commentary

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Forest bioenergy, carbon capture and storage, and carbon dioxide removal: an update

Summary

As global emissions of carbon dioxide (CO_2) continue to exceed levels compatible with achieving Paris Agreement targets, attention has been focusing on the role of bioenergy as a 'renewable' energy source and its potential for removing CO_2 from the atmosphere when associated with carbon capture and storage (CCS). The European Academies' Science Advisory Council (EASAC) examined these issues in 2017/18, but since then many peer-reviewed papers and international reviews have been published. EASAC has thus revisited these important issues and updates its earlier findings in this commentary.

EASAC's earlier analysis of the effects of substituting fossil fuels with forest biomass showed that the lower energy density of biomass and supply-chain emissions were increasing atmospheric CO_2 and thus accelerating the pace of global warming. Carbon accounting rules that record biomass exploitation as land use change and emissions from biomass combustion as zero were contributing to this trend. More recent findings increase the urgency of applying standards compatible with the science in both European Union (EU) and national policies on large-scale biomass use in electricity generation—especially those involving imports of wood pellets from other countries. Biomass should not be regarded as a source of renewable energy under the EU's Renewable Energy Directive (RED) unless the replacement of fossil fuels by biomass leads to real reductions in atmospheric concentrations of CO_2 within a decade or so. Reporting requirements under the EU Emissions Trading Scheme should be amended to reflect the real contribution of biomass energy to climate change mitigation over this timescale, to avoid incentivising practices that contribute to an overshoot of Paris Agreement targets.

The EASAC analysis of the role of negative emission technologies (NETs) had noted the importance of CCS and the lost opportunities resulting from the lack of progress in its development in Europe. Since then, some progress has been made in the concept of transport and storage clusters that can accept captured CO_2, but the priority remains to actually implement carbon capture technologies for large fossil-carbon emitters.

Regarding the role of NETs involving carbon dioxide removal (CDR), this update refines our earlier conclusions as follows:

- Existing Nationally Determined Contributions (NDCs) need to be strengthened and mitigation made the first priority ahead of any reliance on future NETs.
- The current failure to reverse the growth in global emissions means that meeting Paris Agreement targets depends increasingly on deployment of NETs.
- Reversing deforestation, reforestation, increasing soil carbon levels and enhancing wetlands remain the most cost-effective and currently viable

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For further information:
secretariat@easac.eu
www.easac.eu

approaches to CDR, and should be implemented now as low-cost solutions relevant both to developed and to developing countries. The capacity of these sinks, however, is likely to be fully used within a few decades.

- The role of bioenergy with carbon capture and storage (BECCS) remains associated with substantial risks and uncertainties, both over its environmental impact and ability to achieve net removal of CO_2 from the atmosphere. The large negative emissions capability given to BECCS in climate scenarios limiting warming to 1.5°C or 2°C is not supported by recent analyses, and policy-makers should avoid early decisions favouring a single technology such as BECCS. A suite of technologies is likely to be required.

- Significant technological progress has been achieved with direct air capture with carbon storage (DACCS) but it is not yet possible to identify a preferred technology.

- Enhancing weathering and *in situ* and *ex situ* carbon mineralisation requires further basic research before its potential can be properly assessed.

- Climate models suggest that early application of NETs in parallel with mitigation offers a greater chance of achieving Paris Agreement targets and avoiding catastrophic environmental and social impacts, than applying NETs at a larger scale later this century.

- EU and national governments should identify a European research, development and demonstration programme for NETs which is in line with their own skills and industrial base.

1 Introduction

During 2018, the EU's RED has been revised, and the EU has also envisaged that CDR may be deployed post-2040 in its long-term targets to address climate change [1]—following an assessment by the Joint Research Centre that future climate scenarios based on current NDCs would require substantial amounts of CDR to be able to meet Paris Agreement targets of not exceeding 1.5°C or 2°C above pre-industrial levels [2]. EASAC contributed to debate within the EU through its analyses of the net climate impacts of forest bioenergy use [3, 4], and the potential for CDR through the application of negative emission technologies (NETs) [5]. Since EASAC's reports were published, scientific papers have continued to emerge, and analyses have been completed by the Intergovernmental Panel on Climate Change (IPCC) [6], the UK Royal Society and Royal Academy of Engineering [7] and the US National Academy of Sciences (NAS) [8]. EASAC thus decided to update its earlier analyses in the light of recent increases in scientific knowledge. We divide this update into three parts related to forest bioenergy, carbon capture and storage (CCS), and NETs. This update is particularly relevant in the light of the EU's commitment (with other High Ambition Coalition group countries) at the COP24 meeting in Poland to toughen existing commitments to reduce greenhouse gas (GHG) emissions to stay within the 1.5°C Paris Agreement target.

