commentary

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Forest bioenergy update: BECCS and its role in integrated assessment models

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Summary

Forest biomass continues to be a major source of ‘renewable’ electricity in Europe, and receives substantial subsidies and exemption from carbon pricing regimes. Despite evidence that current use is failing to achieve effective mitigation of climate change, future climate scenarios towards net zero by 2050 or in limiting warming to Paris Agreement targets envisage very large *increases* in bioenergy use, a significant proportion of which may come from forests—either directly through harvesting or indirectly by replacing forests with energy crops. Much of the increased demand for biomass is to feed bioenergy plants equipped with carbon capture to deliver a net removal of carbon dioxide (CO_2) from the atmosphere.

From a climate perspective, the key question in the use of biomass to replace fossil fuels is how long it takes to achieve a net reduction in atmospheric CO_2 levels. This is determined by the time taken to offset the increased emissions from biomass (relative to fossil fuels) by reabsorption of CO_2 through regrowth of the harvested forest (the carbon payback period). On the basis of the experience of Europe’s large-scale conversions from coal to forest biomass, this delay is too long to contribute to meeting Paris Agreement targets. In the light of this experience, it is reasonable to ask why would policy-makers be guided to increase biomass uses for energy by orders of magnitude in the future, especially because such trends run counter to recent priorities in the UN Framework Convention on Climate Change and Convention on Biological Diversity to restore ecosystems and reverse deforestation. There are two underlying reasons.

Firstly, there is an assumption that, by applying carbon capture and storage (CCS) technology, bioenergy with CCS (BECCS) can remove gigatonnes of CO_2 from the atmosphere each year by 2050. Secondly, by offering both energy production and carbon dioxide removal (CDR), the integrated assessment models (IAMs) that are used to develop and test future climate scenarios have often pointed to BECCS as a preferred technology to achieve a given climate target.

As EASAC observed in its earlier analyses of negative emission technologies, banking on future technologies such as BECCS to compensate later for inadequate emission reductions today places significant risks on future generations, since failure to deliver the removals anticipated would intensify climate change and require even more extreme measures to contain it. In this commentary, we update our earlier work on BECCS and consider how the role of forest biomass is treated in IAMs. This report is intended to provide policy-makers with improved guidance on balancing calls for substantial investment in BECCS against the range of enhanced measures for short-term mitigation or alternative means of CDR.

Previous EASAC reviews had looked at the potential of BECCS to remove CO_2 from the atmosphere, the technical issues of feedstock and performance, conflicts with food supply, ecosystem restoration and biodiversity, forests’ carbon stock (above and below ground), nitrogen losses, unsustainable water withdrawals and adverse impacts on Sustainable Development Goals. The deployment of the underlying CCS technology continues to be slow and operational experience limited; thus uncertainties remain over how much CO_2 can be captured from combustion gases and the extra energy required (parasitic energy cost). There is a trade-off between the amount of CO_2 removed from the stack gases and the energy required in the capture and storage stages, and the latest evidence suggests that performance is currently significantly below that assumed in models. Evidence has also strengthened concerns that the CO_2 that leaks into the environment along the long supply chain, combined with the risk of carbon losses from land use change and in the capture and storage stages, can reduce the carbon removal efficiency substantially, thus delaying or even neutralizing any net removals from the atmosphere.

Recent analyses of the amounts of sustainable biomass available for BECCS drastically reduce earlier estimates. That from the International Energy Agency considers that around 5 gigatonnes (Gt; $1\,Gt = 10^9$ tonnes) of biomass could be available each year globally (to deliver 100 exajoules (EJ; $1\,EJ = 10^{18}$ joules) of energy), but other estimates of global 2050 biomass supply that meet sustainability criteria have been further reduced to 40–60 EJ/yr. At the same time, it is estimated that likely demand from applications in the sustainable bioeconomy other than energy will increase. As a result, demands without bioenergy could amount to over 65 EJ/yr just for wood materials, pulp and paper, and feedstock for priority applications in the ‘bioeconomy’ (e.g. bioplastics).

This commentary looks at the latest evidence on the ability of BECCS to deliver net removals of CO_2 from the atmosphere and finds that there are substantial risks of it failing to achieve net removals at all, or that any removals are delayed beyond the critical period during which the world is seeking to meet Paris Agreement targets to limit warming to 1.5–2°C. In a world where land is scarce and subject to competing demands, it is important to recognise that the area of land required to generate energy from biomass is 50–100 times larger than for solar and wind and thus land usage for bioenergy is inefficient.

On current evidence, any BECCS projects should be of limited scale, all feedstocks provided locally with very low supply chain emissions, and feedstock payback times should be very short. The ideal might be to identify waste-to-energy BECCS options (municipal or agricultural waste), but other potential feedstocks could include annual grasses or short-rotation coppicing with local supply. In view of the leakage of greenhouse gas (GHG) in the production, treatment and extended transport supply chains of existing large power stations, the science does not support launching into the conversion of existing large-scale forest biomass power stations to BECCS. Recent studies have also emphasised the severe risks of underperformance of strategies based on CDR by BECCS, with the danger of significantly exacerbating warming in the event of delayed mitigation or failure to deliver the removals assumed by IAMs. Moreover, it is critical to develop effective monitoring, reporting and verification systems.

With such limitations on the potential performance of BECCS, this commentary looks at the reasons for the prominent role given to it in many IAMs. It identifies several reasons why BECCS may be over-emphasised, including the following:

- Cost minimization models may have difficulty in taking account of and anticipating the rapid and massive reductions in other renewable energy costs.
- BECCS seems more attractive economically because of the assumption that it delivers both low-carbon energy and CDR. However, assumptions on BECCS efficiencies and removals seem too optimistic at the present state of the technologies.
- Unrealistic estimates of the quantity of biomass available that is sustainable and does not conflict with food production, ecosystem retention, environmental and social constraints, and increased demand from other uses.
- Assuming a high discount rate that favours deferment of investments into the future.

A further issue is that of the payback period of the biomass feedstock used in BECCS. With forest-based feedstocks firmly established in the current business models for power stations, expanding demand in the future may continue to rely on such sources that are associated with decadal to century payback periods. This may result in models doing the following:

- overestimating short-term impacts so that time-sensitive targets (e.g. net zero by 2050) will be missed even if the model assumes they can be achieved;
- delaying by decades any net removals, so that temperature could overshoot critical tipping points, even if later some CO_2 is removed from the atmosphere.

The literature describing the structure and assumptions in the major IAMs in use suggests that many assume carbon neutrality. In view of the policy debate being informed by the Intergovernmental Panel on Climate Change (IPCC), International Energy Agency (IEA) and other models envisaging large increases in bioenergy use, it is critical that this uncertainty be resolved before policies and investments lock-in a technology that may prove ineffective. There should be an urgent dialogue between IAM modellers and users such as the European Union (EU) and IEA to ensure that the temporal nature of biomass use – especially where this involves feedstocks of payback periods exceeding a few years – is fully incorporated into the relevant IAMs. Meanwhile, policy-makers should suspend expectations that BECCS can deliver significant CDR removals by 2050 until models have identified the sensitivity of atmospheric CO_2 levels to different feedstock payback times and can be confident that time-related targets (e.g. net zero by 2020) can be achieved.

In addition to this primary conclusion, this update points to implications for other aspects of EU policy.

The European Commission's 'Fit for 55' package advocates a 'cascade' in the priorities for forest biomass use. Our analysis supports the rigorous application of this, whereby energy uses are restricted to wastes or residues that have no higher-value usage and would otherwise be discarded. In contrast, current policies and the associated subsidies and benefits from exemption from the Emissions Trading System are in conflict with the hierarchy by supporting the lowest value application of energy. The anticipated growth in demand as the bioeconomy develops suggests that the Commission should update its cascade guidance to include the demands from other initiatives to increase carbon capture in construction and promote the sustainable bioeconomy against the background that the amounts of sustainable biomass are likely to be less than future demands. Current policies with their subsidies for power generation (and for biofuels) should be critically reviewed, since they divert valuable and scarce biomass resources to applications that are not only low in the cascade priorities but also fail to reduce atmospheric levels of CO_2 on a timescale relevant to meeting Paris Agreement targets.

Regarding the future need for CDR, there is no doubt about the severity of the challenges facing humanity, and society needs to aggressively pursue all options to slow climate change. However, CDR technologies remain highly uncertain and mitigation remains the priority to urgently reduce global emissions. To avoid the 'moral hazard' of displacing climate risks to future generations, investing in the support of future technologies should not be allowed to reduce immediate mitigation measures. To minimise the climate risk and ensure transparency, mitigation and CDR should thus be treated separately in national and international targets.

1 Introduction

In Europe, bioenergy accounts for the majority (*ca.* 60%) of renewable energy and approximately 10% of total energy supply (EC, 2019a), with much of the biomass derived from forests both within and outside the EU. Debate continues on the role of forests in providing bioenergy against the other roles that they can play, including *inter alia* providing carbon sinks and stocks, supplying forestry products such as lumber and pulp, reversing biodiversity loss, delivering ecosystem functions such as water and climate regulation (Jenkins and Schaap, 2018) and a range of health and social co-benefits that are increasingly under threat (Trumbore *et al.*, 2015). In Europe in particular, one trend in the past decade has been to convert former coal-fired power stations to use forest-derived pellets, despite uncertainties over the net climate impacts (see, for example, Schulze *et al.*, 2012; Röder *et al.*, 2015; Laganière *et al.*, 2017; Searchinger *et al.*, 2018; Sterman *et al.*, 2018); and a similar trend is also being observed in Asia. Associated with this, the global market in wood pellets has been growing, with pellets shipped very large distances, exemplified by the export of pellets from western Canada to Europe through the Panama Canal or from Australia to Japan. Industry estimates a global value for wood pellets of over US$10 billion in 2020 with annual growth rates of 7–10% and quantities of over 35 million tonnes per year (Mt/yr).[1,2] Funk *et al.* (2021) calculate that in the current situation where emissions associated with imported biomass may be omitted from national accounts, demand for wood pellets globally could rise to 120 million tons per year by 2050.

EASAC's previous work (EASAC, 2017; 2019) analysed the climate impacts of replacing fossil fuels (mostly coal) with woody biomass and pointed out that the climate benefits claimed by power generators[3] are based on the ability to treat emissions at the point of combustion as zero. This means that emissions from the stack can be excluded from both national emission reporting and carbon pricing systems. When direct renewable energy subsidies and exemption from the EU Emissions Trading System (or equivalent) are added, subsidies can exceed €1 billion per year to a single facility (Ember, 2020). This subsidy is provided despite the emissions of carbon dioxide (CO_2) per kilowatt-hour of electricity generated from large-scale biomass conversions being higher than when fossil fuels were used, owing to the complex and lengthy supply chain, loss of carbon stock in the forest providing the feedstock[4] and lower efficiencies in converting the carbon in biomass to electricity (Norton *et al.*, 2019).

The scale of the disconnect between claimed emission reduction and real increases in emissions has recently been analysed by Brack *et al.* (2021) who found that a total of 482 million tonnes of carbon dioxide (Mt CO_2) were emitted from combustion of solid biomass in Europe (EU27 and UK) in 2019. However, owing to the accounting rules (which assume that forest carbon had already been reported under the land use category when harvested), these are not included in national emission inventories. The EU28's claim that energy-related emissions fell by 26% between 1990 and 2019 depends on this accounting approach. If the amounts actually entering the atmosphere were counted, the reduction would have been just 15%. The increased emissions in the short term have undermined Europe's climate change mitigation efforts and, from a climate perspective, negated the progress from energy sources that are effective in reducing emissions (solar, wind, hydropower and nuclear among them).

