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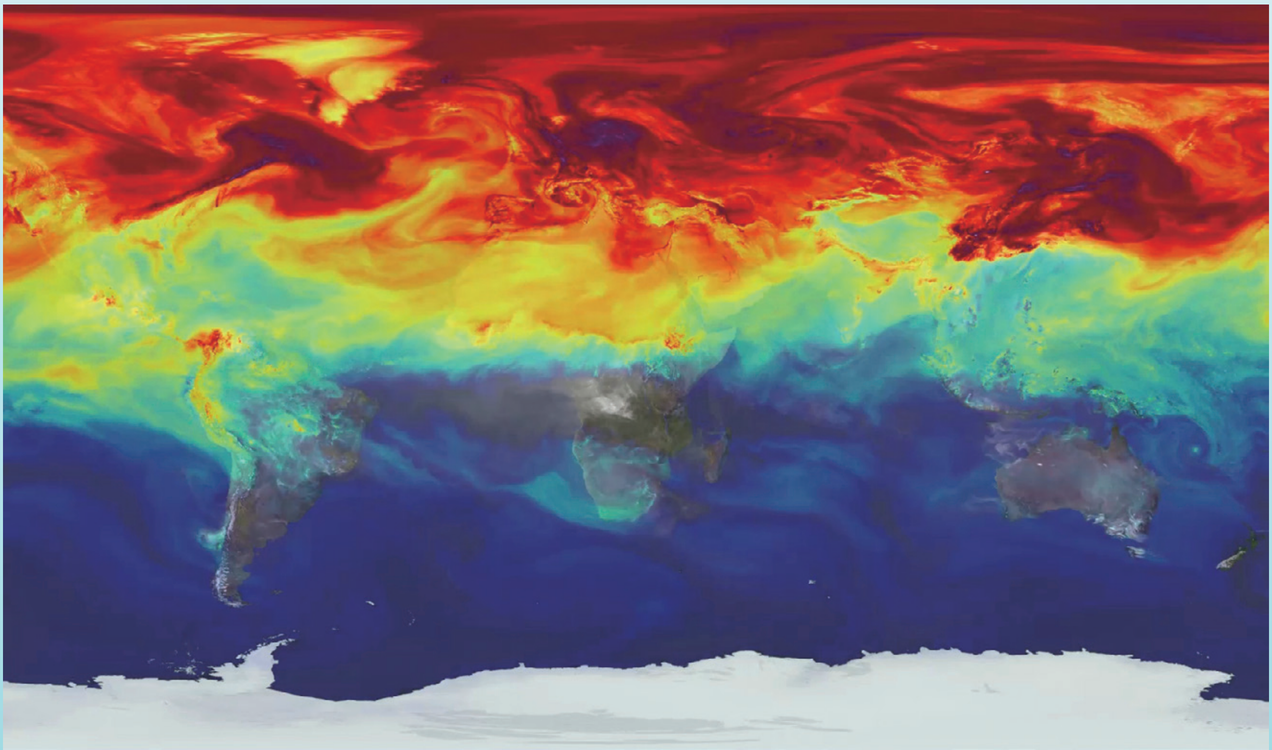
Negative emission technologies: What role in meeting Paris Agreement targets?



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EASAC

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Contents

Foreword

Having achieved a global consensus at the Paris meeting of the UN Convention on Climate Change in December 2015, there may be a tendency to think the problem of climate change is finally on the way to being solved. This may be one reason for the lack of recognition in the public and political debate of the severity of the emission reductions required to achieve the target of restricting warming to within 2 °C of pre-industrial levels, let alone the 1.5 °C aspiration enshrined in the Paris Agreement.

One factor possibly contributing to a lack of urgency may be the belief that somehow ‘technology’ will come to the rescue. The present report shows that such expectations may be seriously over-optimistic. Intergovernmental Panel on Climate Change (IPCC) future scenarios allow Paris targets to be met by deploying technologies that remove carbon dioxide from the atmosphere. However, putting a hypothetical technology into a computer model of future scenarios is rather different than researching, developing, constructing and operating such a technology at the planetary scale required to compensate for inadequate mitigation.

Evaluations comparing the emission reduction plans submitted by countries with those required on the basis of science, show how large a gap remains between countries’ plans and the reductions required. The IPCC has shown that only limited amounts of carbon can be emitted in future without breaching the Agreement’s targets, and each year’s emissions take another chunk of carbon out of the available budget and makes achieving the objectives that much harder. It is no exaggeration to see responding to the real threats of climate change as *a race against time*: the longer action is delayed, the more acute and intractable the problem becomes.

Whether consciously or subconsciously, thinking that technology will come to the rescue if we fail to sufficiently mitigate may be an attractive vision. If such technologies are seen as a potential fail-safe or backup measure, they could influence priorities on shorter-term mitigation strategies, since the promise of future cost-effective removal technologies is politically more appealing than engaging in rapid and deep mitigation policies now. Placing an unrealistic expectation on such technologies could thus have irreversibly damaging consequences on future generations in the event of them failing to deliver. This would be a moral hazard which would be the antithesis of sustainable development.

A range of potential approaches exist for removing carbon dioxide (CO_2) from the atmosphere, at least in theory, and we thus decided to assess the potential of such technologies on the basis of recent peer-reviewed literature. The results of this, which brought together experts from several EASAC member academies, are in this report. It shows that technologies capable of taking out CO_2 from the atmosphere are certainly no ’silver bullet’—a point that should drive policy-makers to renewed efforts to accelerate emissions reduction. At the same time, however, humanity will require all possible tools to limit warming, and these technologies include those that can make some contributions to remove CO_2 from the atmosphere even now, while research, development and demonstration may allow others to make a limited future contribution. We thus conclude it is appropriate to continue work to identify the best technologies and the conditions under which they can contribute to climate change mitigation, even though they should not be expected to play a major role in climate control at the present time.

Global warming and the associated climate change are a global problem, and thus reducing the greenhouse gases driving this process is a global challenge. Historically the European Union has taken a leading position in the international negotiations on this critical challenge, and it is our hope that this analysis will not only reinforce the Union’s determination to tackle climate change but allow it to place the prospect of any future negative emission technologies in its proper perspective.

Thierry Courvoisier
EASAC President

Summary

Climate scenarios that keep global warming within Paris Agreement limits rely on large-scale application of technologies that can remove CO_2 from the air on a huge scale. This is necessary to compensate for the inadequacy of currently planned mitigation measures, which would lead to cumulative emissions of greenhouse gases (GHGs) overshooting the levels that are compatible with avoiding dangerous climate change. The credibility of such scenarios needs to be properly assessed since relying on such technologies to compensate later for failures to adequately mitigate emissions has serious implications for future generations.

Having reviewed the scientific evidence on several possible options for CO_2 removal (CDR) using negative emission technologies (NETs), we conclude that these technologies offer only limited realistic potential to remove carbon from the atmosphere and not at the scale envisaged in some climate scenarios (as much as several gigatonnes (one billion or 10^9 tonnes) of carbon each year post-2050). Negative emission technologies may have a useful role to play but, on the basis of current information, not at the levels required to compensate for inadequate mitigation measures. Implementation is also likely to be location-, technology- and circumstance-specific. Moreover, attempts to deploy NETs at larger scales would involve significant uncertainties in the extent of the CDR that could be achieved, as well as involving high economic costs and likely major impacts on terrestrial or marine ecosystems. The dominant role assigned in IPCC integrated assessment models to NETs (in particular bioenergy with carbon capture and storage: BECCS) has yet to take fully into account these limitations. Scenarios and projections of NET's future contribution to CDR that allow Paris targets to be met thus appear optimistic on the basis of current knowledge and should not form the basis of developing, analysing and comparing scenarios of longer-term energy pathways for the European Union (EU).

Future scenarios without NETs, however, show the great difficulty of reaching net zero emissions of CO_2 by 2050, which is why NETs have received much attention recently. However, the limited potential for CDR underlines the need to strive as hard as possible to mitigate emissions (through energy efficiency and energy saving by technical and regulatory measures, rapid deployment of renewable energies, land use management, reducing emissions of other GHGs, etc.) to make any need for NETs more manageable. Specifically:

- Firstly, the EU (and other Contracting Parties) should concentrate on rapidly reducing GHG emissions as laid out in the Paris Agreement's 5-year review process of national emission reduction plans.
- Secondly, some of the most technologically credible approaches involve increasing soil carbon and forest biomass, but we remain in an era where deforestation and soil degradation are continuing to *add* substantial quantities of GHGs. Clearly, as well as considering forests to remove substantially larger amounts of CO_2, humanity needs to control the *loss* of forests, while stopping soil degradation and restoring soil carbon levels requires this to be included in the criteria for agricultural management.
- Thirdly, we emphasise the importance of solving remaining technical challenges in removing CO_2 from point sources via carbon capture and storage (CCS), and developing viable business models for CCS implementation to remove CO_2 from fossil-fuel power station emissions and from other energy-intensive industries (cement, steel, etc.). Despite the inherently higher efficiencies of CDR when applied to concentrated point sources, CCS plans in Europe have been shelved so that whatever experience is being gained globally is outside Europe. The loss in momentum in implementing CCS technologies not only has serious implications for mitigation pathways, but also one of the most commonly cited NETs (BECCS) assumes the availability of cost-effective 'off-the shelf' CCS, while another (direct air capture) relies on the widespread availability of CO_2 storage. At present, economic incentives for deploying CCS are inadequate (whether through the very low carbon price or targeted government support), while those for NET development are lacking.