2 Forest biomass instead of coal in electricity generation

EASAC's analysis of the role of bioenergy within sustainable forestry management [3] and the deficiencies in the concept of carbon neutrality [4] led to the conclusion that current large-scale replacement of coal in electricity generation by biomass pellets was increasing atmospheric CO_2 levels with little or no consideration of when these initial adverse effects on climate may be reversed through regrowth (the payback period[1]). While the simple concept of carbon neutrality had merely presumed that carbon released into the atmosphere when biomass was burnt would be reabsorbed through regrowth at some stage, the limited amount of time remaining before Paris Agreement targets are exceeded on current trends[2] means that the payback period is highly significant. Taking this into account, EASAC had concluded [3] that '*relying on forest biomass for the EU's renewable energy … increases the risks of overshooting the 1.5°C target*' and that forest biomass should only be regarded as eligible for renewable energy incentives if it reduced the risk of overshooting Paris targets; thus a technology that fails to achieve a significant net reduction in atmospheric CO_2 levels within payback periods of a decade or so should not be supported. At present, depending on the forest being harvested and the nature of the biomass being extracted, payback periods can range from 10 years to never [3, 9].

Recent reviews of the many possible bioenergy scenarios that consider all climate effects [10] show how forest bioenergy systems can have higher cumulative CO_2 emissions than a fossil reference

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[1] Payback period is the time taken for a forest to reabsorb the CO_2 generated as a result of its use as biomass energy.
[2] The IPCC estimates that the Paris Agreement 1.5°C target will be exceeded (on current trends) between 2030 and 2052.

system (from a few decades to several centuries), while other factors which must be considered are any effects on N_2O emissions and biogeophysical impacts, such as albedo change. The biomass sources which can reliably provide a short-term climate mitigation effect are biomass that would otherwise be burned without energy recovery, rapidly decomposing residues and organic wastes, and biomass outtakes from forests affected by high mortality rates. Detailed life cycle studies have confirmed the dominant effect of the reduction in forest carbon stocks as a result of increased wood harvesting, and the long periods required (decades to centuries) before the initial increase in emissions is reabsorbed. In the Finnish case, the benefits from avoided fossil emissions through material and energy substitution are lost mainly by the reduction in the forest carbon sink, so that it is exceptionally unlikely that increased utilisation can provide significant reductions in net carbon emissions within 100 years [11].

Conditions regarding payback periods have not been included in the revised RED (REDII), and concerns have thus been expressed that if REDII conditions are used as a model for biomass policies in other countries, substituting coal with biomass (e.g. through international trade in wood pellets) could seriously damage carbon stocks in global forests, thereby accelerating rather than slowing global warming [12].

Since the UK was one of the first countries to import large quantities of wood pellets for electricity generation, the results of recent scrutiny are relevant. In September 2018, new standards were announced which drastically reduce the supply-chain emissions allowed for any new facilities receiving renewable energy credits[3] [13]. An earlier decision had required future dedicated biomass facilities receiving renewable energy credits to be deployed with combined heat and power with a minimum of 70% overall efficiency [14]—compatible with the conditions presumed to apply for large-scale facilities under REDII. Most recently, the UK Committee on Climate Change has recommended [15] that any new use of biomass for electricity should be subject to much stricter governance on sustainability criteria and only receive incentives as renewable energy when combined with CCS. EASAC notes that such revisions better reflect the underlying science of the links between bioenergy and climate change, and encourages other Member States to avoid deleterious impacts on climate of their own national biomass policies. Moreover, existing facilities that burn forest biomass on a large scale in EU countries should be reviewed to properly quantify emissions over the whole life-cycle, estimate payback periods, and measures considered to reduce their negative effects on climate.

EASAC [3, 4] also pointed to the perverse incentives that result from the accounting rules of the United Nations Framework Convention on Climate Change, which record forestry harvesting emissions together with those from land use, land use change and forestry (LULUCF) and (to avoid double-counting) as 'zero' when burnt. As pointed out, '*current rules allow countries to record imported biomass as zero emission on combustion, giving a false impression of the importing country's progress towards reducing emissions, and shifting responsibility for LULUCF reporting to the exporting country*'. Currently there is no requirement in the EU's Emission Trading Scheme (ETS) to consider the length of the payback period when reporting biomass emissions as zero.

Reporting requirements are urgently needed which better reflect real emissions and their impact on climate. For instance, the application of a factor reflecting 'net emissions impact' (NEI) has been proposed [16] which would be applied to the actual amounts of CO_2 released through the power station stack and reported under the ETS. The NEI could be adjusted according to the amount of time needed for the biomass facility to achieve a net reduction in atmospheric CO_2 concentrations. With short payback periods (e.g. when using just forestry residues), the emissions reported to the ETS could be reduced by applying an NEI of less than 1, since a net reduction in emissions can be achieved soon enough to contribute to climate change mitigation. In contrast, where the biomass feedstock achieves no net reduction in emissions over long periods (for example where whole trees are harvested (see [3, 9]) and thus increases the risk of overshooting Paris Agreement targets, actual emissions would have to be reported under the ETS (i.e. with an NEI of 1).

EASAC thus encourages the European Commission to explore options to introduce more robust accounting rules under the ETS to emissions from converted power stations, in order to differentiate between different sources of forest biomass. Emissions reporting would then reflect the real contribution of biomass energy to climate change mitigation in comparison with other forms of renewable energy.