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[1] Thrän *et al.* (2018).

[2] https://www.businesswire.com/news/home/20210702005362/en/Global-Wood-Pellet-Market-2021-to-2026—Growth-Trends-COVID-19-Impact-and-Forecasts—ResearchAndMarkets.com

[3] For example, Drax claims, 'Since 2012, our absolute carbon emissions have fallen more than 85%, with four of the six generating units at Drax Power Station converted to biomass from coal.'; Enviva states, 'Enviva exports its sustainable wood pellets primarily to the U.K., Europe, the Caribbean and Japan, enabling its customers to reduce their carbon emissions by more than 85% on a life-cycle basis …'.

[4] For instance, surveys of tree density near pellet mills in the USA supplying UK power stations had 554 fewer trees per hectare than other forests further away (Aguila *et al.*, 2020).

Biomass energy is classed as renewable because it is assumed that the carbon in harvested materials will be removed from the atmosphere through regrowth and, over time, the carbon emitted on combustion will be reabsorbed. This 'carbon neutrality', however, involves a time lag between when biomass is harvested and when the released carbon is reabsorbed through regrowth; this is called the carbon payback period. In this, bioenergy is no different from other renewable energies (wind, solar, etc.) where there is always an initial increase in emissions (through materials, construction, etc.) before a net reduction in emissions is achieved after the facility starts producing electricity with low or zero emissions. In the case of solar and wind, typical payback times are just months to a few years, with lifetime averaged emissions ranging from 11 to 41 kilograms of carbon dioxide equivalent per megawatt-hour (kg CO_2 eq./MWh)[5]. With bioenergy, however, the generator continues to emit throughout its operating lifetime[6] at rates that are higher than those from the fossil fuels that the biomass replaced. This leads to an initial increase in atmospheric CO_2 levels that is compensated by presumed reabsorption of CO_2 at the harvested forest through regrowth. The time the latter takes to offset the additional emissions resulting from biomass use (the payback period) depends very much on the type of biomass used: short-rotation crops and residues from sustainable forestry operations may have short payback periods but harvesting whole trees and additional extraction of stemwood has been shown to have payback periods of many decades or even centuries (see, for instance, Agostini *et al.*, 2014; Stephenson and Mackay, 2014; Nabuurs *et al.*, 2017; Sterman *et al.*, 2018; Camia *et al.*, 2021). This is in direct conflict with the purpose of transitioning to renewable energy since, rather than helping reduce atmospheric levels of CO_2, levels are increased for periods likely to exceed the decade or so remaining before the 1.5°C Paris Agreement target is reached. EASAC has argued that the urgency of the climate crisis requires that the use of forest biomass for electricity generation should not be considered renewable (and eligible for subsidies) unless they involve short payback periods of a similar order to those of competing technologies including solar and wind. This position is reinforced by IPCC (2021) calls for '*urgent and immediate large-scale reductions*'[7].

While the climate impact of current uses of forest biomass in large generating facilities is still fiercely debated (see, for instance, Cowie *et al.*, 2021; Norton *et al.*, 2021), bioenergy continues to play an increasing role in future projections of energy demand, with a major driver in future projections being the use of 'bioenergy with carbon capture and storage' (BECCS) as a negative emission technology (NET). The integrated assessment models (IAMs) used to explore future scenarios that limit warming to 1.5–2°C often rely on BECCS to remove many gigatonnes of CO_2 each year by 2050 and beyond, which could require large areas of the planet to be converted to energy crops (EASAC, 2018; IPCC, 2018).

Just as the climate benefits of replacing fossil fuels by biomass are questionable, similar concerns have been raised over the ability of BECCS to deliver reductions in atmospheric CO_2 levels in a useful timescale (e.g. EASAC, 2019; Quiggin, 2021). This raises the critical question of whether the models that assign large roles to BECCS in the future are fully reflecting the latest evidence on the complexity of bioenergy's interrelations with climate, in particular the temporal nature of that relationship.

IAMs play a critical role in informing policy debates on how to reach specific goals (e.g. net zero by 2050). Consequently, if indeed the models are overestimating the contribution of biomass to climate change mitigation, there is a risk that large investments in the corresponding technologies could be made and prove ineffective, or any beneficial effects could be delayed beyond the period remaining to limit warming to the 1.5°C target reaffirmed in COP26. In effect, this leads policy-makers in the wrong direction.

To address this question, we update our previous work on forest bioenergy. Firstly, we briefly describe the role of IAMs and their inclusion of biomass in future scenarios, then discuss the literature on the range of demand and potential supplies of biomass that emerge from such models. We then review current evidence on the ability of BECCS to remove CO_2 from the atmosphere, and consider how IAMs deal with issues of carbon debt and payback periods. We conclude with a discussion of the implications of our findings for policy. This commentary was concluded before the release of the IPCC AR6 Working Group III report, and thus does not take into account any of its findings.

2 Integrated assessment models (IAMs) and the role of bioenergy

2.1 IAMs

IAMs are used in many fields (especially economic modelling), but in the climate context IPCC (2013)

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[5] Average life-cycle estimates for rooftop solar photovoltaic systems, 41; onshore wind,11; offshore wind, 12; and nuclear, 12 (all in kg CO_2 eq./MWh) (see Ember, 2020 citing https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_annex-iii.pdf).

[6] In one of the best documented cases (Drax station in the UK), stack emissions average 955 g CO_2 eq./kWh, with another 124 g/kWh emitted in the processing and supply chain (for comparison, Drax's coal stack emissions are 898 g CO_2 eq./kWh).

[7] See press release at https://www.ipcc.ch/2021/08/09/ar6-wg1-20210809-pr/.

describes them as '*simplified, stylised numerical approaches to represent enormously complex physical and social systems.*' IAMs are compiled from detailed sectoral models (modules) that range from those based on physical laws (the basic models of how the climate reacts to changes in the sun's radiation, to GHG concentrations, cloud cover, etc.) to those based on economic and socio-economic theories. IAMs integrate several component modules but in the process must simplify them to stay within available computing capacity. These simplifying assumptions and uncertainties in the key input data, such as future population and economic growth, resource availability, the pace of technological change, and regulatory and economic policies, mean that IAM results come with significant caveats[8], and provide broad insights about future pathways, rather than specific and absolute answers.

Even so, IAMs are the most widely used means through which interconnected complex systems can be integrated spanning the climate, environment, human systems and alternative policy options. Adjusting the input assumptions across modules that deal with different parts of this system allows modellers to explore successive future states and the possible effects of different policies, and to identify unexpected side-effects, trade-offs and co-benefits. Inevitably, assumptions that drive IAMs are uncertain; for example, these might be due to limits on available data, difficulty in incorporating changes in behaviour and in forecasting technological innovations, and in modelling the responses of complex ecosystems to change. Rather than providing predictions or forecasts, IAMs explore differences in the effects of policies in different 'scenarios' or 'storylines'.

From a policy perspective, the two main types of question asked are 'what would happen if …?' and 'how could we get to …?'. Baseline scenarios explore what would happen if the world does nothing to reduce GHG emissions. Another set of scenarios could then look at what would need to happen if warming is to be limited to 1.5 or 2°C. In this, models may be structured to find the least-cost means of achieving a given temperature limit. As Dooley *et al.* (2018) point out, this '*places IAMs in a position of considerable authority regarding future climate policy*', and models are critical in influencing climate policy globally and nationally. They underpin the decarbonization pathways published by the IPCC, the energy futures issued by the IEA and background modelling of the EU and elsewhere.

2.2 The role of bioenergy in IAM future scenarios

Three of the four IPCC illustrative model pathways to achieve the 1.5–2°C Paris Agreement targets rely to some extent on NETs of which BECCS is dominant. For instance, Figure SPM 3.b of IPCC (2018) includes BECCS-derived removals of up to 20 Gt CO_2/yr from 2060 onwards.

There has been much debate over the extent of CO_2 removal that could be achieved (e.g. Muratori *et al.*, 2016; Gough *et al.*, 2018; ICEF, 2021), and what would constitute a reasonable, appropriate and ethical supply. In this context, Slade *et al.* (2014) summarized over 120 estimates of global biomass availability, where the technical potential ranged from less than 50 to more than 1,000 EJ/yr[9]. Creutzig *et al.* (2015) performed an expert assessment of the amounts of biomass that could be available while meeting sustainability requirements, concluding that biomass providing up to 100 EJ of energy could be available with 'minimal' environmental impacts (this corresponds to 5.5 Gt of biomass (oven-dry) by 2050, with up to 2.5–5.0 Gt CO_2/yr captured and stored). The studies generally assume a large share of biomass feedstocks coming from agricultural residues, forest residues and other wastes (industrial, municipal and manure). Such findings align with the US National Academy of Sciences' estimate of the potential global carbon removal rate from BECCS (3.5–5.2 Gt CO_2/yr) (National Academy of Sciences, 2018) and a recent expert survey on feasible BECCS deployment that led to a median deployment of 2.25 Gt CO_2 in 2050, rising to 5 Gt CO_2 by 2100 (Grant *et al.*, 2021a).

Concerns over the possibility of harvesting such quantities and/or the negative impacts have been expressed by many authors. For instance, these are related to the following:

- inter-generational equity (e.g. Anderson and Peters, 2016; Obersteiner *et al.*, 2018);
- adverse impacts on other resources (e.g. Smith *et al.*, 2016);
- land use competition and social acceptability (e.g. Vaughan and Gough, 2016);
- ethical issues and risk of use (e.g. Lawrence *et al.*, 2018);
- effects on natural ecosystems, loss of carbon stocks above and below ground, land for food and feed

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[8] For a detailed discussion of IAMs, see Carbon Brief (2021): https://www.carbonbrief.org/qa-how-integrated-assessment-models-are-used-to-study-climate-change.

[9] One exajoule (EJ) is equal to 23.88 millions of tonnes of oil equivalent (Mtoe).

crops and pastureland (e.g. Popp *et al.*, 2017; Heck *et al.*, 2018);

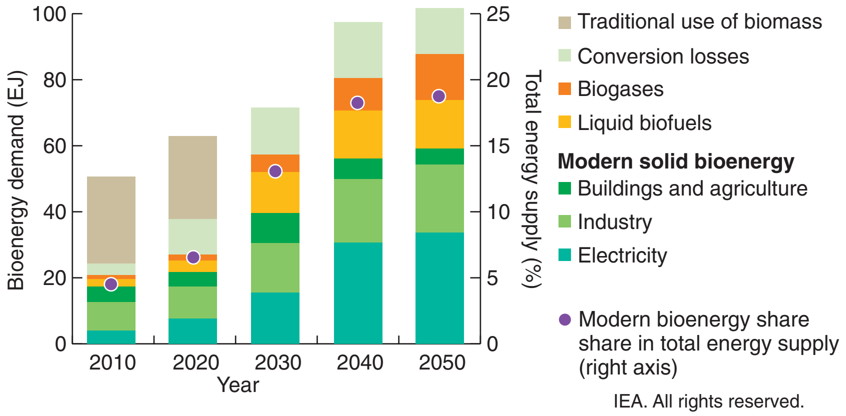
- likely conflicts with biodiversity (Dooley *et al.*, 2021);
- equity and justice when international land-dependent supply chains are involved (Cronin *et al.*, 2021);
- the sheer scope of both innovation and upscaling required from an immature technology (Lenzi *et al.*, 2018; Nemet *et al.*, 2018).