Despite the limitations of NETs, halting increases in the concentration of GHGs in the atmosphere remains a race against time, and humanity will require all possible tools to limit warming to within Paris Agreement targets. NETs include measures (re/afforestation and increasing soil carbon contents) that are able to be encouraged now with appropriate policy support (such as the '4 per mille' initiative), and the EU should consider more effective measures for enhancing carbon stocks (as noted in our recent report on multi-functionality of the EU's forests (EASAC, 2017)), as well as incorporating consideration of soil carbon levels in agricultural policy. The other NETs are at different stages of research and development where lead times are long, and thus, even now, it is appropriate to work (in conjunction with the industries potentially providing

or applying such technologies) to identify the best technologies and the conditions under which they can contribute to climate change mitigation.

While this analysis considers the potential role of NETs at the global scale, our analysis is relevant to the EU's policies on CCS, on research priorities, and on the EU's position within international bodies, including the UN Framework Convention on Climate Change, where a political discussion on the potential role of NETs and on how to translate any global CO_2 removal targets to national actions will be needed.

1 Introduction and scope of this report

The Paris Agreement of December 2015 committed its Contracting Parties to act towards the objectives of keeping a global temperature rise this century well below 2 °C above pre-industrial levels, and to pursue efforts to further limit the temperature increase to 1.5 °C. Estimates at the time of the conference (Climate Action Tracker, 2015) concluded that, even if the nationally determined contributions are fully implemented and policies of similar strength are implemented after 2030, they would still lead to a median warming of 2.7 °C by the end of the century. IPCC (2014a) linked the temperature anomaly with the cumulative total of greenhouse gas (GHG) emissions since the Industrial Revolution, calculating carbon budgets that are compatible with a 66% chance of limiting warming to specific temperatures. The budget necessary to limit warming to 1.5 °C appears likely to be exceeded if current rates of emissions continue for another 5 years; that for a 2 °C limit after 20 years, and even a 3 °C limit would be exceeded after 55 years[1].

The question thus arises whether if, after taking all possible measures to reduce GHG emissions, the carbon budgets compatible with Paris Agreement targets are exceeded, humanity has options to avoid further global warming. Since warming results from the effect of solar radiation at a given level of atmosphere absorptivity, one can reduce warming either by reducing the concentration of radiation-absorbing gases in the atmosphere (carbon dioxide (CO_2), methane, nitrous oxide, fluorocarbons, etc.) or by reducing solar irradiance (solar radiation management). Since CO_2 is the major GHG[2], technologies to remove GHGs from the atmosphere (called negative emission technologies: NETs) focus on carbon dioxide removal (CDR).

A range of potential approaches exist for removing CO_2 from the atmosphere, at least in theory, and have been reviewed by some national science academies and in the peer-reviewed literature. Even though the extent of the need for such technologies is still unclear, models show the great difficulty of meeting Paris Agreement targets without them, and thus their potential viability is significant now from a policy perspective. Firstly, there is a long lead time between research and implementation so that research would still be required now even if implementation is envisaged some decades in the future. Secondly, if NETs are seen as a potentially credible fail-safe or backup measure, they could influence priorities on shorter-term mitigation strategies, since the promise of future cost-effective removal technologies may be more politically appealing than engaging in rapid and deep mitigation policies now (Anderson and Peters, 2016). In the event of mitigation failing to deliver a safe future operating space for humanity, failure of such technologies to deliver would then condemn humanity to a dangerously warming world.

The European Commission (EC) has already initiated some work on negative emission technologies. The EuTRACE (2014) project brought together European expertise on the assessment of the potential, uncertainties, risks and implications of various options for climate engineering (including CDR) and concluded that this is not an option for near-term climate policy. Nevertheless, the report did state that it was sensible to continue to investigate climate engineering techniques to understand their potential in the second half of this century and beyond. Since that report, analyses of the various options have continued, and EASAC thus decided to conduct an updated and system-wide overview of candidate negative emission technologies, and to provide a critical analysis of their future potential. In this report, we thus provide an overview of the technologies considered and our conclusions, and provide a more detailed description of each of the candidate technologies in the annexes. This been prepared with the advice and assistance of the Expert Group listed on page 19 and endorsed by EASAC member academies.

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[1] https://www.carbonbrief.org/analysis-only-five-years-left-before-one-point-five-c-budget-is-blown

[2] CO_2 contributes approximately two-thirds of the increase in anthropogenic radiative forcing, so reducing emissions of other GHGs (including chlorofluorocarbons, and the increasing hydrochlorofluorocarbons and hydrofluorocarbons with long residence times and very high global warming potentials) is also critically important. These and various shorter-lived climate pollutants are the focus of measures to reduce their emissions (see, for example, https://www.c2es.org/science-impacts/short-lived-climate-pollutants) and not within the terms of reference of this study.

2 Achieving the targets of limiting warming to 1.5 °C or well below 2 °C

With the coming into force of the Paris Agreement following the ratification of countries responsible for over 55% of global emissions, increased attention is focusing on the means by which Contracting Parties can implement the Agreement and achieve its objective of limiting global warming to 'well below 2°C above pre-industrial levels' and 'to pursue efforts ***to limit the temperature increase to 1.5°C above pre-industrial levels***' (Article 2a) (UNFCCC, 2015). As the primary means of achieving this, the Parties agreed to *'aim to reach global peaking of greenhouse gas emissions as soon as possible … so as* ***to achieve a balance between anthropogenic emissions by sources and removals by sinks of GHG in the second half of this century***' (Article 4.1), at which time net emissions would be zero.

Even before the Agreement, scientific analysis had demonstrated the extreme difficulty of achieving these goals by mitigation alone. Investigations into the possibility of carbon removal from the atmosphere had thus already started and led to many peer-reviewed papers, which have been reviewed by some national science academies (see, for example, Royal Society, 2009; National Research Council, 2015). Since the Paris Agreement was concluded, research has continued and allows us to clarify further the scale of the challenges and uncertainties involved, the quantities of carbon removal likely to be required, and the timescales.

According to the IPCC's Synthesis Report (IPCC, 2014a), no more than around 1000 billion tonnes (1000 gigatonnes (Gt)) of CO_2 can be emitted between 2011 and 2100 for a 66% chance (or better) of remaining below 2 °C of warming. Since the report's publication, more than a fifth of the remaining budget has been emitted in just the past 5 years, and staying within this budget requires an end to carbon emissions from fuel production and energy conversion, transport and energy use by 2050 (Anderson, 2015). Since some sources of emissions are extremely difficult to eliminate (e.g. air transport, agriculture), some IPCC scenarios envisage the deployment of negative emission technologies (to remove GHGs from the atmosphere) after 2050 to compensate for such continued emissions. The critical role of NETs can be seen in the IPCC's scenario database[3] where, of the 400 scenarios that have a 50% or better chance of achieving no more than 2 °C warming, 344 assume the successful and large-scale deployment of some form of NET (Anderson, 2015). So, what are the potential NETs and on what scale would they be required?

Box 1 explains in more detail the rationale for considering NETs in emission scenarios. The scale of such negative emissions was estimated by Smith *et al.* (2016) to require extraction of 3.3 Gt of carbon (GtC) per year after 2050 to stabilise atmospheric concentrations at levels consistent with a 2 °C limitation (430–480 parts per million (ppm) CO_2eq[4]). However, such estimates have significant uncertainties depending on the models used in future scenarios and in the extent of emission reductions achieved. Both higher and lower estimates can be supported. Millar *et al.* (2017) calculated that up to approximately 200 GtC could still be emitted to the atmosphere while meeting the Paris 1.5 °C target, delaying and possibly reducing the need for NETs. On the other hand, Hansen *et al.* (2016) argued that even achieving the 1.5 °C and 2 °C temperature targets will still leave the relatively 'slow' climate processes (including feedbacks that amplify climate change; Rohling *et al.*, 2012; Masson-Delmotte *et al.*, 2013) to operate at an increasing rate as global temperature increases. In view of the inertia built into the climate system, these may be extremely difficult for humanity to control. The most likely threatening slow processes are ice sheet melt and consequent sea level rise, and carbon cycle feedbacks such as increased release of CO_2 and methane from warmer soils and oceans.

In addition, there are other risks in pushing the climate system out of its Holocene (post-glacial) range: methane release from melting permafrost and methane hydrates is also a potentially important feedback. Such considerations suggest that a goal of removing at least 100 GtC[5] (equivalent to 47 ppm of atmospheric CO_2) in the 21st century, with more vigorous removal (of 153 to >200 GtC) thereafter could be necessary to maintain atmospheric concentrations of CO_2 at safe levels. Annual extractions of above 3 GtC (i.e. 11 $GtCO_2$) are thus indicated by both Smith *et al.* (2016) and Hansen *et al.* (2016). Moreover, more ambitious targets are postulated (Fuss *et al.*, 2014; Rogelj *et al.*, 2015; Gasser *et al.*, 2015). Finally, taking a different approach by considering potential extreme and catastrophic impacts, Rothman (2017) finds that the mass of carbon that human activities will likely have added to the

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[3] http://www.iiasa.ac.at/web/home/research/researchPrograms/Energy/IPCC_AR5_Database.html

[4] CO_2eq (carbon dioxide equivalent or Ceq) is the total global warming forcing effect including all GHGs. For instance, the 2016 concentration of CO_2 in the atmosphere was 403.3 ppm, but the other GHGs raise this to 526 CO_2eq (Blasing, 2016).

[5] Such figures may also be expressed in terms of CO_2, and converting carbon (atomic mass 12) to carbon dioxide (molecular mass 44) involves increasing by a factor of 3.67.

oceans by the year 2100 is similar to that associated with several mass extinctions in the past 542 million years, while Xu and Ramnathan (2017) concluded that to avoid 'catastrophic' and 'low probability-high impact (existential)' warming could require removal of 1,000 GtC from the atmosphere by 2100.

