50–200 [5–3,460] |
| **Resource requirements and impacts (2100)[b]** | | | | | | |
| *Total land required (million ha)* | *320 [970]* | – | – | *380–700* | *Very low (unless solar PV used for energy)* | *2 [10]* |
| Land required (million ha/$GtCO_2$) | 80 | 16–100 | 0 | 31–58 | 0 | 3 |
| *Total water required ($km^3/y$)* | *370 [1040]* | – | – | *720* | *10–300* | *0.3 [1.5]* |
| Water required ($km^3/GtCO_2$) | 92 | 0 | 0 | 60 | 0.8–24.8 | 0.4 |
| Impact on nutrients (Mt N, P, K/y) | 0.5 | N: 8.2<br>P: 2.7<br>K: 19.1 | N: 21.8<br>P: 5.5<br>K: 4.1 | Variable | 0 | 0 |

| | Land-based | | | | | |
|---|---|---|---|---|---|---|
| | Saturable | | | | | |
| | Afforestation/ reforestation | Biochar | Soil carbon sequestration | BECCS | DACCS | Enhanced weathering |
| Side effects (scale-dependent) | | | | | | |
| Air pollution | — | — | — | × | ? | × |
| Albedo[b] | × (or reduced GHG benefit where not negative) | — | — | Variable, depends on source of biofuel (higher albedo for crops than for forests) and on land management (e.g. no-till farming for crops) | ? | — |
| Biodiversity | × | — | — | × | ? | — |
| Ecosystem changes | — | — | — | — | ? | — |
| Food security | × | × | • | × | ? | — |
| Ground/water pollution | — | — | — | — | ? | × |
| Soil quality | • | • | • | — | ? | • |
| Mining and extraction | — | — | — | — | ? | × |
| Trace GHGs | — | • | × | × | ? | — |

• Desirable change; × Undesirable change; — No significant change; ? No estimate available.

Notes: DACCS is theoretically only constrained by geological storage capacity; estimates presented consider upscaling and cost challenges.
BECCS potential estimates are based on bioenergy estimates in the literature (EJ/yr), converted to $GtCO_2$
Potentials cannot be added up, as CDR options would compete for resources (e.g. land).
[a] Assessed ranges by Fuss et al. (2018), *Negative emissions—Part 2: Costs, potentials and side effects*.
[b] Based on 2100 estimate for mean [max] potentials by Smith et al. (2016), *Biophysical and economic limits to negative $CO_2$ emissions*.

Source: Compiled from IPCC (2018), *Global Warming of 1.5°C*; Morrow et al. (2018), *Why Talk about Carbon Removal?;* Smith et al. (2016), 'Biophysical and economic limits to negative $CO_2$ emissions'.

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Cover image: Corn grows near an ethanol plant near Lena, Illinois, in 2004.

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