An expert assessment of the assumptions made in IAMs that include negative emissions concluded that high uncertainties remain about the potential of BECCS to remove large amounts of CO_2 from the atmosphere (Vaughan and Gough, 2016; Grant *et al.*, 2021a), and that unrealistically optimistic assumptions could lead to the overshoot of critical warming limits and have significant impacts on near-term mitigation options. Furthermore, Fajardy and MacDowell (2017) pointed to the inevitable trade-off between amounts of CO_2 captured and energy generated with cases where the BECCS facility requires more energy than it generates in order to maximise the amounts of CO_2 captured.

In the IEA (2017) 'beyond 2°C' scenario', BECCS deployment removes 4.9 Gt CO_2/yr by 2060; however, IEA's most recent (IEA, 2021) net zero analysis has reduced its reliance on BECCS, with 1.9 Gt CO_2 removed in 2050 via BECCS or other NETS such as direct air capture and carbon storage (DACCS). As shown in Figure 1, bioenergy is assumed to provide a total of 100 EJ/yr by 2050 and beyond. The EU's Fit for 55 package (Box 1) makes several assumptions on future demand for biomass, including that demand for biomass in the power sector will more than double by 2050 to 100 Mtoe (4.19 EJ).

These earlier assessments required large areas to be allocated to growing crops for bioenergy, which is in direct conflict with recent developments in the United Nations Framework Convention on Climate Change (UNFCCC) and Convention on Biological Diversity (CBD) that seek to expand areas for reforestation and for reversing biodiversity loss by restoring lost or degraded ecosystems. Indeed, Reid *et al.* (2020) observed that land should now be treated as scarce and subject to competing demands, so that the priority should be to use land as efficiently as possible. In this context, van Zalk and Behrens (2018) point out that the area of land required to generate energy from biomass is 50–100 times larger than for solar and wind and thus land usage for bioenergy is highly inefficient because plants only capture a few per cent of solar energy. Moreover, the energy that plants do use is efficient in the production of complex molecules (proteins, carbohydrates, fats, lignin, etc.), the potential value of which is lost when burnt. Many authors thus see a much lower potential for energy crops: Field *et al.* (2008) estimated that approximately 27 EJ/yr could be harvested from land that would not compete with food, while Canadell and Schulze (2014) put the quantity of bioenergy that could be produced with a high degree of environmental sustainability at 26–64 EJ/yr.

A recent analysis by the Energy Transitions Commission (ETC, 2021) compares the amount of land available between the competing uses of food to feed a growing global population, maintaining well-functioning ecosystems and for alternative forms of climate mitigation (e.g. reforestation). They noted that to produce even just 50 EJ/yr of biomass for energy could require about 280 million hectares (Mha), equivalent to approximately 20% of global cropland, thus potentially competing with food production or causing additional deforestation.



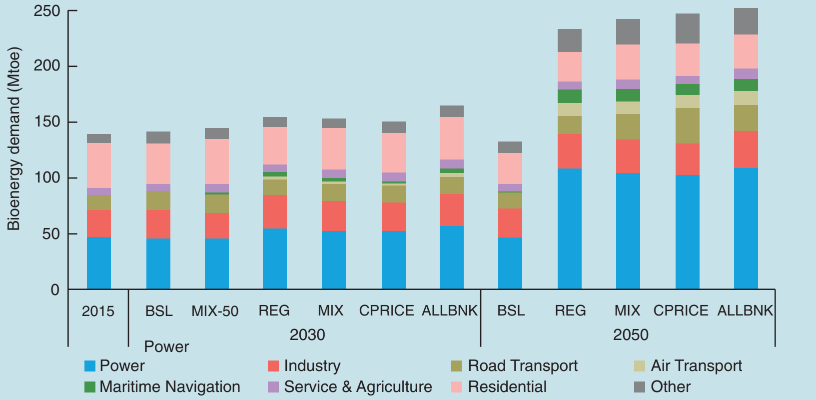
IEA. All rights reserved.

Modern bioenergy use rises to 100 EJ in 2050, meeting almost 20% of total energy needs. Global demand in 2050 is well below the assessed sustainable potential

Figure 1 Projections on bioenergy demand in the IEA's net zero by 2050 scenario (IEA, 2021).

Box 1 EU Fit for 55 assumptions on forest bioenergy (EC, 2020; 2021a)

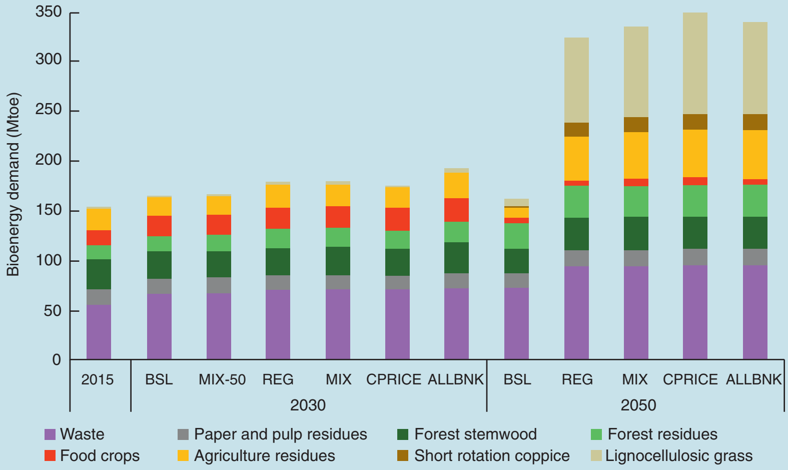
The background paper for the Fit for 55 policy (EC, 2020) projected a range of scenarios to achieve 'net zero' by 2050. All scenarios relied on a substantial use of biomass for energy. Power generation and residential heating today make up most of the biomass demand. By 2030, the use of biomass in the residential sector is expected to decrease slightly but by 2050, there would be more than a doubling of the bioenergy dedicated to the production of electricity, both with and without CCS (Box 1 Figure 1).



Source: PRIMES model

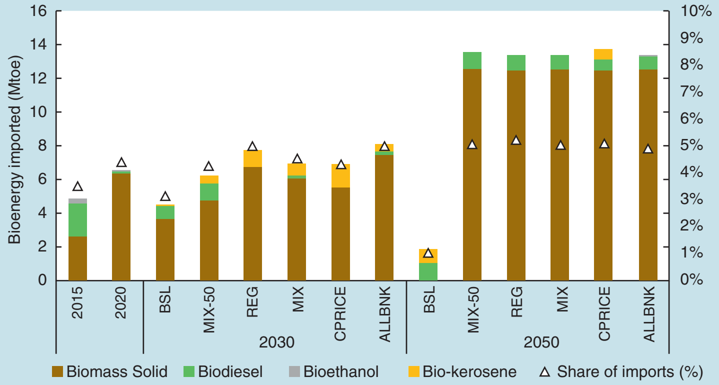
Box1 Figure 1 Use of bioenergy by sector and scenario (1 Mtoe = 0.0419 EJ; 1 EJ = 23.88 Mtoe).

While much of the additional demand is assumed to come from energy crops, harvested stemwood will increase slightly (Box 1 Figure 2).



Box 1 Figure 2 Breakdown of bioenergy feedstocks.

Currently solid biomass makes up most of the biomass imported from third countries with imports to the UK the main source of demand for pellets outside the EU. The scenarios to achieve net zero by 2050 envisage these will increase up to 14 Mtoe (Box 1 Figure 3). Within the uses it is assumed that BECCS will remove more than 250 Mt CO_2/yr.



Source: PRIMES model

Box 1 Figure 3 Imports of bioenergy.

ETC (2021) proposed strict criteria for considering biomass as sustainable on the following basis:

- achieving low levels of carbon emissions across the full life-cycle of growth, collection and transformation to energy;
- minimizing emissions that arise from land use change (direct and indirect);
- accounting for any foregone sequestration had the land use remained unchanged;
- environmental considerations beyond GHG emissions, such as soil health and biodiversity; as well as
- social considerations (e.g. land rights and indigenous cultures).

On these criteria, a 'prudent estimate' of 2050 biomass supply was considered to be 40–60 EJ/yr for all uses. By contrast, potential demands for biomass could amount to over 65 EJ/yr even when considering just four priority applications: wood materials, pulp and paper, and feedstock for bioplastics and for bio-based aviation fuel. Even higher demand could emerge if supplying other sectors that look to biomass as a decarbonization route. On this assessment, therefore, there is very little 'spare' sustainable biomass for BECCS—unless more land can be freed up through reducing demand for pasture as a result of dietary shifts away from animal proteins, new technologies (e.g. macroalgae) or by phasing-out incentives for biofuel use in sectors such as road transport (Figure 2), in which case the IEA's assumption of 100 EJ could be met. Similar conclusions were reached by a study of future demand (Material Economics, 2021) where demands from textiles, chemicals and other biomaterials are expected to grow in a net zero economy for Europe, increasing demand by 1.3–2 EJ/yr: up to a 50% increase in demand relative to the current European demand for wood products, pulp and paper, etc.

ETC (2021) also noted the differences in land demands from competing CDR technologies. Dedicated land use for energy crops would require about 500,000 km^2 to sequester 1 Gt CO_2 each year through BECCS. If the source of biomass were forest residues, an area of five times this size might be required to produce enough residues to sequester 1 Gt CO_2 each year. In contrast, DACCS is at least 10 times more land-efficient assuming