The emergency nature of actions to remove carbon is also emphasised by Hansen *et al.* (2017) who note the acceleration in climate-forcing factors over the past decade, and that this has already taken global temperatures out of the Holocene range to average temperatures last experienced in the Eemian interglacial period (about 120,000 years ago when sea levels were 6–9 metres higher than present). Most recently, Marcucci *et al.* (2017) concluded that opportunities to restrict warming to 1.5–2 °C targets may already be passed, and would require negative emission technologies on a large scale. They modelled the role of bioenergy production with carbon capture and storage (BECCS) and direct air capture with carbon storage (DACCS) and found that 7.9–10.6 $GtCO_2$ (2.1–2.9 GtC)

Box 1 Rationale for negative emissions in future climate scenarios

Because of the long residence time of CO_2 in the atmosphere, once emitted it continues to increase the amount of heat absorbed for hundreds of years. The key measure of the impact of CO_2 on global warming is thus the accumulated amount of the gas in the atmosphere. The IPCC (2014a) calculated how much more CO_2 can be tolerated in the atmosphere for a given rise in temperature, introducing the concept of the **carbon budget**, which is the total amount of CO_2 that can be added without exceeding the target temperatures. This 'budget' relates to the total amount emitted since the Industrial Revolution, so the more that is emitted now, the less leeway remains and the more difficult becomes the task of constraining future emissions to within the budget limits.

The budget for a 66% probability of meeting the 2 °C Paris Agreement target was around 1000 Gt of CO_2 ($GtCO_2$). Since the start date of 2011, some 200 Gt have been emitted, leaving around 800 Gt which is the *total amount that can be emitted in the future* if there is to be a 66% chance of limiting warming to within 2 °C. With current emissions (including emissions from land-use change) close to 40 Gt per year, it is very clear that dramatic reductions in emissions need to take place immediately. In recognition of this, the Paris Agreement aimed to achieve zero net emissions by the second half of this century. This would require emission pathways symbolised by Figure 1.

Figure 1 shows not only the dramatic reductions required, but also that there remains the challenge of reducing sources that are particularly difficult to avoid (these include air and marine transport, and continued emissions from agriculture). Many scenarios to achieve Paris Agreement targets have thus had to hypothesise that there will be future technologies which are capable of removing CO_2 from the atmosphere. Including such an assumption allows scenarios typified by Figure 2. In this figure, an emissions reduction pathway that is less challenging and which allows for continued emissions in excess of natural sinks to 2100 and beyond is compensated by a hypothetical technology that removes the excess CO_2 that continues to be emitted, and compensates for the overshoot in the budget owing to an inability to adequately constrain emissions. Net emissions are reduced sufficiently and become negative after 2070 only by applying negative emission technologies at increasingly high rates after 2035–2040.

Several points emerge from these figures. Firstly, there is a very large gap remaining between the commitments made in Paris and those needed to limit warming to 2 °C let alone 1.5 °C. The greater the emissions now, the less remains for future years and generations. Secondly, the inclusion of CDR in scenarios is merely a projection of what would happen if such technologies existed. It does not imply that such technologies would either be available, or would work at the levels assumed in the scenario calculations. As such, it is easy to misinterpret these scenarios as including some judgement on the likelihood of such technologies being available in future.

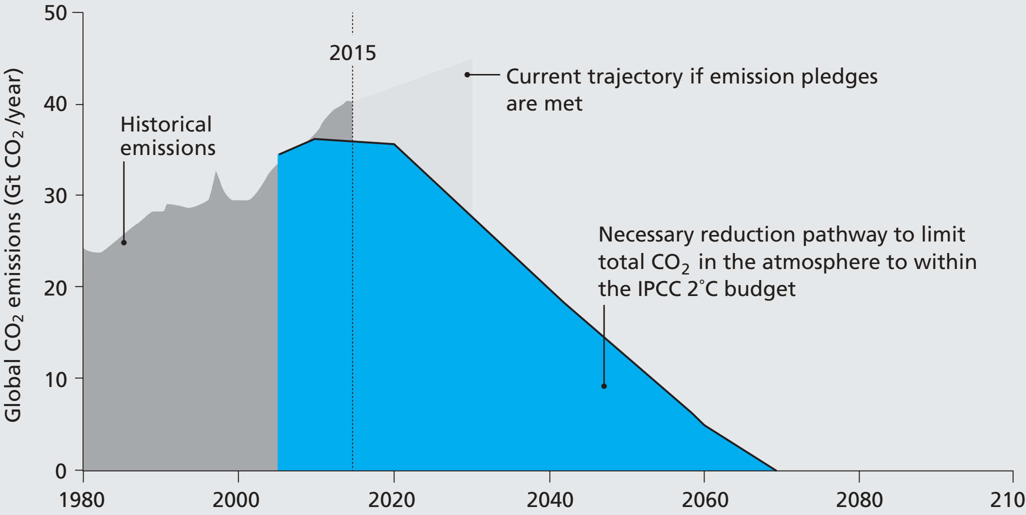

Figure 1 Emission pathways required to limit emissions to within the IPCC budget for 2 °C. N.B.: the carbon budget of approximately 800 GtC is the total area under the emissions (in pink). Source: adapted from Anderson and Peters (2016).

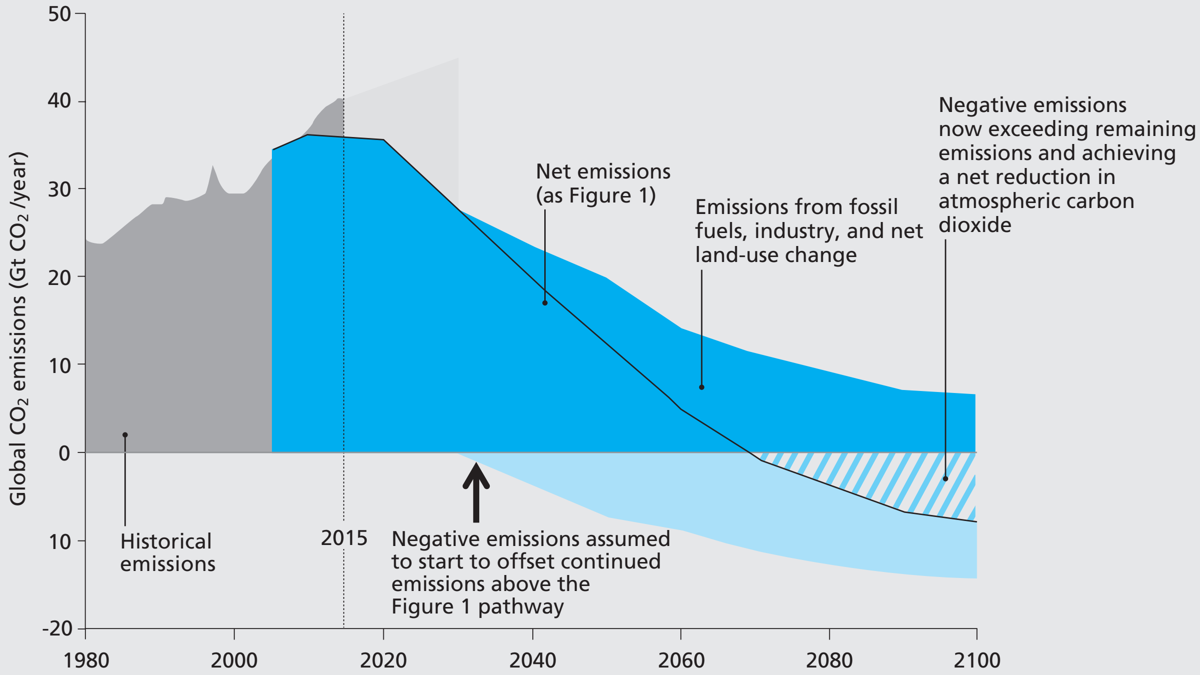

Figure 2 Inclusion of CO_2 removal in scenarios, thus allowing larger emissions without breaching the IPCC carbon budget. Source: adapted from Anderson and Peters (2016).

Table 1 Range of estimates regarding role of NETs to meet Paris Agreement targets

	$GtCO_2$	GtC
Amount of carbon budget remaining to comply with Paris target of 2 °C	800	230
Amount of carbon budget remaining to comply with Paris target of 1.5 °C	130–700*	40–200*
Current rate of emissions (fossil fuel and cement)	36	10
Post-2050 annual removal of CO_2 assumed by applying BECCS in IPCC models	12.1	3.3
Range of assumptions for annual removals in other literature	7–70	2–20

*Millar *et al.* (2017) calculations are only for a 1.5 °C scenario.

removal by BECCS combined with 8–32 $GtCO_2$ (2.2–8.7 GtC) removal by DACCS by 2100 would be required to hold or return average temperatures to below the 1.5 °C level. The range of scenarios consistent with achieving Paris Agreement targets is thus wide, as summarised in Table 1.

This background to the current debate shows that, in this consideration of potential technologies, it is essential to remember that this is *a race against time*: the longer action is delayed, the more acute and intractable the problem becomes (Vaughan *et al.*, 2009).

3 Types of negative emission technologies

NETs can be assigned to general categories as follows:

1. Afforestation and reforestation.
2. Land management to increase and fix carbon in soils.
3. Bioenergy production with carbon capture and storage (BECCS).
4. Enhanced weathering.
5. Direct capture of CO_2 from ambient air with CO_2 storage (DACCS).
6. Ocean fertilisation to increase CO_2.

In addition, since CCS is a critical component of categories 3 and 5 above, as well as a direct mitigation technology for point sources of CO_2, we have included CCS in our considerations. Recently attention has also been given to the possible **use** of captured CO_2, but this is the subject of a separate study by the EU's Science Advisory Mechanism[6] and will not be dealt with here.

We discuss each of the above technologies in Annexes 1–7. In this section, we provide a brief description of each, together with their positive and negative factors, uncertainties and overall potential.

3.1 Afforestation and reforestation (Annex 1)

Afforestation and reforestation absorb CO_2 through plant growth. A positive point is that these are existing 'technologies' which can be applied at low cost. A negative point is that to absorb gigatonne quantities of CO_2, large (and ever-increasing) areas would be required to absorb CO_2 through forest growth (or regrowth). Capacity estimates for the global potential of afforestation and reforestation are 1.1–3.3 GtC/year (Smith *et al.*, 2016) given sufficiently large areas of land (320 million to 970 million hectares or ~20–60% of the current global area of arable land).