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[3] From the 2020 standard for existing plants (200 kg CO_2/MWh) to 29 kg CO_2/MWh for plants commissioning after 1 April 2021 to 31 March 2026.

3 CCS

EASAC [5] pointed to the lack of progress in CCS development and demonstration projects within the EU. We noted the lost mitigation opportunities in not applying CCS to fossil-fuel power stations and energy-intensive industries, and that a lack of 'off-the-shelf' efficient CCS compromised the potential uses of NETs which rely on carbon capture and/or carbon storage (see next section). Lessons from project cancellations had shown the importance of developing incentives that enable business models to account for the different technologies and stakeholder motivations in the three stages of capture, transport and storage. Since our report, the USA has assigned tax credits to CCS projects [17], providing a financial incentive for CCS (and CO_2 use) development. The UK conducted an analysis of strategies to reduce costs [18], and recently announced an Action Plan to enable the development of the first carbon capture usage and storage facility in the UK, commissioning from the mid-2020s. One aspect may be to establish transport and storage hubs [19] similar to those envisaged in Norway [20], so that CO_2 capture plans could be developed in locations where high-emitting industries are close together, and could use government-supported transport and storage facilities with lowest economic costs.

EASAC welcomes these belated first steps and reiterates its earlier conclusion that '*efforts should continue to develop CCS into a relevant and relatively inexpensive mitigation technology*', and that '*maximising mitigation with such measures will reduce the future need to remove CO_2 from the atmosphere*'. The European Commission recognises that CCS deployment is still necessary [1]. In view of the most advanced facility for storing captured CO_2 being outside the EU (Norway) as well as the uncertainty over the future position of the UK, the EU may need to coordinate with such facilities to develop an integrated European CCS system.

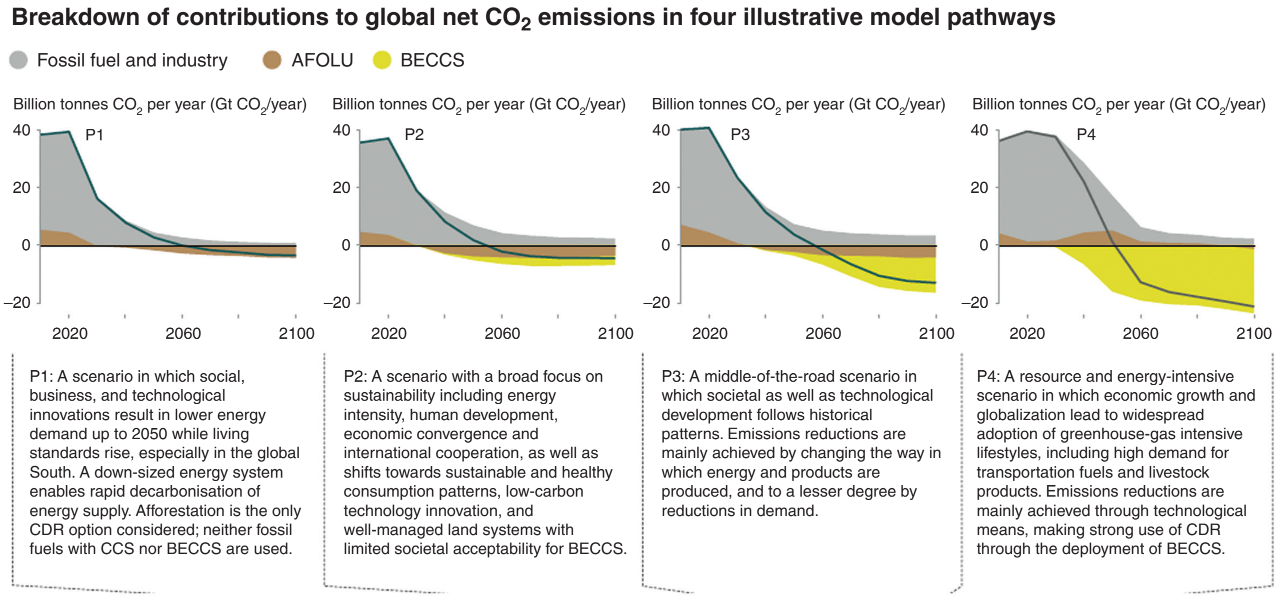
4 CDR and NETs

Recent scientific papers have addressed a number of CDR technologies. For instance, Fuss *et al*. [21] reviewed seven CDR technologies (BECCS, afforestation and reforestation, DACCS, enhanced weathering, ocean fertilisation, biochar, and soil carbon sequestration). The effects of different land use effects of CDR on biodiversity were assessed by Smith *et al*. [22]; the potential for natural carbon solutions by Griscom *et al*. [23]; interactions with planetary boundaries of CDR by Heck *et al*. [24]; and effects of the timing of any introduction of CDR on final global temperatures modelled by Obersteiner *et al*. [25]. As already mentioned, the IPCC released its report on 1.5°C [6], the UK Royal Society and the Royal Academy of Engineering [7] analysed how to achieve net zero carbon emissions for the UK by 2050, and the US NAS published its analysis of research needs for CDR [8]. These allow us to update our earlier conclusions on the potential of afforestation, reforestation and land management; BECCS; enhanced weathering; DACCS; and ocean fertilisation.