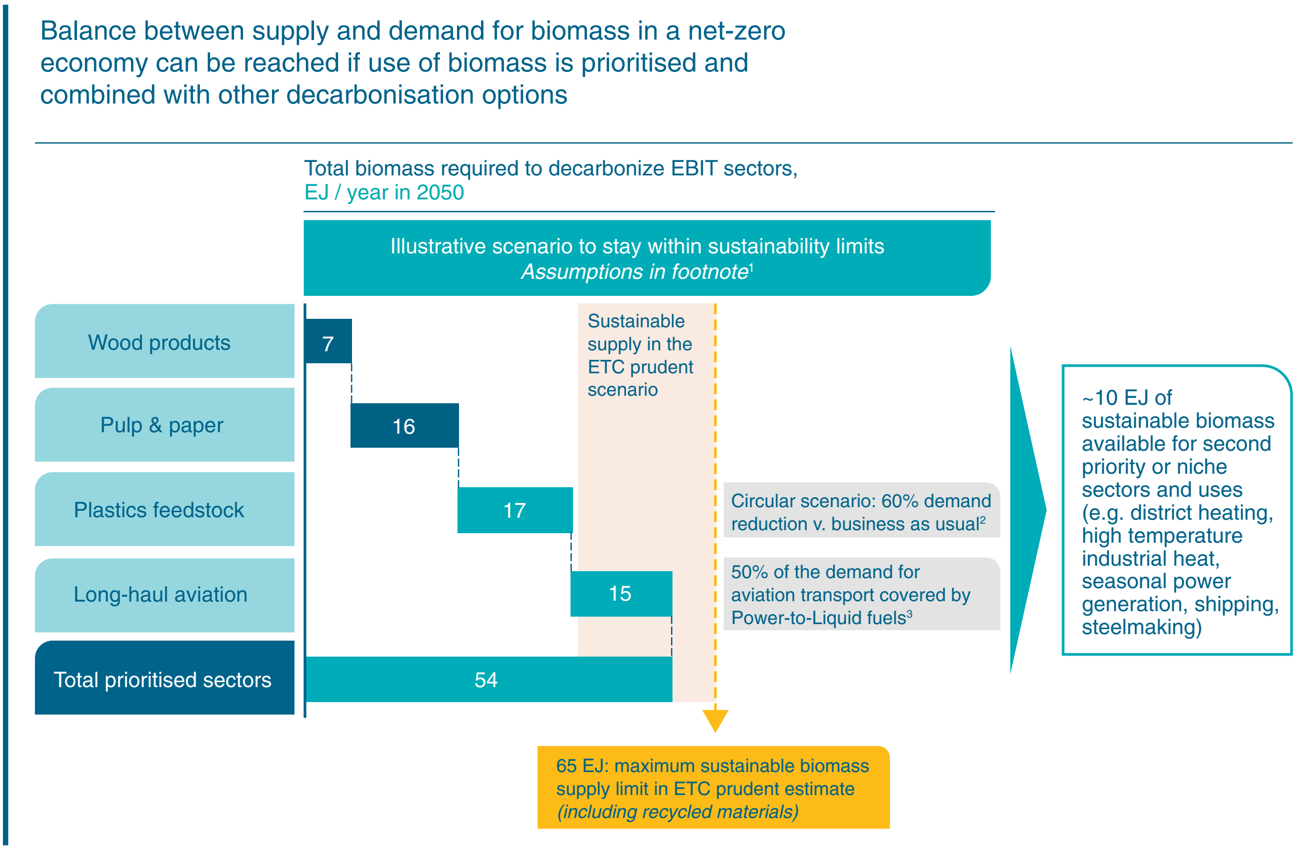


Figure 2 Demand from four priority sectors for biomass and limited amount available for other uses (including bioenergy). EBIT; energy, building, industry and transport. Source: ETC (2021).

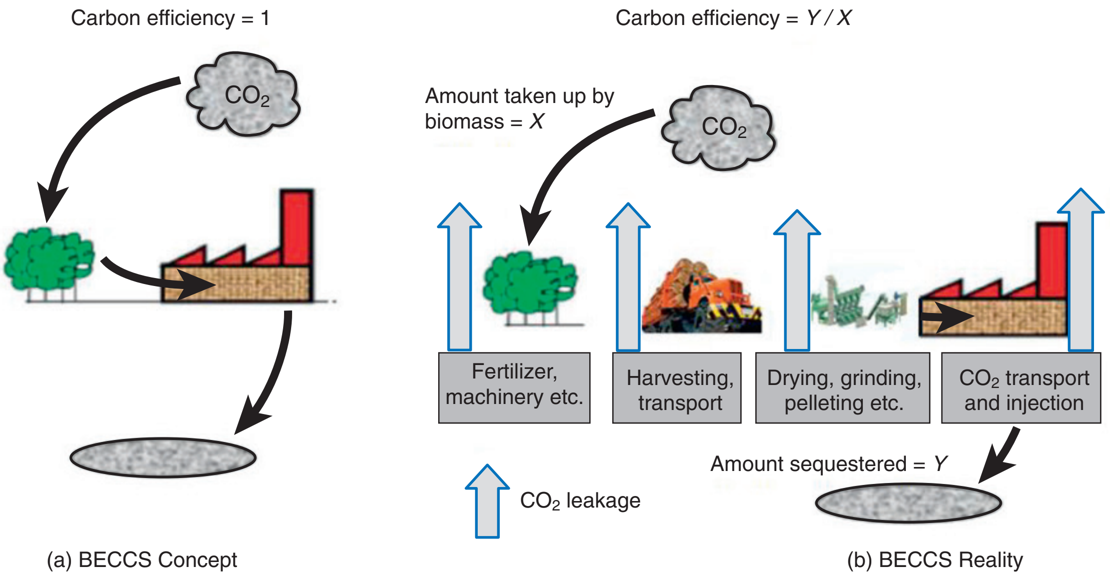


Figure 3 BECCS supply and disposal chain. (a) Simple concept. (b) BECCS as a system. Carbon (removal) efficiency is the amount of carbon sequestered less the sum of emissions along the supply chain, divided by the amount of carbon in the biomass burnt. Supply chain emissions can include foregone sequestration, additional emissions or nitrous oxide (N_2O) if fertilizer is used.

the necessary renewable energy is provided by solar panels.

Regarding availability of biomass in Europe, Rosa *et al.* (2021) calculated that the amounts of biomass from existing point sources (pulp and paper, biomass co-fired, waste-to-energy, and wastewater treatment facilities), and crop residues, organic food waste, and livestock manure were capable of removing up to 200 $MtCO_2$/yr, which is less than that assumed in the EU's 2050 scenario (Box 1) and well below some IAM scenarios, which deploy BECCS at scales of 5–10 $GtCO_2$/yr by 2050 (Peters and Geden, 2017). Meeting such higher targets for CDR would require other NETs, expanding the available crop (e.g. from abandoned land) or expanding imports of biomass.

3 Recent studies on the potential of BECCS to remove CO_2

As described in the previous section, there is much uncertainty on the feedstocks available for BECCS and associated land competition; however, as García-Freites *et al.* (2021) point out, BECCS also faces challenges around technology costs, scaling-up, lack of strong policies and regulatory frameworks, public concerns over CO_2 leakage and ensuring that it genuinely delivers net negative emissions. At present, BECCS technologies have yet to be deployed commercially at scale, and only about 2.5 Mt/yr of CO_2 is currently sequestered by BECCS facilities (ICEF, 2021), with as much as 25 $MtCO_2$/yr in planning or development, which is several orders of magnitude below the many gigatonnes per year of CDR in IAM scenarios achieving Paris Agreement targets.

Fundamental to the role of BECCS is to what extent and when a BECCS project can deliver a net removal from the atmosphere. The concept is simple enough, but the reality is substantially more complex (Figure 3).

The amount and timing of emissions from the production and harvesting of the biomass used, the efficiency of the combustion and carbon capture stages, and the transport and final deposition of the captured CO_2 will vary with each project, and may thus be subject to great uncertainty. EASAC (2019) noted that the leakage of GHG in the cultivation, harvesting, drying and transport stages, together with the parasitic energy demand and incomplete capture of CO_2 from the stack, combine to substantially reduce the carbon efficiency of the whole system. Some life-cycle analyses (e.g. Smith and Torn, 2013), suggested that even for a dedicated biocrop such as switchgrass, leakages of CO_2 in cultivation, processing and transport are greater than the CO_2 captured at the point of combustion, so that carbon efficiency is less than 50%.

A similar calculation based on the international shipping of woody biomass pellets would have to account for the following as fugitive emissions that impede or prevent a BECCS system from delivering any net negative emissions:

- foregone sequestration (allow for the carbon that would have been absorbed in a growing forest had it not been harvested for BECCS);
- emissions in harvesting, transport to the pellet mill;
- drying and pelleting;

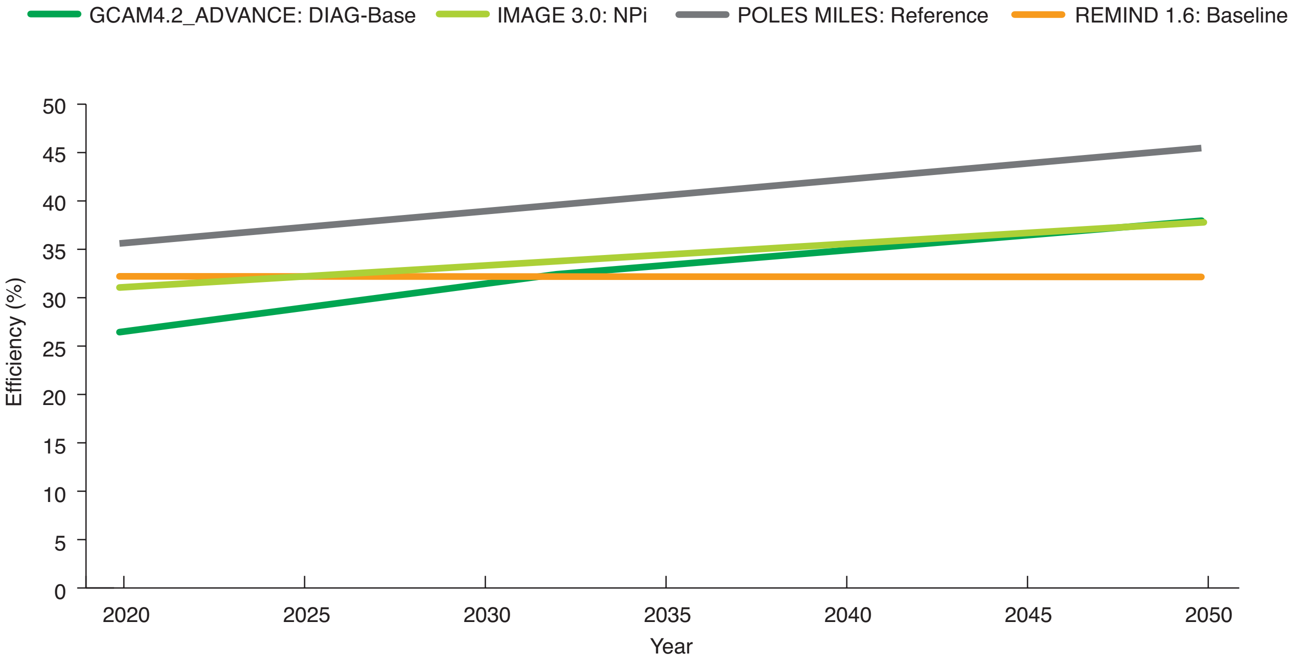


Figure 4 Efficiency of BECCS assumed in four IAMs (Krey et al., 2019; Quiggin, 2021).

- emissions in transport to a port, marine transport to the port in the country of use and local road or rail transport to the BECCS plant;
- additional emissions from the extra fuel needed to provide the parasitic energy of the CCS process (relative to the biopower plant without CCS);
- the proportion of CO_2 in the stack gas that will not be captured;
- emissions on the CO_2 transport and storage stages.

One key factor is that a trade-off exists between achieving high rates of CO_2 capture and the energy penalties involved (Fajardy and MacDowell, 2017). This is because the CO_2 absorbent used in the capture cycle requires heat to separate the solvent from the captured CO_2 and additional energy is required to compress the captured CO_2 and transport to storage sites. As a result, there is much uncertainty in the possible outcomes of a BECCS project, both in terms of cumulative net carbon removal over the facility's lifetime and the time required for a given facility to start removing CO_2 from the atmosphere. As Harper *et al.* (2018) note, outcomes strongly depend on the type of biomass and the fate of initial above- and below-ground biomass; they point out that carbon removed by BECCS could easily be offset by losses due to land use change, and therefore forest-based mitigation could be a more effective means of CDR.

BECCS also presumes the availability of efficient, reliable and cost-effective CCS technology, but this has been marred by substantially delayed deployment (EASAC, 2018) so that, despite the recent progress reported by the Global CCS Institute (2021), technical, economic, financial and policy uncertainties remain in this core technology. Broad *et al.* (2021) used scenario analysis for the UK to highlight how sensitive model results can be to changes in capture rate assumptions for BECCS and other CCS technologies. Often assumed to improve to very high levels by 2050, even small (3–5%) reductions in efficiency had stark effects on the amounts of biomass and physical infrastructure required to achieve the necessary CDR. Quiggin (2021) also noted that IAMs generally assume a 90% or higher capture rate. However, on the basis of R&D trials at a UK facility, achieving this could reduce the overall efficiency of a BECCS-to-power facility from 36.2% without CCS to 20.9% with it, substantially lower than the efficiencies assumed within the IAMs shown in Figure 4 (Krey *et al.*, 2019), which are between 31.3% and 38.8%. Resolving these uncertainties can only emerge over time as experience is gained on actual CCS projects at scale over the next 10 years or so.