Potential problems exist in the release of stored carbon during the disruption of planting or land-use change, nitrous oxide emissions where increased amounts of fertiliser are used, and effects on biodiversity. Forests and associated changes in land use may also affect climate through increased evapotranspiration, changes in cloud cover, and reflectance of solar radiation (albedo). There are also concerns over the availability of land against competition for food with a growing global population and (in the same way as natural terrestrial carbon stocks) vulnerability of the captured carbon to harvesting (legal and illegal logging), fires, pests and diseases. Carbon stored in living biomass may not be secure, and necessary measures and resources would need to be applied to protect and maintain expanding forest. Water requirements could be an important limit, particularly in dry regions.

Examples of afforestation and reforestation can already be seen in the EU with a net increase in forest carbon stock of 756 million tonnes of carbon annually in recent years (Luyssaert *et al.*, 2010), and a major replanting programme in China where over US$100 billion has been invested in replanting in the past decade to increase forest cover by 434,000 km^2. The latter, however, has demonstrated some of the challenges that must be overcome if replanting is to generate dense forests with high carbon stocks rather than the sparse, low plantations observed in many areas (Ahrends *et al.*, 2017). China's experience shows that more work is required to identify suitable environments for future afforestation to sequester carbon, prevent soil degradation and enhance biodiversity.

3.2 Land management to increase carbon in soils (Annex 2)

Modifying agricultural practice offers potential for increasing carbon storage in soils[7], and is already the aim of the post-COP21 '4 per mille' initiative which many EU countries have joined. Smith (2016) estimated that increasing soil organic carbon (SOC) could remove up to 0.7 GtC/year from the atmosphere. Recent studies (Minasny *et al.*, 2017; EASAC, 2017a) suggest that SOC increases would peak after 10–20 years as the SOC levels approached saturation, but if SOC could be increased across the top 1 metre of soil, increasing SOC could have the potential to absorb 2-3 GtC/year. However, some studies indicate much more limited potential for carbon removal from the atmosphere at a global scale (Powlson *et al.*, 2014). Clarifying the potential of land management thus requires additional research before policy implications can be fully assessed; meanwhile, incentives to integrate SOC increase into agriculture are currently lacking.

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[6] This has been asked, '*by the end of April 2018 to provide scientific opinion on the challenges and opportunities of novel carbon capture and utilisation technologies in particular with respect to their climate mitigation potential*' (EC, 2017). A recent publication on this topic by members of the Royal Flemish Academy of Belgium for Science and the Arts (KVAB) is at Martens *et al*. (2017).

[7] Increasing the carbon content in depleted soils also has the strong positive externality of restoring and maintaining soil properties such as structural stability, and thus improves agricultural productivity- contributing to food security (EASAC, 2017a).

In addition, pyrolysis of biomass to form charcoal (biochar) can produce a soil additive that can keep carbon in the soil for many years. Smith (2016) concluded that biochar's negative emission potential would be up to 0.7 GtC/year, although possible albedo effects due to darkening of the soil have not been factored in. However, until the use of coal and other high-emission fossil fuels have been phased out, the alternative use of charcoal as fuel may have greater potential in climate mitigation (Williamson, 2016).

3.3 Bioenergy with carbon capture and storage (BECCS) (Annex 3)

This involves either specific energy crops (such as fast-growing perennial grasses, or short-rotation coppicing) or increased forest biomass (equivalent to afforestation and reforestation in Annex 1) which replace fossil fuels as a source of thermal energy, and capturing the CO_2 produced and storing it underground. This is a NET because producing the biomass fuel involves the absorption of CO_2 from the atmosphere, and returning that to the atmosphere on combustion is avoided by capturing it from flue gases and storing it in geological reservoirs. BECCS is thus dependent on large-scale production of biomass fuel and the ready availability of efficient and cost-effective CCS technology. BECCS has already featured explicitly in some IPCC scenarios: for example a median BECCS deployment of around 3.3 GtC/year is included in scenarios consistent with the <2 °C target (430–480 ppm CO_2eq).

The positive aspect of BECCS is that growing biomass is an existing technology, and that CCS is also a viable technology: see Annex 7). Some BECCS demonstration projects also exist. However, deployment at the scale required to remove gigatonne quantities of carbon would require very large areas of land (land requirements range from ~1 to 1.7 hectares for each tonne of carbon equivalent removed each year for forest residues, ~0.6 hectares for agricultural residues, and 0.1–0.4 hectares when purpose-grown energy crops are used). When assessing the credibility of deploying BECCS on the scales envisaged in integrated assessment models (Gough and Vaughan, 2015), there remain fundamental questions to be answered:

- Productivity and resource requirements differ greatly between types of land and biomass; moreover, impacts on the preexisting carbon stocks can reduce of *even reverse* the carbon removal potential of BECCS (Wiltshire and Davies-Barnard, 2015).

- BECCS demands for land would potentially compete or overlap with land availability for reforestation/afforestation, as well as needs for food production. Applying BECCS at large scales may cause dramatic changes to ecosystems (Williamson *et al.*, 2016) if ecosystem protection measures are lacking.

- BECCS may also be limited by nutrient demand, or by increased water use, particularly if feedstocks are irrigated and when the additional water required for CCS is considered.

- Because of the energy used across the biomass supply and processing chain, even if all flue gas carbon were to be captured, BECCS would still release a significant proportion of the carbon captured in crop growth.

- BECCS scenarios assume CCS is deployable 'off-the-shelf' (cf Annex 7), and the availability of disposal sites for the captured CO_2.

The technical potential for BECCS as a NET thus needs to be evaluated on a case-by-case basis and cannot (as is currently the case in some integrated assessment models) be seen as a primary means of reducing atmospheric CO_2 levels. Overall, the US National Research Council (2015) concludes that BECCS is not relevant until fossil fuel use is restricted (and thus additional energy sources are required) and after all fossil fuel power is already treated with CCS. Slade *et al.* (2014) also note that uncertainties that underpin global estimates of biomass potential need to be further assessed through *'empirical studies, experimentation and cross-disciplinary learning'* before policy on biomass can be properly informed. At present, policy-makers face inherent uncertainties in assessing different bioenergy policy options.

3.4 Enhanced weathering (Annex 4)

Enhanced weathering is where geochemical processes that naturally absorb CO_2 at slow rates are enhanced by some physical or chemical mechanism. When silicate or carbonate minerals dissolve in rainwater, CO_2 is drawn into the solution from the atmosphere. The potential of carbon removal by enhanced weathering (including adding carbonate or silicate minerals such as olivine and basalt to both oceans and soils) has been estimated to be perhaps 1 GtC/year by 2100 (Köhler *et al.*, 2010). One technique could involve spreading finely ground mineral silicate rocks over large areas of land, as is already done in some cases to reduce the acidity of soils for agriculture (Taylor *et al.*, 2016). Other industrialised processes involving dilute solutions have high water requirements. The accelerated weathering concepts that have been explored are the result of theoretical explorations and limited laboratory testing, and industrial process demonstration or pilot-scale applications are lacking. These techniques would require the mining, transport and utilisation of very large quantities of minerals (~1 to more than 3 Gt of rock per gigatonne of carbon removed).

No pilot or demonstration processes are currently underway to determine the scientific, technical and economic advantages and disadvantages, but recently some field studies have started on the potential of using basalt in agriculture to increase carbon uptake while at the same time improving agricultural productivity.[8] Overall, the land areas required for spreading and/or burying large quantities of crushed silicate or carbonate minerals are large, such that the mining and logistical costs may represent an important barrier, compounded by the fact that the plausible potential for carbon removal is lower than for other NETs.

3.5 Direct air capture and carbon storage (DACCS) (Annex 5)

Direct air capture of CO_2 involves a system where air from the atmosphere flows over a contactor that selectively removes the CO_2, which is then released as a concentrated stream for disposal or use, while the sorbent is regenerated and the CO_2-depleted air is returned to the atmosphere (APS, 2011). The main potential technologies involve liquid absorbents or solid adsorbents.

The positive aspects include that removal using liquid absorbents (e.g. monoethanolamine) of (more concentrated) CO_2 from natural gas is already in use, and at the demonstration stage for removal of CO_2 from power station or industrial flue gases (Luis, 2016). The first commercial direct air capture plant (990 tonnes of CO_2 per year) started in 2017 in Switzerland using a solid adsorption process. Viable technologies thus exist today, and are in the development or commercial prototype stage for different capture processes. The requirements are for a rapid and efficient uptake (by either absorption or adsorption), easy CO_2 release and sorbent regeneration mechanisms, with low energy inputs for air handling and the extraction of CO_2, and the same options for long-term storage for the collected CO_2 as are already required for CCS.

The negative points include the size (and capital cost) of the equipment owing to the very large quantities of air that need to be passed through the contactor, the energy penalty associated with sorbent regeneration, water demands to replace evaporation and potential effects of low CO_2 concentrations on nearby vegetation. The starting concentrations for DAC at ambient levels of CO_2 in the atmosphere (about 400 ppm: 0.04%) means that costs are inevitably substantially higher than extracting CO_2 from more concentrated point sources (APS, 2011).

Reviewers such as APS (2011) and National Research Council (2015) conclude that DACCS could become worthwhile after any remaining point sources had already been fitted with CCS. However, imaginative means of minimising energy requirements continue to emerge (e.g. utilising local winds, solar power) and novel sorbents continue to offer alternative process options, with potential to significantly reduce costs. A recent study (Marcucci *et al.*, 2017) concluded that even with a large-scale deployment of a hypothetical and successful BECCS, CDR would be insufficient to meet the Paris targets but that substantial deployment of DACCS (several gigatonnes of carbon removals per year by 2100) would allow these targets to be met.