The IPCC has restated the difficulty of meeting the Paris Agreement targets by mitigation alone, and estimate that, on current trajectories, 1.5°C warming will be exceeded between 2030 and 2052. As a result, all of the four scenarios offered by the IPCC to limit warming to 1.5°C include applying technologies to remove CO_2 (Figure 1). One (scenario 1) limits the CDR to fully realising the potential of increasing absorption through land management (agriculture, forestry and other land use), but the other three envisage the deployment (removing from 5 to 20 gigatonnes (Gt) CO_2/year) of BECCS. Although, as IPCC notes, inclusion in scenarios of large-scale BECCS does not imply that this is considered the best option for CDR and there is flexibility in substituting with other CDR measures if these become available. The NAS report [8] also concludes that NETs will probably be needed at very large scales (approximately 10 Gt CO_2/year globally by mid-century and 20 Gt CO_2/year globally by 2100) and point to a huge potential market of US$500 billion/year in CDR.

Regarding the role of **afforestation, reforestation and other natural climate solutions**, this remains the least costly and most easily deployable existing CDR technology. Managing the natural capability of the biosphere to absorb carbon has the potentials estimated as shown in Figure 2 [23].

EASAC [5] had emphasised the need to reverse current trends towards deforestation and soil degradation which continue to add substantial quantities of CO_2 and other greenhouse gases to the atmosphere, at the same time as seeking to increase land carbon stocks. This conclusion is reinforced in [23] and strengthens the case for factoring in the large sequestration potential into agricultural and wetlands management (see also [26]), and accelerating the inclusion of climate impacts in agricultural production. The extremely high carbon density of wetlands and the valuable ecosystem services they provide, together with the relatively low cost of reinstatement, were also emphasised by the NAS study [8]. Other recent studies [27] have emphasised the large potential to reduce GHG emissions through more efficient production methods in agriculture and by encouraging shifts to



P1: A scenario in which social, business, and technological innovations result in lower energy demand up to 2050 while living standards rise, especially in the global South. A down-sized energy system enables rapid decarbonisation of energy supply. Afforestation is the only CDR option considered; neither fossil fuels with CCS nor BECCS are used.

P2: A scenario with a broad focus on sustainability including energy intensity, human development, economic convergence and international cooperation, as well as shifts towards sustainable and healthy consumption patterns, low-carbon technology innovation, and well-managed land systems with limited societal acceptability for BECCS.

P3: A middle-of-the-road scenario in which societal as well as technological development follows historical patterns. Emissions reductions are mainly achieved by changing the way in which energy and products are produced, and to a lesser degree by reductions in demand.

P4: A resource and energy-intensive scenario in which economic growth and globalization lead to widespread adoption of greenhouse-gas intensive lifestyles, including high demand for transportation fuels and livestock products. Emissions reductions are mainly achieved through technological means, making strong use of CDR through the deployment of BECCS.

Figure 1. IPCC scenarios of four routes to achieving the Paris Agreement 1.5°C target.