As described in section 2.2, there are many potential sources for the large quantities of biomass envisaged in scenarios. Vaughan *et al.* (2018) suggest that half could be derived from agricultural and forestry residues and half from dedicated bioenergy crops grown on abandoned agricultural land and expansion into grasslands, with land for forests and food production protected. Under their scenarios, two-thirds of energy crops would be produced in China, Brazil, Russia and developing regions, presenting challenges for governance to avoid emissions from land use change and other sustainability criteria, as well as a challenge in matching the energy demand to the locations of the biomass production to avoid transport emissions. Muri (2020) also found that the geographical location of BECCS and the nature of the previous land use were critical in determining whether impacts mitigated or exacerbated climate change. She calculated that making use of land at mid-latitudes could mitigate to some extent (slight cooling of –0.1°C) whereas replacing tropical forest with biocrops would warm the climate by +0.17°C.

In terms of interactions with the Sustainable Development Goal agenda, Humpenöder *et al.* (2018) found that large-scale bioenergy production could worsen the following sustainability indicators: deforestation, CO_2 emissions from land use change, nitrogen losses, unsustainable water withdrawals and food prices. Moreover, if the false promise of BECCS and other CDR technologies as a 'silver bullet' leads to delayed mitigation and fails to deliver the removals assumed by the models, this would add to warming which McLaren (2020) estimates could be as high as 1.4°C.

We discuss further the implications of these uncertainties for policy in section 5 but first consider the uncertainties and assumptions in IAMs that are related to the use of biomass.

4 IAMs and the temporal aspects of forest biomass

4.1 Types of biomass feedstock

With some governments highly dependent on bioenergy to meet renewable energy targets and already considering funding BECCS as part of their 2050 net zero strategies (e.g. CCC, 2018; BEIS, 2021a), it is relevant to consider how models differentiate between feedstocks with and without long carbon payback periods. Before considering the actual assumptions in IAMs, some recent research (since EASAC, 2018; 2019) on the climate impacts of feedstocks with different payback times may be of interest.

Röder and Thornley (2016) examined the GHG reduction potential of different bioenergy systems with time in three systems:

1. Annual harvest of a perennial crop, for example *Miscanthus*, where CO_2 is sequestered during a 9-month growth period, then stored for typically 6 months before release.
2. Harvest of short-rotation coppice on a 3-year cycle (e.g. willow or eucalyptus) where CO_2 is sequestered over a multi-year period, then harvested and released typically 6 months later.
3. Removal of forest residues where CO_2 is re-sequestered over several decades.

Of these, systems 1 and 2 provided energy with little effect on stored carbon and so can deliver short-term emission reductions. System 3, however, involved release of carbon that had been sequestered a long time ago and instead could have been used for durable goods or could have stayed in place. Significant increases in emissions occurred even over a long-term time horizon. This emphasised the importance of knowing how emissions and sequestrations vary over time, which constitutes a challenge for IAMs. Cooper *et al.* (2020) also highlighted that bioenergy emissions are often temporally dispersed and that, in view of the small global carbon budget remaining to stay below 1.5°C of warming, the short-term impacts on atmospheric levels of CO_2 were significant as well as the longer timescale traditionally reported within conventional life-cycle assessments.

In another paper, Röder *et al.* (2019) studied the time-dependent emissions from three different forest sources (USA, Spain, Canada) supplying wood to generate electricity in the UK. The bioenergy-only harvesting (Spanish eucalyptus coppicing) failed to deliver any climate benefit (relative to the existing electricity mix) at any time. In the US case, only residues from a forest harvested for lumber and pulpwood were used for bioenergy, and net reductions in emissions could be achieved in a few years. In the Canadian case, trees damaged by pests and disease provided wood that otherwise could not be used for lumber or pulp, thus providing an economic opportunity to clear naturally disturbed forests and re-establish healthy and biodiverse stands which the authors considered sufficient to justify the short-term increase in emissions.

Recent reviews by the EU's Joint Research Centre (Camia *et al.*, 2021) showed the wide range of payback times associated with different types of biomass—especially between the shorter times of residues from forestry harvested just for traditional forestry products and those where harvesting was increased to provide biomass from whole trees, where payback periods of 50 years or more were likely. Up to half of the total wood used for energy in the EU was primary woody biomass harvested from forests and thus in that category of longer payback periods. Similarly, US-sourced wood pellets burnt in UK power stations comprised just over 50% from whole trees (Brack *et al.*, 2021). With long payback period feedstocks firmly established in the current business models for power stations, expanding demand in the future runs the risk of continuing or increasing reliance on whole trees, and thus models need to consider not just categories 1 and 2 of Röder and Thornley (2016), where 'carbon neutrality' can be assumed, but also forest bioenergy with longer payback periods; in particular to research how much the degree and timing of climate impacts differs between feedstocks and regions.

4.2 Current IAMs and their treatment of biomass

As Krey *et al.* (2019) observe, IAMs use different methodological approaches and apply different system boundaries that are often inherited from their historical roots, whether energy systems analysis, human and natural systems (e.g. agriculture and forestry, climate) or from economic models. In simulating decarbonization of the electricity sector, 15 different global and national IAMs exhibited significant differences in the type of methodology used (e.g. simulation versus optimization) and model structures, in how they dealt with different technological options and in their economic and technological assumptions. As a result, policy-relevant conclusions were substantially different in the technologies and deployment paths implicitly recommended; yet the factors underlying these different outcomes were not always transparent to policy-makers.

Moving to the treatment of bioenergy, Popp *et al.* (2014) looked at how specific IAMs[10] dealt with BECCS and found major differences, both in the time and level of bioenergy deployment and in the share of different biomass resources deployed. A large IAM intercomparison study (Rose *et al.*, 2020) included bioenergy use (Daioglou *et al.*, 2020) and BECCS (Muratori *et al.*, 2020). Biomass supply availability (all uses) ranged from 100 to 400 EJ/yr, with feedstock including energy crops, logs and residue feedstocks from agriculture, forestry or municipal waste. Models assumed very large deployment of BECCS, providing up to 55% of primary energy supply by 2100 (up to 28% by 2050), not only for electricity but also for liquid fuel production. Constraints on deployment included economic/market competition with other carbon-free technologies; biomass feedstock availability and land use competition (especially with food); and carbon storage limitations. The models exhibited a lack of flexibility in system design linked to (*inter alia*) limits applied to deploying new technologies, limits to available finance, low abilities to roll out new infrastructure, or other exogenous constraints. None of the models considered in this study offered any indication that different payback periods had been considered for the different feedstocks that were included.

Recently, Quiggin (2021) suggested that the dominance of BECCS in IAMs could be due to the models often being structured to find the least-cost means of achieving a given temperature limit (Gambhir *et al.*, 2019). Since (in theory) BECCS is assumed to produce energy *and* remove atmospheric CO_2 simultaneously (Köberle, 2019), it can seem to offer a more cost-effective solution than options that only contribute through one economic route (e.g. energy from solar, wind, etc., or CDR from DACCS or enhanced weathering). Quiggin (2021) also noted that the costs of solar photovoltaic and wind systems have fallen much faster than projected, so that costs incorporated in the models may be significantly higher than current or likely future costs. As a result, Grant *et al.* (2021b) found that cost reductions in renewables have already eroded the value of BECCS by at least 15–26%. This suggests that there may already be a bias towards BECCS, even if it delivers the anticipated mix of energy and removals assumed in the models. Since, as we observed above, the latter may be too optimistic, then the IAMs' bias towards BECCS will be further amplified.

To investigate the detailed assumptions built into IAMs, Butnar *et al.* (2020) reviewed six leading IAMs[11] and the way in which they modelled BECCS and its supply chain: from cultivating and harvesting biomass through to CO_2 capture and injection into geological storage (Figure 3). Details of the many inbuilt assumptions and parameters may not be included in publications, posing challenges for transparency. Butnar *et al.* (2020) found that the basis for biomass supply and availability of geological storage were the two most transparent factors in the models studied. Less obvious were some of the assumptions made in the various stages of the supply chain for the feedstocks considered. Regarding forestry biomass, most models assumed feedstocks to be provided by dedicated biocrops or from 'sustainable' forest management. In the latter case, similar to IEA (2021), it was presumed that feedstocks avoided '*the risk of negative impacts on biodiversity, fresh water systems, and food prices and availability*'.

No allowance for carbon debt or payback times was apparent, and could indicate that models have assumed carbon neutrality for all feedstocks. Also, the study showed that some models excluded some stages of the CO_2 capture, transport and storage process. Other implicit assumptions that affect outcomes included the discount rate which is set high at 5%, thus favouring the deferment of investment into the future (Köberle, 2019) and much higher than rates recommended for existential threats such as climate change (see Stern, 2007; EASAC, 2020). In addition, it is not clear to what extent IAMs take into account potential disruptive effects of future climate change.

As pointed out by Butnar *et al.* (2020), IAMs have proved invaluable in providing plausible climate-change mitigation futures and for informing debate on policy options for GHG emission reductions to achieve the

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[10] AIM, GCAM, IMAGE, MESSAGE-GLOBIOM and REMIND/MAgPIE.

[11] Image, Message/Globiom, GCAM, Remind/MAgPIE, AIM and TIAM-UCL.

Paris Agreement targets. There is always a danger, however, that the scenarios may be seen by policy-makers and the public as futures that can be delivered. As a result, the heavy reliance on BECCS in futures that can comply with the Paris Agreement has been criticised as potentially misleading in two respects: firstly, by implying that a technical fix is waiting to compensate for the inadequacies of current mitigation measures; and secondly, in pointing to BECCS as the preferred technology for CDR. It is thus important to ensure that models properly consider the temporal aspects of biomass feedstocks and avoid biases that lead to the role of bioenergy being overstated as a result.

4.3 Implications of feedstock carbon payback times for IAM scenarios

As pointed out by Röder and Thornley (2019), assuming carbon neutrality and ignoring carbon payback periods may be a reasonable approximation for short-rotation crops or for organic wastes; however, assuming carbon neutrality for forest biomass pellets fails to recognise that atmospheric CO_2 levels increase (relative to a fossil fuel alternative) and that payback periods are highly dependent on the type of feedstock and use. This could affect both the ability to meet time-related targets and bring forward or extend the overshooting of the 1.5°C target. For instance, a model that assumes carbon neutrality will show a shift to forest biomass from fossil fuels as reducing emissions immediately, whereas in reality any net reduction in emissions to the atmosphere would be delayed by decades or longer, until the payback period is exceeded.

Estimating when a given BECCS project might start to remove CO_2 from the atmosphere can be complex. Hanssen *et al.* (2020) took into account initial carbon losses from land conversion in assessing when a BECCS facility would deliver negative emissions and found that, on a 30-year time horizon using a range of feedstocks (fast-growing grasses and woody bioenergy crops), negative emissions could only be achieved from crops grown on abandoned land or in some temperate and sub-tropical areas where crop growth was rapid and the carbon stock of the previous land low. In other cases (including boreal and tropical forests), the BECCS facility would fail to remove enough CO_2 to offset the initial carbon losses on land-use conversion until much later (e.g. an 80-year timeline used in that study). Such delays would need to be factored into scenarios achieving net zero or negative emissions by any target year such as 2050 or 2100.