3.6 Ocean fertilisation (Annex 6)

Planktonic algae and other microscopic plants take up CO_2 and convert it to organic matter, some of which sinks as detritus and is sequestered in the deep ocean. It is suggested that enhancement of this process could affect atmospheric CO_2 concentrations significantly over several decades to centuries (National Research Council, 2015) by as much as tens to over 100 ppm. Since the photosynthetic processes depend, among other factors, on the availability of nutrients, 'ocean fertilisation' has long been considered as one possible means of capturing CO_2 (Williamson *et al.*, 2012). The most promising micronutrient examined to date is iron because of the large ratios of carbon to iron in plankton (OIF: ocean iron fertilisation). However, studies have identified several possible drawbacks. The types of plankton cannot be controlled and will depend on other factors (such as the availability of silicon necessary for some species), and iron addition may stimulate the growth of diatom species, some of which are associated with toxic algal blooms. Ecological impacts on the marine food web and fisheries, and downstream effects on nutrient supply, productivity and food web dynamics, are also difficult to predict. OIF should ideally promote the formation of plankton with larger cells that may encourage more rapid sinking, but this may affect higher trophic levels, including fish, seabirds and marine mammals, in unpredictable ways. Moreover, a very large increase of plankton production is required to achieve significant amounts of sequestration, because most of the carbon fixed is released when the plankton decays or is consumed, and only a small proportion reaches the deep ocean (Wallace *et al.*, 2010). The sequestration potential is therefore unlikely to exceed 1 GtC per year (National Research Council, 2015), and OIF is thus associated with very high levels of uncertainty and ecological risks for a relatively small sequestration potential.

3.7 Carbon capture and storage (CCS) (Annex 7)

Annex 7 describes the current slow progress on developing and implementing large-scale CCS, and contrasts this with the scenarios of 5–10 years ago

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[8] Leverhulme Centre for Climate Change Mitigation; see lc3m.org.

which envisaged rapid deployment post-2020 to remove substantial quantities of CO_2 from fossil fuel power stations and energy-intensive industries (EII) such as cement, steel, etc. It has also been pointed out above that some of the NETs (in particular BECCS) are entirely dependent on cost-effective, reliable and mature 'off-the-shelf' CCS infrastructure.

Currently, the technology for extracting CO_2 from oil/natural gas fields (such as Norway's Sleipner field) is well established, but separating it from power stations is still at a relatively small scale (of the order of 1 million tonnes/year CDR) and at demonstration or early commercialisation stages of identifying and overcoming technical problems, including minimising the 'parasitic' energy costs (the loss of efficiency in the overall conversion of fuel to electricity). The slow progress in the demonstration and commercialisation phases of CCS reflects the lack of adequate incentives (carbon price or other government incentives), as a result of which the opportunity is not yet being grasped for future innovation to reduce costs through both 'learning by diversity' and 'learning by replication' (Reiner, 2016). In both European and Member State research programmes, momentum has been lost, with commercial-scale development projects withdrawn owing to lack of adequate government support. Moreover, public concerns over the safety and environmental issues related to proposed use of onshore storage reservoirs remain.

Recent evaluations confirm the critically important role of CCS in any strategy for limiting temperature rise to 2 °C, and even more so for limiting temperature rise to 1.5 °C, and that pursuing CCS requires a whole-chain, innovation systems approach, including coordination of actors and infrastructure (Ekins *et al.*, 2017). A combination of public and private initiatives, with public funds contributing more to the infrastructure required to support transport and disposal of the separated CO_2 in abandoned hydrocarbon traps, could be economically attractive (Oxburgh, 2016). Research continues on more efficient capture processes which incur lower parasitic energy costs, and WEC (2016) projects a 30% cost reduction potential from second-generation technologies. Since European plans to develop and apply CCS to power generation and other fossil-fuel point sources have stalled, CCS is not contributing to CO_2 emission reduction; nor is it developing to the point where it can offer an 'off-the-shelf' technology to be applied in some NETs. Research and development[9] on remaining technical challenges and new business models are required if CCS is to contribute to mitigation in the short term and NETs in the longer term. Because uncertainty exists over the future of coal-fired power plants (owing to the falling costs of wind and solar power, and some national policies to phase out coal-fired electricity), CCS development needs to be applicable to a range of EII sources of CO_2.

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[9] In this context, Horizon 2020 includes research themes relevant to CCS, including in 2017, LCE27 (measuring, monitoring and controlling the risks of CCS and unconventional hydrocarbons); LCE-28 (highly flexible and efficient fossil fuel power plants); LCE-29 (CCS in industry, including bio-CCS); LCE-30 (Geological storage pilots).

4 Policy implications

4.1 The challenge and importance of mitigation

The current situation in Europe is that, following the European Trans-disciplinary Assessment of Climate Engineering (EUTrace) project, climate engineering (which includes solar radiation management as well as negative emission technologies) is not considered a credible option in the near term but is something that cannot be ruled out in the longer term. Our analyses support the first of these conclusions, but we believe that it is possible to be more specific about the potential of future policy options. A critical question is whether any of the perceived NETs justify the important role they have been given in future climate scenarios which comply with the Paris targets?

Scenarios to meet Paris Agreement targets described in Chapter 2 envisage a need for CO_2 removal of 3 GtC or more per annum over an extended period post-2050. However, such estimates assume that all mitigation strategies anticipated under the Paris Agreement will be met, which currently appears less likely following the planned withdrawal from the Paris Agreement by the USA. Failure to meet mitigation targets (which anticipate the periodic upgrading of countries' nationally determined contributions) will only add to the need for carbon removal at even higher rates than 3 GtC/year, and annual removals of up to 10 GtC have been envisaged (see, for example, Rogelj *et al.*, 2015).

We note that some CDR may be achieved by enhancing the rate of some natural removal processes. These include carbon-friendly agriculture, reforestation and afforestation; ocean iron fertilisation; and land- and ocean-based accelerated weathering. Some of these are already being applied (e.g. China's major investments in reforestation, the '4 per mille' initiative on increasing SOC). Other processes seek to capture CO_2 from the atmosphere and dispose of it by geological sequestration (BECCS and DACCS). However, as discussed in section 4.2, there are serious questions over whether any (separately or cumulatively) have the potential to deliver carbon removals at the gigatonne scale and rate of deployment envisaged as necessary in IPCC scenarios. Some may have potential to make local removals at the scales of millions of tonnes per annum, but uncertainties over their technological, economic and environmental viability remain.

In view of the great difficulty in achieving zero net emissions scenarios without NETs and their likely limited potential, we emphasise the need to strive as hard as possible to mitigate emissions so that any need for NETs is reduced and therefore more manageable. This urgency is emphasised by most recent data on carbon emissions which, after 2016's calculations of 9.9 ± 0.5 GtC/year from fossil fuels and 1.3 ± 0.7 GtC/year from land use change (Le Quéré et al, 2017), are reported as rising for 2017 by approximately 2% (Global Carbon Project, 2017). **Given the somewhat unclear technical and economic viability of NETs in the longer-term future, the EU should thus continue to be fully committed to mitigation as laid down in the EU's nationally determined contributions in the Paris Agreement.**

4.2 Considering NETS as part of the whole Earth system

The NETs reviewed in the annexes and summarised above differ in their technological status, ranging from simple approaches typified by afforestation to technologies still at the research and development phase. Costs range from well-characterised to highly uncertain. Maximum potential capacity estimates for CDR in recent reviews (see, for example, National Research Council, 2015; Smith *et al.*, 2016), and in the Annexes, are in Table 2.[10] A more recent estimate emerges from Psarras *et al.* (2017), who reviewed the potential distribution of CDR between different NETs and calculated a global upper limit for CDR of 3.3 (BECCS), 3.3 (DACCS), 1.6 (afforestation and reforestation, land management) and 1.4 (enhanced weathering) GtC/year.[11]

Our analyses in the annexes and in the previous section, however, indicate that CDR capabilities also vary in the nature and scale of potential side effects, and include the possibility that their CDR capacity may be less than currently assumed or even counter-productive. Moreover, biophysical, biogeochemical (i.e. nutrients), ecological, energy, water and economic resource implications of large-scale implementation of the NETs differ significantly. Such factors need to be taken fully into account in any realistic assessment of the potential of NETs; a point well recognised by other authors (see, for example, Keller *et al.* 2014; Anderson and Peters 2016; Smith *et al.* 2016). Making a realistic

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[10] The literature includes a wider range of figures than those in Table 2 (Chapter 2), and readers are referred to the papers and reviews (especially NRC (2015)) for more detail.

[11] Note that CDR capabilities here are based on technical, logistical and economic factors and not on their ability to meet Paris Agreement targets; the latter are discussed in Chapter 2.

Table 2 Summary of strengths, weaknesses and uncertainties of NETs (refer to text and annexes for details)

	AR	LM	BECCS	EW	DACCS	OIF	CCS
Technical status	Existing	Existing	Demonstration	Research	Demonstration/ commercial	Research	Commercial and demonstration
Potential in literature (Gt C/year)	1.1–3.3	2–3	3.3	1	3.3+	<1	4+
Cost	L	L	M	M	M/H	L/H	L
Is the amount of CO_2 removed consistent across different applications?	Case specific	Yes	Case specific	Rate uncertain	Yes	Uncertain	Yes
Carbon removal secure in long-term?	Vulnerable (1)	Vulnerable (2)	Vulnerable (1)	Yes	Yes (3)	Uncertain	Yes (3)
Possible reverse effects on climate? (4)	Yes	No	Yes	No	No	Yes	No
Large ecosystems and biodiversity effects likely	Yes	No	Yes	Uncertain	No	Yes	No

AR, afforestation and reforestation; LM, land management; EW, enhanced weathering. Approximate costs: L, less than €100/tCO_2; M, €100–400/tCO_2; H, more than €400/tCO_2. Notes: (1) To climate change, fires, pests, diseases, forestry policy changes. (2) Warming increasing soil respiration, return to intensive agriculture. (3) On assumption that secure geological sites used for storage. (4) For example, release of other GHGs, effects of land use change, albedo. **N.B.: this table is to assist in highlighting the strengths and weaknesses of the various NETs and should only be used as a guide to the main issues identified in the text and annexes, not as a definitive summary of this analysis.**

assessment of the potential of NETs is thus fraught with uncertainties, as also summarised in Table 2.