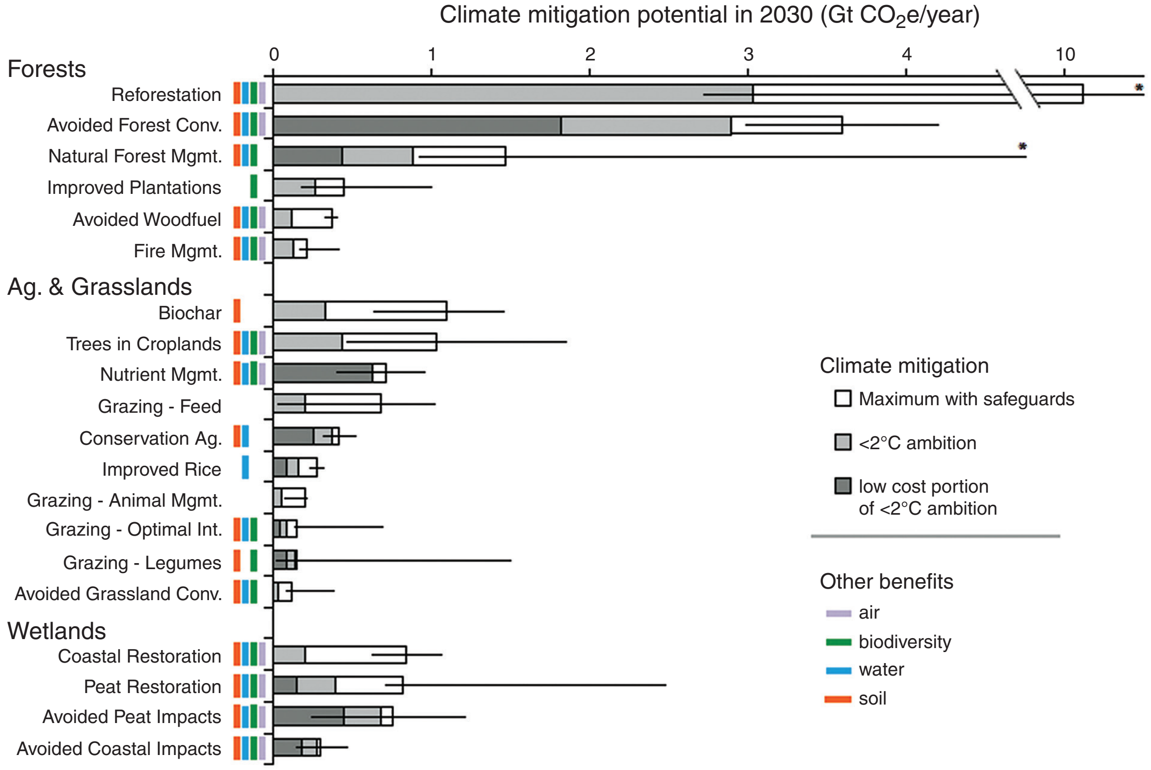


Figure 2. Carbon mitigation potential of various natural carbon solutions [23].

less meat-intensive diets [28]; these points were also emphasised by the IPCC [6]. However, these methods cannot provide a complete long-term sustainable solution, because the capacity of the biological reservoirs will be saturated within a few decades, and because they are not secure as they could revert to carbon sources unless appropriate management is maintained indefinitely. Continued research[4] on other

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[4] For example, low molecular mass organic acid salts added to soils increase the alkalinity of tropical soils, which traps CO_2 as organic matter in the soil and is being considered as a new avenue in soil management for carbon trapping and stabilisation [29].

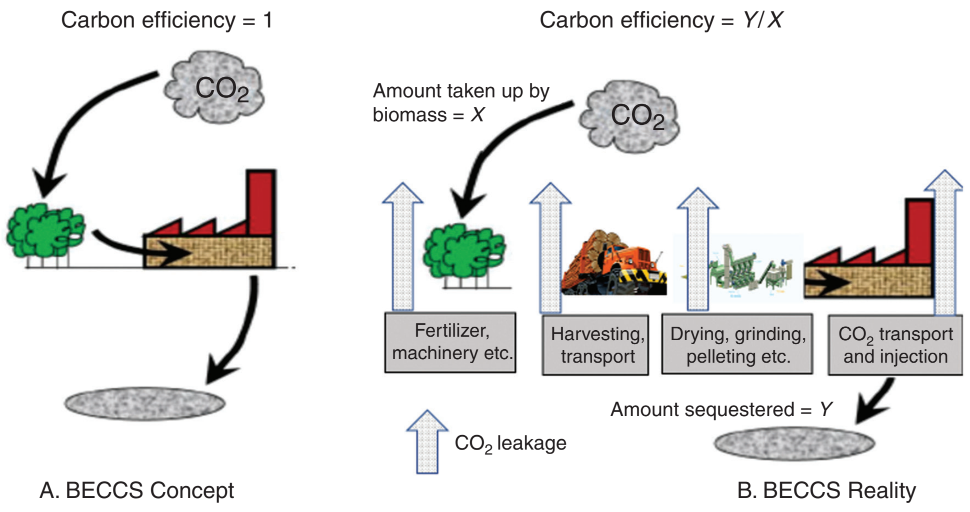

Figure 3. Simple BECCS concept and real life-cycle emission flows.

methods with greater potential and security of storage is therefore also required.

Regarding **BECCS**, this continues to be the dominant NET in IPCC and other [e.g. 25] scenarios achieving Paris targets. In addition, the UK scenario for achieving net zero emissions by 2050 [7] envisaged the application of BECCS to both domestic and imported biomass. EASAC [5] pointed to the risks identified in multiple studies of large-scale deployment of BECCS (especially on water, fertiliser, biodiversity, competition for land) and these concerns remain. However, recent papers [24] have extended concerns to the planetary scale. From the point of view of planetary boundaries[5], deployment of BECCS at the scale in IPCC models could potentially help mitigate climate change, but at the expense of further exceeding the planetary boundaries related to biosphere integrity, land use and biogeochemical flows, while bringing freshwater use closer to its boundary. The impacts of BECCS on terrestrial biodiversity have also been further examined [22] and BECCS found to have generally negative effects, while other land-based CDR methods have neutral or positive impacts (soil carbon sequestration), or are context-specific (forestation).

A key question raised in our earlier analysis [5] was the degree to which the CDR assumed in climate scenarios is likely to be achievable in practice. Extensive work has been performed on BECCS, and its overall efficiency in removing CO_2 from the atmosphere comprehensively reviewed [30]. The simplistic vision of BECCS (Figure 3A) is that one ton of CO_2 captured in the growth of biomass would equate to one ton of CO_2 sequestered geologically—which we can regard as a carbon efficiency of 1. However, as with the simplistic concept of carbon neutrality in the bioenergy debate, this is far from the reality. GHG emissions throughout the biomass supply-chain 'leak' carbon, which reduces the carbon efficiency (Figure 3B). Some life cycle analyses [e.g. 31] of the entire process chain for a BECCS crop to final carbon storage in the ground have shown leakage of CO_2 to be greater than the CO_2 captured at the point of combustion, thus resulting in carbon efficiencies of less than 50%.