To deliver 'negative emissions' on the timescales envisaged by the IAM scenarios, the carbon contained in the biomass harvested must be fully re-sequestered within these periods. For the 2050 targets, this can only be achieved by limiting biomass to that harvested from fast-growing crops on unused or degraded land, or with the limited amounts of forest residues that would otherwise degrade swiftly *in situ* and are consistent with maintaining biodiversity. The latter may place a significant constraint even on removal of residues (Odor *et al.*, 2006). In contrast, much of the current woody biomass pellets (section 3) are sourced from additional harvesting from forests with much leakage in the supply chain so that any net negative effects would be well beyond the target timescales, and would fail to slow climate change in the way projected in the models. As noted in our earlier update on NETs (EASAC, 2019), the benefits from avoided fossil emissions through material and energy substitution can easily be lost by the reduction in the forest carbon sink, delaying any net reduction in emissions for 100 years or more (Soimakallio *et al.*, 2016). We now consider the policy implications of the uncertainties identified.

5 Conclusions and policy issues

5.1 The cascade of forestry biomass

The European Commission's 'Fit for 55' package advocates the cascade for forest biomass use shown in Figure 5, where its use for energy is limited to any residues after all higher-value usage, re-use and recycling are prioritised. Earlier we pointed out that current uses of forest biomass for lumber and other forestry products are expected to expand to provide feedstock for products that are difficult to decarbonize (ETC, 2021). When such demands are considered, some studies (e.g. Material Economics, 2021) conclude that the amounts of available biomass may be inadequate by 40–100%. Current policies conflict with the cascade principle by providing subsidies to biomass-based energy that are not available to biomass uses higher in the value chain, as well as exempting the substantial emissions from the Emissions Trading System (an increasingly valuable financial benefit as the price of carbon increases). Current policies thus risk diverting valuable and scarce biomass resources to applications that not only fail to reduce atmospheric levels of CO_2 but are the last choice in the cascade priorities.

The EU is supporting analyses of how to maximise the climate benefits of wood-based construction products that delay the release of carbon by several decades, thus offering long-term carbon capture (e.g. Trinomics *et al.*, 2021) The EU's Bioeconomy Strategy (EC, 2019b) and sustainable bioeconomy initiative (EC, 2021b) also seek to expand high-value applications in the bio economy such as for bio-based chemicals and plastics. In addition, a switch to bio-based fuels in the aviation sector is seen as a growing demand (ETC, 2021). This suggests that the European Commission should update its current guidance on the cascade (EC, 2018) to clarify where biomaterials and specialized uses lie in the hierarchy, reflecting also expectations that the amounts of sustainable biomass available are likely to be less than

Figure 5 Cascade of uses for forest biomass in the EU Fit for 55 package (https://ec.europa.eu/commission/presscorner/detail/en/fs_21_3670; ETC, 2021).

demand in the future (section 2). In the latter respect, a recent meta-analysis by Andersen *et al.* (2021) found that European forest ecosystems are already in decline and it is essential to compare additional demands with the climate benefits of keeping biomass in its living form and conform to the EU's bioeconomy strategy, which requires biomass to be used only within safe ecological limits and to '*strengthen the resilience of land and sea ecosystems, ensuring their contribution to climate mitigation, and enhancing their biodiversity*' (EC, 2019b).

5.2 Current evidence on BECCS and its role in future climate strategies

The continued high uncertainties summarized in section 3 over how much and when any CDR can be achieved through BECCS, and risks of perverse effects on climate, food, biodiversity and other critical Sustainable Development Goals, led ICEF (2021) to introduce the new term 'biomass carbon removal and storage' (BiCRS), which they define as a process that uses biomass to remove CO_2 from the atmosphere, stores that CO_2 underground or in long-lived products, and additionally '*does no damage to—and ideally promotes—food security, rural livelihoods, biodiversity conservation and other important values*'. Waste biomass is the most desirable type of feedstock for BiCRS and, without proper governance and standards, other sources of feedstocks could be counterproductive.

The above analysis is consistent with conclusions in section 3 that development of BECCS/BiCRS projects should focus first on waste biomass. An example of this approach can be found in the current project in California to operate a BECCS facility on 200,000 tonnes of agricultural waste each year.[12] Beyond wastes, the wide range of potential feedstocks was discussed in section 2.2, with a range of payback periods. On current evidence, it is critical that any BECCS projects should be of limited scale and all feedstocks provided locally with very low supply chain emissions, and that any payback times should be very short. In this context, García-Freites *et al.* (2021) looked at methods of achieving the UK's net zero target through three BECCS supply chains: (1) sawmill residues to electricity with CCS; (2) *Miscanthus* to combined heat and power with CCS; (3) willow-biomass integrated gasification combined cycle (BIGCC) to electricity with CCS. This study suggested that the medium-scale combined heat and power option based on *Miscanthus* provided the greatest removal potential per energy generated. Other sources with short payback periods include waste straw (as suggested by Quiggin (2021)), although this could compete with current uses for bedding, building materials, etc.

In view of the leakage of GHG in the production, treatment and extended transport supply chains of existing large power station usage, the science does not support the conversion of existing large-scale forest biomass power stations to BECCS. Rather, any demonstrators should focus on small-scale BECCS trials that use local feedstocks, where options would include energy with carbon capture, or gasification to produce both hydrogen and CO_2. Then, as their performance is reviewed and impacts quantified, BiCRS systems that have additional benefits for biodiversity, soil quality, local economies, etc. can be prioritised. These principles are highly relevant in view of the proposals in the EU Communication on Sustainable Carbon Cycles (EC, 2021b) that set out policies to capture between 300 million and 500 million tonnes of CO_2 by 2050.

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[12] The Mendota BECCS project will produce electricity while capturing CO_2. A refitted biomass plant gasifies agricultural waste to syngas through oxy-combustion technology. Captured CO_2 will be sequestered geologically under the generating site. https://www.cleanenergysystems.com/MendotaBECCS.

An additional complication might arise in accounting and rewarding for BECCS under the Paris Agreement (Torvanger, 2019; Brander *et al.*, 2021) where it applies to the current practice of importing millions of tonnes of pellets for bioenergy. At present, the importing country can treat the imported carbon as recorded in the exporting country's land use emissions accounts and can avoid declaring emissions at the point of combustion. Thus, carbon in the trees exported from the USA, Russia, Canada, etc. to burn in the UK's large biomass power stations enters the atmosphere in the UK, but is treated as zero for the purpose of national emissions and liability for carbon pricing (as described in section 1), due to the presumption that the carbon has already been accounted for in the exporting country's land use statistics. The exported carbon from supplier countries is thus a 'free good' from the importing country's point of view, since the combustion emissions are omitted from national accounts (Funk *et al.*, 2021). In the event of BECCS becoming a large industry, however, where some form of credit is awarded for carbon removals, rules may be needed to assign credits between supplier and importer countries. In this context, Article 6.2 of the Paris Agreement and its new environmental integrity rules[13] could be relevant; these aim to ensure all recorded carbon credits use verifiable and comparable accounting systems between the governments involved in international mitigation activities, and that these should **not** lead to '*a net increase in emissions of participating parties within and between NDC implementation periods.*' These issues will need to be addressed in the current measures to develop a regulatory framework for the certification of carbon removals (EC, 2021b).

5.3 An appropriate role for negative emission technologies (NETs)

There is no doubt about the severity of the challenges facing humanity, and the failure to even start reducing global emissions by 2021 merely adds to the pressure on IAMs to include CDR in scenarios of the future. In this situation, where policy-makers are faced with tough choices, some of which are politically unpalatable (e.g. demand reduction in transport; encouraging dietary changes; tackling the high consumption of elites (Stoddard *et al.*, 2021)), investing in the support of future technologies might seem desirable as an excuse for deferring painful current actions. This 'moral hazard', whereby strong emissions reductions are deferred now on the promise of future technologies yet unproven, merely shifts the burden of costly action and environmental damage to future generations.

The moral hazard of allowing reliance on CDR to weaken current and near-term mitigation efforts (termed 'mitigation deterrence') was illustrated by Grant *et al.* (2021c), who found the emission reductions required over the next decade to be highly sensitive to the assumptions made on future CDR availability. Absolute certainty over the amounts of CDR to be achieved may convince current policy-makers that short-term reductions can be delayed but this is high risk. For instance, if there is even a 20% chance of CDR deployment failure, additional emissions reduction in 2030 of 3–17 Gt CO_2 would be required to compensate. This led Grant *et al.* (2021a) and Quiggin (2021) to strongly argue for national and international targets to formally separate any CDR targets and emissions reduction targets in their climate strategies, so that any CDR is treated as additional to emissions reduction.

As observed by Anderson and Peters (2016), Lenzi (2018), Röder and Thornley (2016) and others, this commentary emphasizes that the priority remains to minimize **the actual need for CO_2 removal** by reducing GHG emissions far faster than is currently being achieved: the sooner that lower emissions are achieved, the less carbon needs removing from the atmosphere, and the less it is necessary to bet on BECCS or other CDR technology. Babacan *et al.* (2020) also emphasise the inefficiency of carbon removal from the atmosphere compared with reducing emissions: up to 20 times as much energy is required to remove a tonne of CO_2 from the atmosphere than to prevent that tonne entering in the first place[14]. In this context, detailed studies of the potential for energy demand reduction (e.g. Barrett *et al.*, 2021) conclude that a comprehensive demand reduction policy could halve final energy demand by 2050 (on the basis of a UK case study), avoiding the need for expensive CDR technologies such as BECCS. However, such reductions would require measures across all sectors of the economy and include healthier diets, trends towards more efficient transport modes and demand reduction, alongside revised building standards and extensive retrofit of existing stock. Such comprehensive policies require leadership, persuasion and system-wide adjustment in incentives. The moral hazard mentioned above arises when governments use the prospect of future CDR technologies as a reason for avoiding such system-wide change.

Warszawski *et al.* (2021) found that over-dependence on CDR and inadequate emphasis on strong mitigation were present in many IAMs, but concluded that avoiding the overshoot of 1.5°C requires all possible measures to reduce global energy demand, decarbonize

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[13] For more detail, see https://www.iisd.org/articles/paris-agreement-article-6-rules or https://ercst.org/postcop26assessment/

[14] Barbacan *et al.* (2020) calculate that renewable energy technologies require 0.05–0.53 kWh for each kilogram of CO_2 mitigated, while carbon embedding or carbon removal approaches are more energy intensive (0.78–10.03 kWh for each kilogram of CO_2 removed). Energy efficiency measures, such as improving building lighting, can offer the most energy-effective mitigation.

energy production, develop low-carbon land-management systems and apply CDR technologies. On the last point, Strefler *et al.* (2021) show that any CDR option with sufficient potential can be applied to achieve the 1.5°C target, and offered a range of scenarios where BECCS is not the dominant CDR technology. Depending on the type of CDR used, the geographical location affected could differ. Latin America would be a dominant contributor to afforestation. Latin America and Asia have the most potential for enhanced weathering, while BECCS and DACCS are more widely distributed.