In addition, most analyses of the potential of individual NETs have focused on the physical, chemical and geological aspects, and less attention has been paid to impacts on the planet's ecosystems. Clearly, transforming the uses assigned to substantial proportions of the Earth's landmass, or interfering on a large scale with the ocean ecosystem, has substantial implications for the Earth's remaining natural ecosystems and the species they support. The Convention on Biological Diversity (CBD) has pointed out that the land use change envisaged in IPCC scenarios that reach Paris targets would lead to '*large losses of terrestrial biodiversity*' and consequently does not support geo-engineering options such as afforestation, BECCS and ocean fertilisation as a policy option for addressing climate change (CBD, 2016).

4.3 Timescales and competition between NETs

A critical criterion is that the CDR process should be applicable for long-term use and that the carbon captured should be secure for several hundred years. This criterion is particularly problematic for strategies involving forestation and enhancement of SOC since warming leads to higher soil respiration and to the risks of larger and more frequent fires[12]. Climate change is also enabling the spread of pests and/or diseases leading to forest die-back. Combined with illegal logging and the possibility of short-term changes in national forest policies affecting forests' use as a carbon bank, BECCS and afforestation and reforestation appear particularly vulnerable.

Another factor is that each NET may be in competition for scarce resources. In the case of biomass-related approaches, a single hectare of land can only be used

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[12] A recent study (Abatzoglou and Williams, 2016) concluded that warming had caused the area affected by forest fires in the western USA to double over the past 30 years as higher air temperatures dry out vegetation, making it more prone to combustion.

for afforestation in which the trees are protected, or for BECCS in which the vegetation is harvested as fuel. Theoretical potentials of both options on the same land would thus involve double counting. Afforestation and reforestation and BECCS (as well as DACCS and enhanced weathering) may compete with demands for land for food and retention of natural ecosystems and biodiversity, which in turn are driven by population growth and changes in diet. Timescales also vary between NETs, with maximum carbon absorption in those involving biomass ranging from a few years to decades.

The dominant role assigned in IPCC integrated assessment models to NETs (in particular BECCS) face serious challenges in taking fully into account these interactions, as well as allowing for factors that potentially may reduce or even reverse CDR capacity. This adds further uncertainties to the calculation of the cumulative potential in integrated assessment models. Current scenarios and projections of CDR's future contribution to CDR which allow Paris targets to be met thus appear rather optimistic on the basis of current knowledge, and should not be seen as offering a realistic pathway to meeting Paris Agreement targets. **When developing, analysing and comparing scenarios of longer-term energy pathways for the EU, these constraints in the potential of NETs should be given appropriate attention.**

4.4 Setting priorities

The focus on forestry as a NET can divert attention from the potential of continued *deforestation* to release very large quantities of CO_2 (1800 $GtCO_2$ remain sequestered in tropical forests (see Annex 1), and Ripple *et al.* (2017) report deforestation of 1.2 billion hectares since 1992). As well as considering reforestation or afforestation, therefore, it is essential to slow and reverse current continued high rates of deforestation which have turned tropical forests from carbon sinks to carbon sources (Baccini *et al.*, 2012) through land use changes to palm oil, soya, pasture, etc. Equally, since efficient and off-the-shelf CCS is a precondition for BECCS (and the carbon storage aspect for DACCS), and CCS is a critical means of increasing mitigation from existing point sources, **efforts should continue to develop CCS into a relevant and relatively inexpensive mitigation technology**.

We note in Annex 7 that technical challenges in applying CCS to coal-powered power stations remain; meanwhile development is also lacking in applying CCS to EII point sources (which may have higher concentrations of CO_2 than power stations and thus be more attractive development models). Moreover, business models for supporting CCS have proved particularly problematic, for instance where governments expect individual capture projects to support full transport and storage infrastructure costs. Provision of the necessary infrastructure around hubs of potential sources of capturing carbon could help address this failure, as is currently under consideration in some local (Teesside Collective) and national (e.g. Norwegian CO_2 storage and disposal infrastructure) initiatives. **Maximising mitigation with such measures will reduce the future need to remove CO_2 from the atmosphere.**

The emphasis we place on mitigation to avoid an overshoot in 'safe' levels of CO_2 is supported by the reality that removal of a given quantity of a greenhouse gas later would not fully compensate for an earlier overshoot of emissions. The existence of a significant time gap (many decades) between an overshoot and its potential compensation means that climatic and environmental consequences of the overshoot would continue and not be fully cancelled by future CO_2 removal. As pointed out by CBD (2016), the consequences of that delay during which warming continues would lead to significant and potentially irreversible consequences for biodiversity and the Earth system.

Although we do not consider any NET as likely to offer the potential for CDR at the scales assumed in future climate scenarios, halting (and eventually reversing) increases in atmospheric GHG concentrations remains a race against time, and humanity will require all possible tools to limit warming to within Paris Agreement targets. Lead times for research and development of such new technologies are long, and thus, even now, it is appropriate to continue work to identify the best technologies and the conditions under which they can contribute to climate change mitigation. This should clearly involve the industries that would either develop or use such technologies. NETs vary between those that are capable of being applied now, those at development/demonstration phase and those still awaiting more basic scientific research to establish their capabilities. **The EU should thus consider what possible policy options may be appropriate to climate policy.** For instance, by considering:

- supporting initiatives such as '4 per mille' by incentivising agriculture to increase SOC;

- providing greater incentives to increase carbon stocks in forests (EASAC, 2017);

- reviewing and updating CCS development and demonstration programmes;

- conducting research on reducing energy and resource costs of DAC;

- maintaining a watching brief for other options to remove CO_2 to compensate for sectors such as aviation where fossil fuels cannot easily be substituted[13]; and

- addressing the weakness of market forces to fund deployment of CCS (and ultimately viable NETs) owing to the low carbon price[14] and questions over the eligibility of NETs within the Emissions Trading Scheme.

4.5 The EU's global role

This analysis considers the potential role of NETs at the global scale, and any implementation of NETs will have to be part of a global response. This raises important questions over how to prioritise and share actions among countries and economic sectors- an issue recently considered by Peters and Geden (2017). A political dialogue over this issue and the role of CDR could take place within the United Nations Framework Convention on Climate Change's 'facilitative dialogue' from 2018 before the next round of updates to the nationally determined contributions. Some scientific studies have already calculated the potential scale of NETs appropriate to larger countries and regions (see, for example, Marcucci *et al.*, 2017). At the same time, the lack of economic incentives for private actors to apply CCS or NETs remains a fundamental barrier to incentivising business to research, develop and deploy the necessary technologies. The EU has an important role to play in this as part of its post-COP21 initiatives, and it is hoped this EASAC analysis will help inform discussion on this. Our analysis is thus relevant to the EU's policies on CCS, on research priorities and on the EU's position within not only the United Nations Framework Convention on Climate Change political discussions above but also in implementing the Sustainable Development Goals, priorities within the International Energy Agency and other bodies.

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[13] Taking note of proposals in the USA for inter-agency action and coordination of research, development and demonstration programmes to reduce the cost and clarify the sustainable use of CDR (Sanchez *et al.*, 2018).

[14] Current carbon prices are just 10–20% of the levels expected to make CCS cost competitive (Annex 7) and even higher prices would likely be needed to incentivise industry funding for NETs. Some initiatives to develop NETs are underway supported by charitable funding (e.g. Leverhulme Centre for Climate Change Mitigation and Virgin Earth Challenge initiatives).

Glossary

BECCS	Bioenergy with carbon capture and storage
CBD	Convention on Biological Diversity
CCS	Carbon capture and storage
CDR	Carbon dioxide removal
DACCS	Direct air capture and carbon storage
EASAC	European Academies' Science Advisory Council
EC	European Commission
EII	Energy-intensive industries
EU	European Union
EuTRACE	European Trans-disciplinary Assessment of Climate Engineering
GHG	Greenhouse gas
IPCC	Intergovernmental Panel on Climate Change
NET	Negative emission technology
OIF	Ocean iron fertilisation
SOC	Soil organic carbon

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The draft report was subject to peer review by experts nominated by EASAC member academies.

Annex 1 Afforestation and reforestation

Forests and their trees are prime regulators within the water, energy and carbon cycles (Ellison *et al.*, 2017) and provide the foundations for carbon storage, for cooling terrestrial surfaces and for distributing water resources. Absorption of CO_2 through forest growth is already accounted for in the land use category of national GHG inventories. In temperate areas, carbon stocks have generally increased in recent years while decreasing in tropical areas owing to forest degradation and deforestation. Reducing the rate of tropical deforestation has been long identified (see, for example, Stern, 2006) as one of the most effective and economic means of limiting emissions and mitigating climate change. Despite this, emissions from deforestation continue at a high rate and accounted for approximately 3.0 billion tonnes per annum (tpa) of CO_2—around 10% of global emissions up to 2010 (Baccini *et al.*, 2012; Harris *et al.*, 2012), largely in tropical forests. Against this background of a net transfer of carbon from forests to the atmosphere, future scenarios have been calculated of reversing these trends and using extensive re/afforestation[15] as a means of removing large amounts of CO_2 from the atmosphere. Indeed, the IPCC Fifth Assessment reported potential carbon sequestration rates of up to 1.5, 9.5 and 14 $GtCO_2$/year (0.4, 2.6 and 3.8 GtC respectively) in 2030 for global afforestation and reforestation activities, under different mitigation scenarios (IPCC, 2014b). One assessment (see, for example, Nillson and Schopfhauser, 1995) taking into account economic, technical and political factors, suggests a maximum annual rate of carbon fixation of 1.48 GtC/year achieved 60 years after the expansion in afforestation and requiring 348 million hectares.