Key factors in determining carbon efficiency are emissions in bio-crop production (e.g. from production and use of fertilisers, agricultural machinery), crop processing, drying and grinding, transport and handling—all of which can be estimated with some degree of accuracy. However, the effects on land carbon stocks must also be included—both from the direct land use change involved in switching to the BECCS crop and from secondary impacts (e.g. in shifting demand for food to new areas) which lead to indirect land use change. These effects can be significant. For example [see 30], with switchgrass grown on marginal land with no net emissions from land use change, the BECCS carbon efficiency is 62%, but reduces to 46% when grassland is converted. In terms of CO_2 captured by other crops, miscanthus in a BECCS system has a capacity to capture 700–1,600 t CO_2/hectare over 50 years where marginal land with no land use effects is used. On the other hand, for willow, the potential on marginal land is 190–390 t CO_2/hectare over 50 years, and when grown on land converted from grassland, carbon efficiency may fall below 50% [30].

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[5] Planetary boundaries are the limits for a number of critical system conditions in the planet's sustainability which should not be exceeded if the current state supporting human civilisation is to be maintained.

BECCS negative emissions are also not delivered from year 1—some time lag (similar to the payback period in bioenergy) will occur before the initial extra emissions from producing the crop and establishing the BECCS facility are recovered. This period is very sensitive to the type of bio-crop and previous land use, and can range from just 1 to over 50 years. The carbon efficiency is the critical factor determining the overall benefits of BECCS since high rates of leakage may mean that there will be a long period during which atmospheric concentrations will be increased before any net removals occur.

Current research thus confirms high variability 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. Significant risks exist of perverse outcomes where the net effect is to increase emissions. Determining the suitability of a BECCS project for CDR thus needs to be assessed on a case-by-case basis, and generalised assumptions on removal rates remain problematic [32][6]. As Harper *et al*. [33] point out, the ability of BECCS to remove carbon could easily be offset by losses due to land-use change, and forest-based mitigation may be more efficient in removing atmospheric CO_2 where land containing high carbon stocks is involved.

Key factors listed in [30] that favour improved carbon efficiencies are the following:

- limiting the impacts of direct and indirect land use changes;
- using carbon neutral heat and power and organic fertilisers;
- prioritising sea and rail over road transport;
- increasing the use of low and zero carbon fuels; and
- exploiting alternative biomass processing options, for example natural drying.

Management may also need to choose between CDR as the primary objective or power generation, since BECCS facilities that are less efficient at converting biomass to electricity could remove more CO_2 at a lower cost than their more efficient counterparts [34]. Although cost estimates for BECCS removal of US\$70/t CO_2 have been suggested [8], the high management intensity required to avoid negative effects and limit effects on sustainability may raise costs to US\$100–200/t CO_2 [21].

The above risks and uncertainties need to be considered when estimating the CDR potential of large-scale BECCS. The IPCC included CDR removals from BECCS in three scenarios (Figure 1) with cumulative removals by 2100 of 151, 414 and 1191 Gt CO_2. This required land areas of 93, 283 and 724 million hectares in 2050 respectively. Integrated assessment models assume bioenergy to be supplied mostly from second-generation biomass feedstocks such as dedicated high-yield cellulosic crops such as miscanthus (as well as agricultural and forest residues) which (see figures cited earlier) may be capable of capturing 700–1600 t CO_2/hectare over 50 years. However, the viability of achieving the highest removal rates demonstrated in experimental plots over large areas and many different types of soil has not yet been demonstrated[7]. Moreover, the replacement of temperate forests to grow the bio-crops offering such high yields has been shown to release so much soil carbon [33] that the BECCS-driven crop would have to be grown for over 100 years (equivalent to the long payback periods discussed in section 2) before the initial surge in atmospheric CO_2 levels from conversion was offset and net negative emissions could be achieved. The idealised assumptions in integrated assessment models about full protection of the land carbon stock by conservation measures may not be justified and detailed evaluations of carbon stock changes and overall carbon efficiencies of each BECCS project would be necessary before overall CDR potential can be assessed. As noted in [36], BECCS deployment at the huge scales envisaged in many scenarios may greatly overestimate our collective ability to manage carbon cycle flows, thereby risking doing more harm than good. Moreover, Mander *et al*. [37] point to the huge technical, material, logistical and financial barriers which would have to be overcome to implement sufficient BECCS facilities to remove the amounts of CO_2 included in scenarios achieving Paris Agreement targets.

EASAC thus maintains our previous assertion that '*current scenarios and projections … which allow Paris targets to be met appear rather optimistic …*', that

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[6] As Creutzig *et al*. [10] note, the climate impacts of bioenergy systems are site and case specific. To deliver net climate benefits with few negative environmental or socio-economic impacts, many factors must be considered: land-use change, biogeophysical changes, displacement of other land and water uses; as well as employment, land access and social assets; and biodiversity.