Overall, we see no reason to change the conclusion reached in EASAC's earlier study that policy should avoid favouring BECCS and proceed first on the cost-effective, nature-based solutions[15] described by Griscom *et al.* (2017), while proceeding with research and demonstration across all potential means of CDR including enhanced weathering and DACCS. Brack and King (2020) came to the same conclusion with their recommendation that the assumption that BECCS is the pre-eminent carbon removal solution should be abandoned, and analysed alongside all other NETs, on the basis of full life-cycle carbon balances (including dropping the assumption that biomass feedstock is inherently carbon-neutral). Lowering the expectations of CDR technologies adds even more pressure to accelerate conventional abatement action as rapidly as possible.

5.4 IAM model refinement

In sections 3 and 4, we pointed to some reasons why inherent assumptions in IAMs may lead to results that favour BECCS being deployed in large amounts to meet future targets to limit warming.

- Cost minimization models may have difficulty in anticipating the rapid and massive reductions in other renewable energy costs.
- BECCS seems more attractive economically owing to the assumption that it delivers both low-carbon energy and CDR. However, assumptions about BECCS efficiencies and removals seem too optimistic at the present state of the technologies.
- Where models assume carbon neutrality, they do not correctly model the time-dependent impacts on atmospheric levels of CO_2. They fail to recognise that emissions from bioenergy per unit of energy generated are many times those of other renewables, and that net emissions relative to fossil fuels will be positive until the payback time has passed.
- Unrealistic estimates of the quantities of biomass available that are sustainable and do not conflict with food production, ecosystem retention, environmental and social constraints, and uses higher up the cascade.
- Assuming a high discount rate that favours the deferment of investment into the future; Grant *et al.* (2021b) found that using a low (1%) discount rate reduces the value of CCS by up to two-thirds.

On the specific question of how best to consider the issues of carbon debt and payback periods in IAMs, it was noted in section 4 that models that assume carbon neutrality will (where forest biomass with lengthy payback times is involved) lead to the following:

- overestimating short-term impacts so that time-sensitive targets (e.g. net zero by 2050) will be missed even if the model assumes they can be achieved;
- delays of decades in the achievement of net removals of carbon from the atmosphere, increasing the risk that temperatures will overshoot critical tipping points (as emphasised in EASAC (2021)).[16]

Since the Butnar *et al.* (2020) review, at least one of the models they studied (IMAGE) has published results that differentiate between payback periods of biomass feedstocks (section 4.3). These confirm our concerns that reliance on biomass without restricting feedstocks to those of short payback periods may fail to deliver the anticipated reductions by 2050 and beyond.

Given the significant increases in biomass use envisaged in current models that have underpinned IPPC, EC and IEA policies and advice, it is critical that models properly address the issue of feedstock carbon debt and payback periods, and conduct sensitivity analyses to determine the effects of using different feedstocks on atmospheric levels of CO_2 at critical dates (e.g. 2030, 2050)[17]. Until this is clarified, policies based on the results of previous models risk encouraging investment that would lock in

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[15] Reforestation, afforestation, recovery of peatlands, mangroves, etc.

[16] It has been argued (e.g. Cowie *et al.*, 2021) that the timing of net emission reductions is not significant if the IPCC carbon budget for a given temperature is not exceeded, so that temperature overshoots followed by later return to below-target levels are acceptable. Recent studies, however, clearly show that temperature overshooting affects the likelihood of many critical physical impacts, such as those associated with heat extremes leading both to higher mitigation costs and to economic losses from the additional impacts (Drouet *et al.*, 2021), while Riahi *et al.* (2021) show that upfront investments needed in the near term to limit temperature overshoot bring long-term economic gains.

[17] For instance, the PRIMES model does have the tools to take carbon payback periods into account, allowing the European Commission to request exploratory studies or modelling for a given scenario (e.g. Fit for 55).

a technology that may prove ineffective. The dangers of going too fast along an ill-chosen route are substantial given the scale of the removals required in some models (section 2.2). Overall, this commentary suggests that the expectation of BECCS delivering significant CDR removals by 2050 should be suspended until the potential shortcomings in the models identified above have been clarified and resolved. Refined and updated models could then be re-run to provide scenarios that incorporate these revisions.

On the basis of current analysis, allowing for payback periods could have the effect of limiting feedstocks to wastes or biomass from short-rotation crops on land with currently little carbon stock, while ruling out the harvesting of forests and conversion of grasslands. This in turn would limit future projections of CDR capacity from BECCS and highlight even more the importance of short-term mitigation. Priorities for NETs would also be affected, reducing (and possibly reversing) the priority of BECCS over other technologies including direct air capture, extraction from sea water, enhanced weathering, biochar in soils, as well as afforestation and reforestation (EASAC, 2018). A wide range of potential technologies is currently under research and development (see, for example, the US, UK and EU programmes: US Department of Energy (2020); BEIS (2021b); EC (2021c)).

5.5 Monitoring and verification

BECCS systems are neither simple nor easy to monitor, extending from growing and harvesting the crops, to processing the biomass and transporting it to the bioenergy plant, all the way to capturing the CO_2 and pumping it into underground depositories. Each step involves some GHG emissions to the atmosphere, and responsibilities and operators differ at each of these stages making regulation and monitoring difficult. With agricultural crops or crops grown on abandoned land, the emissions from land use change may be small or absent. But with additional harvesting from forests, loss of carbon in the soils through changes in management (e.g. a shift from a natural forest to a plantation forest) will incur additional carbon debt and must be properly assessed.

As suggested by Quiggin (2021) and others, this suggests the need to establish an independent institutional system that monitors, reports and verifies data, and calculates the emissions and energy use that relate to BECCS. This may also be required to allocate credits for net removals when supply chains cross national borders (Brander *et al.*, 2021). The term 'sustainable biomass' is already used in bioenergy regulations, so it will be necessary to set standards that also apply to BECCS systems to cover carbon and other GHG emissions, and other environmental issues including water quantity and quality, biodiversity and social impacts. Such systems need to be able to detect 'feedstock drift', whereby initial commitments to limit feedstocks to one 'sustainable source' (e.g. wastes) shift to less sustainable sources for economic or logistical reasons (e.g. to harvesting of whole trees).

Glossary

BECCS	Bioenergy with carbon capture and storage
BiCRS	Biomass carbon removal and storage
CCS	Carbon capture and storage
CDR	Carbon dioxide removal
CO_2	Carbon dioxide
COP	Conference of the Parties
DACCS	Direct air capture and carbon storage
EC	European Commission
EJ	Exajoule (10^{18} joules)
ETC	Energy Transitions Commission
EU	European Union
GHG	Greenhouse gas
IAM	Integrated assessment model
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
NET	Negative emission technology

References

Aguila F.X. *et al.* (2020). Expansion of US wood pellet industry points to positive trends but the need for continued monitoring. *Scientific Reports* **10**, 18607. https://doi.org/10.1038/s41598-020-75403-z.

Agostini A., Giuntoli J., Boulamanti A.K. and Marelli L. (2014). Carbon accounting of forest bioenergy. Conclusions and recommendations from a critical literature review. No. JRC EUR27254 EN. https://publications.jrc.ec.europa.eu/repository/bitstream/JRC70663/eur25354en_online.pdf.

Anderson K. and Peters G. (2016). The trouble with negative emissions. *Science* **354**, 182–183.

Andersen S.P., Allen B. and Domingo G.C. (2021). Biomass in the EU Green Deal: Towards consensus on the use of biomass for EU bioenergy. Policy report, Institute for European Environmental Policy (IEEP).

Babacan O. *et al.* (2020). Assessing the feasibility of carbon dioxide mitigation options in terms of energy usage. *Nature Energy* **5**, 720–728.

Barrett J. et al. (2021). *The role of energy demand reduction in achieving net-zero in the UK*. Oxford, UK: Centre for Research into Energy Demand Solutions.

BEIS (2021a). Net zero strategy. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1033990/net-zero-strategy-beis.pdf.

BEIS (2021b). https://www.gov.uk/government/publications/direct-air-capture-and-other-greenhouse-gas-removal-technologies-competition/projects-selected-for-phase-1-of-the-direct-air-capture-and-greenhouse-gas-removal-programme#bioccus.

Brack D. and King R. (2020). Managing land-based CDR: BECCS, forests and carbon sequestration. *Global Policy* **12** (S1), 45–56.

Brack D., Birdsey R. and Walker W. (2021). *Greenhouse gas emissions from burning US-sourced woody biomass in the UK and EU*. London, UK: Chatham House.

Brander M. *et al.* (2021). Carbon accounting for negative emissions technologies. *Climate Policy* **21** (5), 699–717.

Broad O., Butnar I. and Watson J. (2021) *The role of bioenergy with carbon capture and storage in the UK's net-zero pathway*. London, UK: UCL Institute for Sustainable Resources.

Butnar I. *et al.* (2020). A deep dive into the modelling assumptions for biomass with carbon capture and storage (BECCS): a transparency exercise. *Environmental Research Letters* **15**, 084008.

Camia A. et al. (2021). *The use of woody biomass for energy production in the EU. EUR 30548 EN*. Luxembourg: Publications Office of the European Union.

Canadell J.G. and Schulze E.D. (2014). Global potential of management for climate mitigation. *Nature Communications* **5**, 5282, 1-12.

CCC (2018). Biomass in the low-carbon economy.

Cooper S.J. *et al.* (2020). Exploring temporal aspects of climate-change effects due to bioenergy. *Biomass and Bioenergy* **142**, 105778.

Cowie A. *et al.* (2021). Applying a science-based systems perspective to dispel misconceptions about climate effects of forest bioenergy. *GCB Bioenergy* **13** (8),1210–1231.

Creutzig F. *et al.* (2015). Bioenergy and climate change mitigation: an assessment. *GCB Bioenergy* **7**, 916–944.

Cronin J. *et al.* (2021). Embedding justice in the 1.5°C transition: a transdisciplinary research agenda. *Renewable and Sustainable Energy Transition* **1**, 100001.

Daioglou V. *et al.* (2020). Bioenergy technologies in long-run climate change. Mitigation: results from the EMF-33 study. *Climatic Change* **163**, 1603–1620.

Dooley K., Christoff P. and Nicholas K. (2018). Co-producing climate policy and negative emissions: trade-offs for sustainable land-use. *Global Sustainability* **1** (e3), 1–10.

Dooley K., Harrould-Kolieb E. and Talberg A. (2021). Carbon-dioxide removal and biodiversity: a threat identification framework. *Global Policy* **12** (S1), 34–44.

Drouet L. *et al.* (2021). Net zero-emission pathways reduce the physical and economic risks of climate change. *Nature Climate Change* **11**, 1070–1076.

EASAC (2017). Multifunctionality and sustainability in the European Union's forests.

EASAC (2018). Negative Emission Technologies (NETs)- what role in meeting Paris Agreement targets.

EASAC (2019). Forest bioenergy, carbon capture and storage, and carbon dioxide removal.

EASAC (2020). Transformative change.

EASAC (2021). Commentary for COP26 and COP15.

EC (2018). Guidance on cascading use of biomass with selected good practice examples on woody biomass. https://data.europa.eu/doi/10.2873/911487.

EC (2019a). The European Commission's knowledge centre for the bioeconomy. JRC109354.

EC (2019b). A sustainable bioeconomy for Europe.

EC (2020) Staff background paper SWD(2020) 176 final PART 2/2.

EC (2021a). 'Fit for 55': delivering the EU's 2030 Climate Target on the way to climate neutrality. COM/2021/550 final.

EC (2021b). Sustainable Carbon Cycles. COM(2021) 800 final.

EC (2021c). https://ec.europa.eu/jrc/en/research-topic/carbon-capture-utilisation-and-storage.