Such figures comprise theoretical potentials and estimating the scale achievable in practice and the associated climate impacts must take account of several factors:

- Land required: for instance, Smith *et al.* (2016) estimate that removing 1.1–3.3 $GtCO_2$/year through afforestation would require at 320 million to 970 million hectares of land.

- Nutrient requirements would be substantial (the same study estimates 0.1–1.0 Mt/year of nitrogen, and 0.22–0.99 Mt/year of phosphorus).

- Effects of forestry on climate are wider than just the carbon balance: through albedo changes, GHGs other than CO_2, and emissions of volatile organics and microbes, which in turn can form aerosols and increase cloud formation, affecting the hydrological cycle (Ellison *et al.*, 2017). Depending on latitude, forest structure and management, such biophysical effects may add to or negate the climate effects arising from capturing carbon.

- Use of nitrogen fertilisers increases emissions of nitrous oxide with its high global warming potential (300 times greater than CO_2). Consequently, reduced climate forcing by removing CO_2 can be offset or even reversed by increased nitrous oxide emissions. Calculations suggest the effects are significant and could range from reducing the beneficial effects of reforestation by 75% or even making matters worse, so that the negative impacts of the nitrous oxide would exceed the beneficial effects of CO_2 reduction by 310% (Robertson *et al.*, 2000; Brown *et al.*, 2004; Li *et al.*, 2005).

- Net carbon uptake from the atmosphere does not follow immediately after replanting, and disturbances due to planting may release soil carbon which may take several years or even decades for the growing trees to offset. Maximum uptake will be in the middle growth period (20–60 years depending on species, location and local conditions) after which the rate of absorption starts to slow, although the amount of captured carbon (carbon stocks) continues to rise (EASAC, 2017).

- Captured carbon may be vulnerable to changes in local political priorities (felling/usage or use of forest biomass for energy), as well as illegal logging which is a major contributor to current rates of deforestation. In addition, stocks may be vulnerable to widespread forest disease or fires (potentially exacerbated by climate change) when carbon stocks would be released again to the atmosphere.

- Models do not take full account of the loss of nutrients in soils after deforestation and the state of degraded lands which may be difficult to re-establish as healthy and growing forests.

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[15] Reforestation refers to the restoration of forest on recently deforested land, and afforestation establishing forest on land that has been deforested for 50 years or more.

Annex 2 Land management

A critical depository of carbon is in soils. Many cultivated soils have lost 50–70% of their original SOC (IPCC, 2000), so it should be possible to manage agricultural lands to partly reverse the loss of carbon (Lal, 2007). SOC can be increased by growing cover crops, leaving crop residues to decay in the field, applying manure or compost, using low- or no-till systems, and employing other land management techniques to increase SOC and stabilise soil structure. The mitigation potential of such approaches has been estimated at from 0.07 to 0.7 tCO_2eq/year per hectare, and the greatest potential in warm and moist climates (Smith *et al.*, 2007). Such efforts could be sustained for decades before soil carbon content approached a steady state. However, such measures need to be continuously applied since they are easily reversed if farming returns to more intensive methods.

This approach is the objective of the '4 per mille' initiative, which followed the COP21 meeting in Paris in December 2015. This pointed out that global soils are estimated to contain 1500 GtC to a depth of 1 metre and 2400 Gt to 2 metres. By increasing carbon content by 0.4% per annum, sufficient carbon would be sequestrated to stop the current 2–3 ppm increase each year in the atmospheric concentration of CO_2. Methods advocated include no-till agriculture, more intermediate crops, row intercropping and grass strips, restoring hedges between fields and agroforestry, adjusting grazing periods in pasture, and restoration of degraded lands. This international initiative has the twin aims of contributing to food security and climate change mitigation and has attracted 35 countries' support to date (http://4p1000.org) including 17 EU Member States.

Recently, Minasny *et al.* (2017) surveyed SOC stock estimates and sequestration potentials from 20 regions in the world and found that under best management practices, 4 per mille or even higher sequestration rates can be accomplished. High carbon sequestration rates (up to 1% increase in SOC per year) can be achieved for soils with low initial SOC stock for the first 20 years after implementation of best management practices, while the carbon sequestration rate on grasslands with high initial SOC stocks may be limited to the 0.4% of '4 per mille'. Areas that have reached equilibrium will not be able to further increase their sequestration. They also found that if '4 per mille' is applied in the top 1 metre of global agricultural soils, SOC sequestration potential is between 2 and 3 GtC/year, which is equivalent to around 20–30% of global GHG emissions. In addition, SOC influences soil quality so that sustainable soil management practices aimed at preventing loss and restoring SOC also contribute to food security[16] and have the economic benefits of avoiding the costs of intensive management. However, questions remain whether such potential could be achieved, with other studies suggesting much more limited capability at the global scale of absorbing atmospheric carbon in soils (Powlson *et al.*, 2014).

A further soil modification option is to add 'biochar' to the soil. This is a plant by-product similar to charcoal that can be made from lumber waste, agricultural crop residues, etc. Heating vegetation slowly without oxygen (pyrolysis) produces carbon-rich biochar that can be placed in the soil as fertiliser, so that the biochar can be a net carbon sink if buried, increasing crop yields and adding fertility back to the soil. Woolf *et al.* (2010) point to biochar's potential to improve agricultural productivity (particularly in low-fertility and degraded soils) through reducing nutrient loss and through its water-holding capacity, and calculated a maximum potential to remove up to 1.8 Gt CO_2 /year (0.5 GtC) if applied to all global biomass resources that can be harvested sustainably. Other studies suggest similar potential (for example, Smith (2016) refers to 0.7 GtC/year), while negative effects on soil fertility are possible in some cases where the biochar properties are not well matched to the soil and nitrogen may be immobilised (see Bruckman *et al.* (2016) for a recent review).

The goal is to permanently lock carbon underground instead of letting CO_2 re-enter the atmosphere, so such long-term sequestration requires high biochar stability, which will depend on the type of feedstock and process. Wood is more stable than grasses and manure. Furthermore, changing the carbon content may darken the soil and increase heat absorption from solar radiation. Using biomass for biochar production clearly competes with use for bioenergy or BECCS; which of these is more effective in contributing to climate change mitigation is very dependent on the degree to which biochar enhances crop yields and has favourable impacts on net soil GHG emissions. For such reasons, the net effects may be location-specific and related to the agricultural benefits. A recent review by Psarras *et al.* (2017) does not include biochar as a feasible NET.

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[16] See EASAC's recent report on Food and Nutrition Security (EASAC, 2017a).

Coastal ecosystems such as salt marshes and mangroves have historically stored large amounts of carbon which have been lost through their removal. Habitat restoration will thus contribute to removal of CO_2 from the atmosphere, while also contributing to biodiversity recovery.

The US National Research Council (2015) note that 1800 $GtCO_2$ (490 GtC) remain sequestered in tropical forests which is still around three times the quantity released since 1750 in all land use changes (660 $GtCO_2$, 180 GtC), and similar to the amounts released from fossil fuels since the start of the Industrial Revolution (Allen *et al.*, 2009). The critical component of any climate forest-based mitigation strategy thus remains prevention of additional tropical deforestation, which can also deliver economic benefits rather than costs (Sathaye *et al.*, 2001).

Annex 3 Bioenergy with carbon capture and storage (BECCS)

Concept

BECCS is one of the most discussed NETs. BECCS has been seen (for example, Azar *et al.*, 2010) as a backstop technology to remove CO_2 from the atmosphere in case the world faced an emergency from the climate system (e.g. dangerous carbon cycle feedbacks) and BECCS has subsequently been included in many integrated assessment models to compensate for overshooting safe levels of atmospheric CO_2. In addition, it is currently the only NET explicitly included in IPCC scenarios[17]. The BECCS concept is fairly straightforward. Biomass captures CO_2 during growth and stores it in the form of organic material, such as trunks, stalks, roots, etc. The biomass is subsequently burned in a power plant (or converted in another energy conversion plant), producing electricity (or another energy carrier). The CO_2 that is produced during biomass combustion is captured and stored underground, thereby effectively removing it from the atmosphere. As indicated, the use of biomass for BECCS is not limited to the power sector, but can also be integrated in other sectors, such as hydrogen, biofuel, or biogas production. The technology is currently being demonstrated (albeit on a small scale) at several locations around the world.[18]

Considerable research has been undertaken on optimising biomass use to substitute fossil fuels (see, for example, Steubing *et al.*, 2012; Bui *et al.*, 2017; Cebrucean *et al.*, 2017; De Jong *et al.*, 2017), on the potential of BECCS to deliver negative emissions, and under which circumstances this is the case (see, for example, Schakel *et al.*, 2014; Fajardy and Mac Dowell, 2017). Although these studies confirm the potential of BECCS to remove CO_2 from the atmosphere, they have so far been unable to provide an unequivocal answer on the amount of CDR, and on the overall sustainability of the BECCS value chain. The current research rather suggests this should be evaluated on a case-by-case basis.

The use of biomass as a fuel is not new. It has long been used in industrial applications, as well as for cooking and heating. Currently, it is used at a municipal scale in the form of biomass-fuelled combined heat and power and/or for biogas production (see, for example, Aalborg energie technik, 2017a, b), and at large scale in biomass-fired power plants (e.g. Drax Power Station, UK[19]). Given the necessity to remove gigatonnes of carbon from the atmosphere, the power and heat sector is deemed the first to target for BECCS applications.