[7] Searle *et al*. [35] reviewed yields of five major potential energy crops, miscanthus, switchgrass, poplar, willow, and eucalyptus, all of which had produced high yields in small, intensively managed trials. However, yields were significantly lower in semi-commercial scale trials, owing to biomass losses with drying, harvesting inefficiency under real world conditions and edge effects in small plots. Growing on non-agricultural land will also lower yields. Moderate and realistic expectations for the current and future performance of energy crops are vital to understanding the likely cost and the potential of large-scale production.

the CDR potential of BECCS needs to be evaluated on a case-by-case basis, while BECCS risks and uncertainties remain substantial in other aspects such as water, fertiliser, food security and biodiversity [22, 36, 38]. Deployment of BECCS facilities can also be limited by the distances between biomass sources and storage sites; in the USA, this reduced the theoretical potential of BECCS by 70% [39], where economic viability of BECCS also favoured larger centralised facilities [40].

We remain of the view that the assumption in future climate scenarios that high CDR rates can be achieved across many countries and land types has not yet been demonstrated. Sensitivity analyses showing effects of medium or lower carbon efficiencies in BECCS projects are needed and, until these are done, the extent to which *potential* CDR can actually be delivered by BECCS remains uncertain. This uncertainty is particularly related to the influence of land use change, the ability to maintain the high productivity shown in small-scale field trials in commercial production over huge area, and keeping supply-chain emissions low.

Further work is thus required to quantify sustainable capabilities for BECCS as a CDR and to demonstrate that risks can be managed effectively through not only technical means but also international governance, before being given priority in future climate-change reduction strategies[8]. Moreover, energy policy should not overlook the inherently low efficiency of exploiting photosynthesis (the basic process driving conversion of CO_2 to biomass) for energy since the amount of electricity that can be produced from a hectare of land using photovoltaics is at least 50–100 times that from biomass [41, 42].

Research needs for BECCS were assessed by the US NAS [8] and are listed in Box 1.

Direct air capture has been subject to more detailed analysis in NAS [8] and ICEF [43] studies.

Box 1 Research needs identified by the US NAS [8]

'Finding ways to soften the land constraint (e.g. crops that take up and sequester carbon more efficiently, releasing land by reducing demand for land-intensive meat production).

Models to assess the impact of BECCS on net greenhouse gas concentrations and climate change require the following essential elements:

(1) land use change impacts, including long-term nutrient and productivity changes;

(2) biomass harvesting, processing, and transportation related emissions (supply-chain emissions);

(3) combustion efficiencies and related emissions of different fuels (referred to as 'fuel substitution');

(4) indirect impacts, such as changes in land use or reductions in timber product inventories due to increased biomass demand; and

(5) carbon capture, transport, and storage related emissions.

(6) Changes in albedo and other biophysical processes that alter how greenhouse gases affect the climate.

Currently, no such comprehensive integrated assessment model exists. To accurately assess how BECCS impact greenhouse gas concentrations and climate change, research is required to build a holistic integrated assessment platform that incorporates the essential elements above, as well as albedo and other climate impacts.'

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[8] This view is consistent with the recent NAS study [8] which notes that *'aside from physical constraints on biomass production, life cycle GHG emissions and other potential radiative impacts, there are key uncertainties regarding indirect emissions, adverse effects on food security, impacts on biodiversity and land conservation, competition for water resources, social equity and social acceptance issues … Therefore, large-scale implementation of BECCS is expected to compete with afforestation/reforestation, as well as with food production and delivery of other ecosystem services … Reducing uncertainty in the outcomes is crucial to increase the robustness of decisions that use these models as inputs … More sensitivity analyses should be made in order to understand the implications of various parameters and assumptions.'*

A comprehensive cost analysis [44] for the Carbon Engineering process (aqueous sodium hydroxide absorption) indicates costs of US$94–232 per ton of CO_2 removed (not including transport and storage), suggesting that some of the potential for cost reductions pointed to in our earlier report is being realised.

The NAS review [8] concluded that several approaches to direct air capture are technically feasible, but because CO_2 in air is approximately 300 times more dilute than from a coal-fired power plant flue gas, the separation process for the same end CO_2 purity will probably be costlier than capture from fossil-fuel power plants. Furthermore, the energy requirements for the absorbent regeneration would require an enormous increase in low- or zero-carbon energy, which would compete with use of such energy sources to mitigate emissions from other sectors. Possible solutions could be to use surplus and stranded renewable energy, or waste heat from other processes. The latter has been claimed to substantially reduce costs of CO_2 capture to about US$50 per tonne[9]. DACCS has large CDR potential and warrants research to identify practical means of implementation. Regarding technology, NAS conclude [8] that it is not currently possible to select either solid sorbent or liquid solvent as a leading technology and that research and development on both approaches is needed (a range of research and development priorities can be seen in the NAS review).