Ember (2020). The burning question. https://ember-climate.org/wp-content/uploads/2020/06/2020-Ember-Burning-question-FINAL.pdf.

ETC (2021). Bioresources within a net-zero economy. Making a sustainable approach possible. Energy Transitions Commission.

Fajardy M. and MacDowell N. (2017). Can BECCS deliver sustainable and resource efficient negative emissions? *Energy and Environmental Science* **10**, 1389–1426.

Field C. B., Campbell J. E. and Lobell D. B. (2008). Biomass energy: The scale of the potential resource. *Trends in Ecology & Evolution* **23** (2), 65–72.

Funk J.M. *et al.* (2021). Assessing the potential for unaccounted emissions from bioenergy and the implications for forests: the United States and Global. *GCB Bioenergy*. DOI:10.1111/gcbb.12912

Gambhir A. *et al.* (2019). A review of criticisms of integrated assessment models and proposed approaches to address these, through the lens of BECCS. *Energies* **12** (9), 1747.

García-Freites S., Gough C. and Röder M. (2021) The greenhouse gas removal potential of bioenergy with carbon capture and storage (BECCS) to support the UK's net-zero emission target. *Biomass and Bioenergy* **151**, 106164.

Global CCS Institute (2021). Global status of CCS. CCS accelerating towards net zero.

Gough C. *et al.* (2018). Challenges to the use of BECCS as a keystone technology in pursuit of 1.5°C. *Global Sustainability* **1** (e5),1–9.

Grant N. *et al.* (2021a). The policy implications of an uncertain carbon dioxide removal potential. *Joule* **5** (10), 2593–2605.

Grant N. *et al.* (2021b). Cost reductions in renewables can substantially erode the value of carbon capture and storage in mitigation pathways. *Joule* **4** (11), 1588–1601.

Grant N. *et al.* (2021c). Confronting mitigation deterrence in low-carbon scenarios. *Environment Research Letters* **16**, 064099.

Griscom B. *et al.* (2017). Natural climate solutions. *Proceedings of the National Academy of Sciences of the United States of America* **114** (44), 11645.

Hanssen S.V. *et al.* (2020). The climate change mitigation potential of bioenergy with carbon capture and storage. *Nature Climate Change* **10**, 1023–1029.

Harper A.B. *et al.* (2018). Land-use emissions play a critical role in land-based mitigation for Paris climate targets. *Nature Communications* **9**, 2938.

Heck V. *et al.* (2018). Biomass-based negative emissions difficult to reconcile with planetary boundaries. *Nature Climate Change* **8**, 151–155.

Humpenöder F. *et al.* (2018). Large-scale bioenergy production: how to resolve sustainability trade-offs? *Environmental Research Letters* **13**, 024011.

ICEF (2021). Biomass carbon removal and storage (BiCRS) Roadmap. Innovation for Cool Earth Forum.

IEA (2017). *Energy Technology Perspectives 2017*, Paris: International Energy Agency, https://www.iea.org/reports/energy-technology-perspectives-2017.

IEA (2021). 'Net Zero by 2050 – A Roadmap for the Global Energy Sector', https://www.iea.org/events/net-zero-by-2050–a-roadmap-for-the-global-energy-system.

IPCC (2013). *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* ed T F Stocker et al (Cambridge University Press).

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* ed VMasson-Delmotte *et al.* (Geneva: World Meteorological Organization).

IPCC (2021). Summary for Policymakers. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK: Cambridge University Press.

Jenkins M. and Schaap B. (2018). Forest Ecosystem Services. United Nations Forum on Forests. https://www.un.org/esa/forests/wp-content/uploads/2018/05/UNFF13_BkgdStudy_ForestsEcoServices.pdf.

Köberle A.C. (2019). The Value of BECCS in IAMs: a Review. *Current Sustainable Renewable Energy Reports* **6**, 107–115.

Krey V. *et al.* (2019). Looking under the hood: a comparison of techno-economic assumptions across national and global integrated assessment models. *Energy* **173**, 254–267.

Laganière J. *et al.* (2015). Range and uncertainties in estimating delays in greenhouse gas mitigation potential of forest bioenergy sourced from Canadian forests. *GCB Bioenergy* **9** (2), 358–369.

Lawrence M.G. *et al.* (2018). Evaluating climate geoengineering proposals in the context of the Paris Agreement temperature goals. *Nature Communications* **9**, 3734.

Lenzi D. *et al.* (2018). Don't deploy negative emissions technologies without ethical analysis. *Nature* **561**, 303–305.

Material Economics (2021). EU Biomass Use in a Net-Zero Economy - A Course Correction for EU Biomass.

McLaren D. (2020). Quantifying the potential scale of mitigation deterrence from greenhouse gas removal techniques. *Climatic Change* **162**, 2411–2428.

Muratori M. *et al.* (2016). Global economic consequences of deploying bioenergy with carbon capture and storage (BECCS). *Environmental Research Letters* **11** (9), 095004.

Muratori M. *et al.* (2020). EMF-33 insights on bioenergy with carbon capture and storage (BECCS). *Climatic Change* **163**, 1621–1637.

Muri H. (2020). The role of large—scale BECCS in the pursuit of the 1.5°C target: an Earth system model perspective. *Environmental Research Letters* **13**, 044010.

Nabuurs G.-J. *et al.* (2017). European forests shown no carbon debt, only a long parity effect. *Forest Policy and Economics* **75**, 120–125.

National Academy of Sciences (2018). Negative emissions technologies and reliable sequestration: a research agenda.

Nemet G.F. *et al.* (2018). Negative emissions: III. Innovation and upscaling. *Environmental Research Letters* **13**, 063003.

Norton M.G. *et al.* (2019). Serious mismatches between science and policy continue in forest bioenergy. *GCB Bioenergy* **00**, 1–8.

Norton M.G. *et al.* (2021). Time is of the essence when it comes to forest bioenergy. *GCB Bioenergy* **13** (8), 1210-1211.

Obersteiner M. *et al.* (2018). How to spend a dwindling greenhouse gas budget. *Nature Climate Change* **8**, 7–10.

Odor P. *et al.* (2006). Diversity of dead wood inhabiting fungi and bryophytes in semi-natural beech forests in Europe. *Biological Conservation* **131**, 58–71.

Peters G.P. and Geden O. (2017). Catalysing a political shift from low to negative carbon. *Nature Climate Change* **7** (9), 619–621.

Popp A. *et al.* (2014). Land-use transition for bioenergy and climate stabilization: model comparison of drivers, impacts and interactions with other land use-based mitigation options. *Climatic Change* **123**, 495–509.

Popp A. *et al.* (2017). Land-use futures in the shared socio-economic pathways. *Global Environmental Change* **42**, 331–345.

Quiggin D. (2021). *BECCS deployment. The risks of policies forging ahead of the evidence*. London, UK: Chatham House.

Reid W.V., Ali M.K. and Field C.B. (2020). The future of bioenergy. *Global Change Biology* **26**, 274–286.

Riahi K. *et al.* (2021). Costs and attainability of meeting stringent climate targets without overshoot. *Nature Climate Change* **11**, 1063–1069.

Röder M., Whittaker C. and Thornley P. (2015). How certain are greenhouse gas reductions from bioenergy? Life cycle assessment and uncertainty analysis of wood pellet-to-electricity supply chains from forest residues. *Biomass and Bioenergy* **79**, 50e63.

Röder M. and Thornley P. (2016). Bioenergy as climate change mitigation option within a 2 °C target—uncertainties and temporal challenges of bioenergy systems. *Energy, Sustainability and Society* **6**, 6.

Röder M. *et al.* (2019). Understanding the timing and variation of greenhouse gas emissions of forest bioenergy systems. *Biomass and Bioenergy* **121**, 99–114.

Rose S.K. *et al.* (2020). An overview of the Energy Modeling Forum 33rd study: assessing large-scale global bioenergy deployment for managing climate change. *Climatic Change* **163**, 1539–1551.

Rosa L., Sanchez D. and Mazzotti M. (2021). Assessment of carbon dioxide removal potential via BECCS in a carbon-neutral Europe. *Energy & Environmental Science* **14**, 3086.

Schulze E.D. *et al.* (2012). Large-scale bioenergy from additional harvest of forest biomass is neither sustainable nor greenhouse gas neutral. *GCB Bioenergy* **4** (6), 611–616.

Searchinger T. *et al.* (2018). Europe's renewable energy directive poised to harm global forests. *Nature Communications* **9**, 3741.

Slade R., Bauen A. and Gross R. (2014). Global bioenergy resources. *Nature Climate Change* **4** (2), 99–105.

Smith L. and Torn M. (2013). Ecological limits to terrestrial biological carbon dioxide removal. *Climate Change* **118**, 89–103.

Smith P *et al.* (2016). Biophysical and economic limits to negative CO_2 emissions *Nature Climate Change* **6**, 42–50.

Soimakallio S. *et al.* (2016). climate change mitigation challenge for wood utilization: the case of Finland. *Environmental Science and Technology* **50**, 5127–5134.

Stephenson L. and MacKay D. (2014). *Scenarios for assessing the greenhouse gas impacts and energy input requirements of using North American woody biomass for electricity generation in the UK*. London, UK: Department of Energy & Climate Change, HM Government. http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.696.6944&rep=rep1&type=pdf

Sterman, J. *et al.* (2018). Does replacing coal with wood lower CO_2 emissions? Dynamic lifecycle analysis of wood bioenergy. *Environmental Research Letters* **13**, 015007.

Stern N.H. (2007). *The Economics of Climate Change: The Stern Review* (Cambridge Univ Press, Cambridge, UK).

Stoddard I. *et al.* (2021). Three Decades of Climate Mitigation: Why Haven't We Bent the Global Emissions Curve? *Annual Review of Environment and Resources* **46**, 653–689.

Strefler J. *et al.* (2021). Carbon dioxide removal technologies are not born equal. *Environmental Research Letters* **16**, 074021.

Thrän D. *et al.* (2018). The dynamics of the global wood pellet markets and trade – key regions, developments and impact factors. *Biofpr* **13** (2), 267–280.

Torvanger A. (2019). Governance of bioenergy with carbon capture and storage (BECCS): accounting, rewarding, and the Paris Agreement. *Climate Policy* **19**(3), 329–341.

Trinomics, VITO, Wageningen University, Research, Technische Universität Graz and Ricardo (2021) Evaluation of the climate benefits of the use of Harvested Wood Products in the construction sector and assessment of remuneration schemes Report to the European Commission.

Trumbore S., Brando P. and Hartmann H. (2015). Forest health and global change. *Science* **349**, 814–818.

US Department of Energy (2020). Compendium of carbon capture. https://netl.doe.gov/sites/default/files/2020-07/Carbon-Capture-Technology-Compendium-2020.pdf.

van Zalk J. and Behrens P. (2018). The spatial extent of renewable and non-renewable power generation: a review and meta-analysis of power densities and their application in the U.S. *Energy Policy* **123**, 83–91.

Vaughan N.E. and Gough C. (2016). Expert assessment concludes negative emissions scenarios may not deliver. *Environmental Research Letters* **11**, 095003.

Vaughan N.E *et al.* (2018). Evaluating the use of biomass energy with carbon capture and storage in low emission scenarios. *Environmental Research Letters* **13**, 044014.

Warszawski L. *et al.* (2021). All options, not silver bullets, needed to limit global warming to 1.5 °C: a scenario appraisal. *Environmental Research Letters* **16**, 064037.

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