EASAC noted the limited information on which any potential for the various approaches to **enhanced weathering and carbon mineralisation** could be assessed. Major uncertainties remain on the rates of CDR, on potential side effects (e.g. from the trace elements contained), in methods (and energy requirements) for mining, grinding and dispersal, and the extent of co-benefits in agriculture. A research agenda has also been defined by NAS [8] although this has not fully taken into account work carried out outside North America.

EASAC concluded that **ocean fertilisation** is associated with very high levels of uncertainty and ecological risks for a relatively small sequestration potential, and recent reports [8, 46] are consistent with this assessment. A range of local measures (e.g. restoring and conserving coastal vegetation, marine protection areas and eliminating over-exploitation of marine resources), can however provide significant co-benefits even though their climate impact is limited [46].

A recent study [25] looked at different scenarios in the **timing of negative emissions deployment**. From the point of view of intergenerational equity and climate environment safety, NETs needed to be deployed earlier in moderation and alongside rapid decarbonisation so that global emissions peak and decline as soon as possible. Delays in either mitigation or deployment of NETs increased the risk of serious environmental and social impacts. Scenarios waiting to apply NETs at large scale later this century resulted in serious impacts on biodiversity associated with the loss of natural land and overshoot in carbon emissions compatible with Paris Agreement targets.

This finding is supported by the NAS study [8], which concluded that NETs are best considered along with mitigation options now, rather than as a way of decreasing atmospheric CO_2 concentrations at a later stage to compensate for inadequate mitigation. Costs of NETs and some of the more expensive mitigation options are already overlapping, so the question should be ‘which is least expensive and least disruptive in terms of land and other impacts?’. For instance, since costs of some CDR methods are within range at a carbon price of US$50–100/t CO_2, it may be more economical to apply CDR to compensate for aviation emissions than to substitute with cellulosic biofuels[10].

Taking these more recent studies into account, EASAC refines its earlier conclusions:

- In our earlier report we noted the danger of moral hazard in accepting as legitimate future scenarios that are based on assumed CDR of many gigatonnes of CO_2 each year via unproven technologies. Acceptance of such models may weaken resolve in addressing politically difficult mitigation options in the near term and involves placing a bet on NETs rising to the immense challenge later. Ethically [47] the potential losers of a failed gamble upon NETs are future generations, especially the poorest among them, who would be most vulnerable if it failed and who could not possibly consent.
- The difficulties facing large-scale CDR deployment reinforces EASAC’s conclusion that the priority must remain rapid strengthening of mitigation well beyond current NDCs, and that urgent attention should be given to options for deeper mitigation such as those in the IPCC report [6, see also 48] including lifestyle change, additional reduction of non-CO_2 greenhouse gases and more rapid electrification of energy demand based on low carbon sources of energy.

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[9] A commercial system [45] has recently been installed in the USA at a rate of 4,000 t/year using a solid absorbent system with regeneration using waste heat from adjacent industrial processes. Because of the availability of low-cost heat, this has been estimated to cost US$50/t captured CO_2.

[10] NAS estimate that a surcharge of US$0.5 per gallon would allow aviation emissions to be offset.

- A reliable and cost-efficient CCS technology remains a priority—both for mitigating emissions from point sources and as a support technology for other NETs.

- The short-term NET potential of forestation, soil carbon, and wetlands and coastal carbon sinks is well understood and should be integrated into regional and national planning.

- NETs need to be continuously and critically assessed and considered in conjunction with future mitigation strategy when determining Europe's policy towards achieving Paris Agreement goals. The large negative emissions capability given to BECCS in future climate scenarios is not supported by recent analyses, and policy-makers should avoid early decisions favouring a single technology such as BECCS. A suite of technologies is likely to be required.

- Such technologies (BECCS, DACCS, enhanced weathering) require further research, development and verification before policy decisions can be made on their role in future EU climate policy. Research directions can be suggested as follows:

    - BECCS requires work to determine the negative emission achievable across the whole life cycle, and to develop optimal cropping systems with short and efficient supply chains (as well as to expedite effective CCS).

    - DACCS (where Europe has a commercial operating system) requires further research and development ranging from the selection of chemical absorbents, through design and engineering of the process, to absorbent recycle to minimise energy costs.

    - Enhanced weathering and mineralisation has considerable potential but requires basic research into material selection and preparation, and the potential impact of large-scale dispersion.

- The US NAS study and the key research avenues given in Minx *et al*. [49] provide a starting point from which the EU and Member States should assess and identify a European research, development and demonstration programme for NETs which is aligned with their own skills and industrial base.

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Printed on 100% recycled paper by Schaefer Druck und Verlag GmbH, Teutschenthal, Germany.

EASAC Secretariat
Deutsche Akademie der Naturforscher Leopoldina
German National Academy of Sciences
Postfach 110543, 06019 Halle (Saale), Germany
Tel +49 (0)345 4723 9833; fax: +49 (0)345 4723 9839
Email: secretariat@easac.eu

EASAC Brussels Office
Royal Academies for Science and the Arts of Belgium (RASAB)
Hertogsstraat 1 Rue Ducale, 1000 Brussels, Belgium
Tel: +32 (2) 550 23 32
Email: brusselsoffice@easac.eu
Web: www.easac.eu