Figure A3.1 shows three cases of biomass use for power and heat generation, indicating the corresponding impact on net CO_2 emissions. In sub-figure (a), biomass is harvested and subsequently fired in a power plant. When the supply of biomass is associated with low CO_2 emissions, the CO_2 emissions coming from the overall value chain have been seen as approximately neutral, since the CO_2 released by combustion can be reabsorbed as the vegetation regrows. This type of biomass application has been applied for hundreds of years for power and heat generation. To reach negative emissions, biomass firing has to be coupled with capture and storage of CO_2 (sub-figure (c)); sub-figure (b) shows a third alternative, where biomass is co-fired in existing coal-fired power plants, coupled with CCS. This has the benefit that major changes to the existing power plant are unnecessary if the biomass content is limited (Tumuluru *et al.*, 2012; Schakel *et al.*, 2014; Bui *et al.*, 2017). The overall chain emissions can nevertheless still be negative[20]. This option could be particularly useful as a transition technology.

Technical status

From a technology perspective, practical experience, modelling studies and laboratory experiments, show that (co)-firing of biomass is possible with (small modifications to) existing mills and burners (Tamura *et al.*, 2014). Biomass volatisation and combustion is, however, different from coal combustion, leading to different burnout characteristics and heat distribution in the boiler. Therefore, the placement of burners and heat exchangers in the boiler may have to be adapted, on the basis of the type and ratio of fired biomass (Tamura *et al.*, 2014). The lower heating value and different combustion characteristics of biomass also lead to lower boiler exit temperatures, and thus lower efficiency.

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[17] In the IPCC AR5 report (IPCC, 2014), 101 of the 116 RCP 2.6 scenarios rely on BECCS to reach the 450 ppm CO_2 level.

[18] Milne and Field (2012) cite 16 projects worldwide at various stages of completion based on existing sources of bioenergy (pulp and paper, ethanol and others).

[19] Drax company generates 7% of the UK's electricity, of which 70% comes from wood pellets (https://www.drax.com/about-us/).

[20] For instance, in an evaluation by Schakel *et al.* (2014), co-firing of 30% wood or straw pellets in a super-critical pulverized coal or IGCC (integrated gasification combined cycle) power plant was coupled with benchmark absorption-based CCS technology capturing 90% of the emitted CO_2. The analysis included the complete BECCS value chain, from cultivation, harvesting, and pre-processing, to transport and conversion of wood and straw for power generation in conjunction with CCS. The estimated CO_2 reduction versus the coal power reference cases (without co-firing and CCS) was of the order of 108%, effectively removing carbon from the atmosphere.

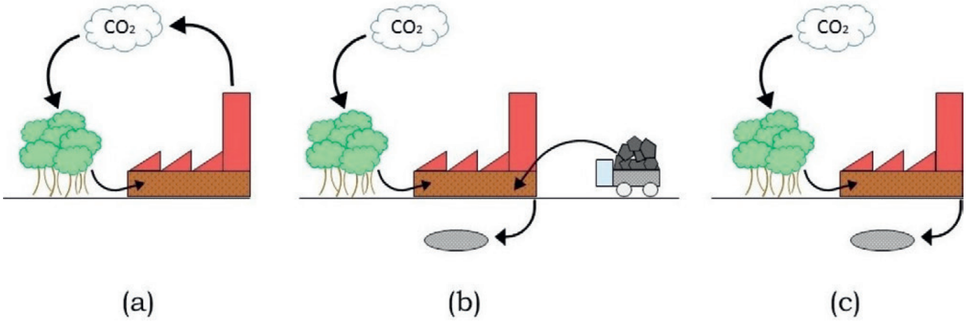

Figure A3.1 Integration of biomass in heat and power generation sector: (a) 100% biomass firing in a power plant for power and heat generation with close to neutral net emissions; (b) Co-firing biomass and coal for power generation coupled with CCS; negative emissions are achieved depending on the biomass content; (c) 100% biomass firing combined with CCS.

Power plant tests have shown that the different combustion characteristics and lower temperatures reduce NO_x formation (Bhuiyan *et al.*, 2016). Other tests also suggest that the amount of SO_x emissions reduces with increasing biomass content (Bhuiyan *et al.*, 2016; Bui *et al.*, 2017). This means that existing environmental controls suffice to maintain emission limits. Ash and particulate levels, on the other hand, may increase, depending on the ash levels in the biomass used. Grass-like biomass typically contains more ash than woody biomass, and therefore produces the highest amounts of (fly) ash in the power plant (Bhuiyan *et al.*, 2016), requiring more severe filtration downstream of the boiler. Further engineering issues related to biomass ash include alkali-induced slagging, agglomeration and corrosion. Solutions for these issues are sought in the application of additives such as minerals or metals, co-firing of the biomass with coal or leaching out chlorine and alkali species before using the biomass (Niu *et al.*, 2016). Measures against corrosion are also sought in the use of more resistant, and thus expensive, alloys.

Apart from as a solid, biomass can also be used in fluid form, for example combusting biogas. The challenge of (co)-firing biogas in a gas turbine is mainly in maintaining flame stability, because it has a high inert CO_2 content. Solutions with sequential firing seem a promising means to tackle this issue. The high amount of inert CO_2 also leads to lower flame temperatures, and hence to lower turbine efficiencies. Audus and Freund (2005) examined the efficiency of biomass-fired integrated gasification combined cycle technology combined with CCS but found it more expensive than a coal IGCC (integrated gasification combined cycle) with CO_2 capture; however, Uddin and Barreto (2007) calculated that when used in co-generation (or combined heat and power (CHP)) systems, biomass was very energy- and emission-efficient and cost-competitive compared with other conversion systems.

Finally, pretreatment technologies are key to cost, and climate-effective biomass supply chains (Batidzirai *et al.*, 2013; Hoefnagels *et al.*, 2014; Lamers *et al.*, 2015). Current biomass supply from, for example, North America to Europe includes chipping, drying and pelletisation of wood, enabling co-firing, and increasing the energy content (Hoefnagels *et al.*, 2014; Lamers *et al.*, 2015). When the industry matures and volumes become larger, torrefaction (see, for example, Bates and Ghoniem 2012; 2013; 2014) has the potential to further reduce both costs and CO_2 footprint of biomass supply chains (Batidzirai *et al.*, 2013; 2016). Torrefaction (a thermal process to convert biomass into a coal-like material) will also help to mobilise international trade of agricultural residues and energy crops. Further down the road are technologies to pretreat wet biomass streams, also unlocking these as energy sources. An example is hydrothermal carbonisation, which turns wet biomass streams into a solid, coal-like, material (Batidzirai *et al.*, 2016).

Resource demands

Given the need to remove several gigatonnes of CO_2 from the atmosphere using BECCS[21], very large amounts of biomass would be required (Table A3.1). In their 2015 review of NETs, the National Academy of Sciences (National Research Council, 2015) assessed the land, water and nutrient requirements of dedicated energy crops. They estimated that producing 100 EJ/year (EJ, exajoule: 10^{18} joules) (approximately 20% of global energy production) could require up to 5% of the current land surface (excluding Greenland and Antarctica) – 500 million hectares[22] – on the assumption that approximately 10 tons of dry biomass are produced per hectare annually. They noted that,

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[21] 12 $GtCO_2$/year (Smith *et al.*, 2016); 3–10 GtC2/year (IPCC expert report, 2015); 15–18 $GtCO_2$/year (The Royal Institute of International Affairs, 2017).

[22] 500 million hectares: 1.5 times the size of India.

Table A3.1 Key figures for the application of BECCS in the heat and power sector when delivering 3.3 GtCeq/year of negative emissions in 2100 (Smith et al., 2016)

Type of biomass	Energy production (EJ/year in 2100)	Land area required (million hectares in 2100)	Water required (km^3/year in 2100)
Purpose-grown crops	170	330–1320	720**
Agricultural residues	170	1980*	—***
Forest residues	170	3300–5610*	—***

*Note that the land requirement for residues is shared with the production of agricultural crops and timber.
**Water use (km^3/year in 2100): (1) from crop production 280; (2) for CCS including cooling water: 450.
***The water use for agricultural and forest residues was not provided in the study.

with global food demands projected to nearly double over the next 50 years with a growing global population (Foley *et al.*, 2011; Tilman *et al.*, 2011), energy crops will, in the absence of dramatic yield increases and reduction in land devoted to livestock, be in direct competition with food crops for arable land, and require conversion of the remaining areas of natural habitats with associated extensive biodiversity loss.

To be environmentally and socially acceptable, it is essential that biomass is sourced sustainably and with a minimum of so-called CO_2 leakage in the value chain. In the latter respect, an analysis by Smith and Torn (2013) of a BECCS system based on switchgrass indicated that for every 1 tonne of carbon sequestered, leakage of emissions in the supply chain would be 1.11 tonnes,[23] while further releases of nitrous oxide could be stimulated by the large quantities of fertiliser required. As pointed out in EASAC's recent review (EASAC, 2017), and by Agostini *et al.* (2015); Fajardy and Mac Dowell (2017) and Wiltshire and Davies-Barnard (2015), critical to the calculation of net effects on CO_2 emission are the assumptions made on the land used for growing BECCS crops and their effects on direct and indirect land use change. In the Wiltshire and Davies-Barnard (2015) study, effects ranged from a potential removal of 100–120 GtC between 2020 and 2100 if bioenergy crops could be grown on abandoned land, to potential scenarios of worsening warming by adding 100 GtC to the atmosphere if forests were converted to bioenergy crops under intensive agriculture. Use of biomass in CDR thus needs to be considered on a case-by-case basis (see, for example, Van der Hilst *et al.* 2012, Brinkman *et al.*, 2017; Verstegen *et al.*, 2017).

Various sources of biomass have been examined: from agricultural and forestry residues to forest biomass and dedicated energy crops such as miscanthus, switchgrass and short rotation coppice willow. There is a trade-off between feedstock quality, land area requirements and price: purpose-grown energy crops need less land because they have a higher energy density per hectare than, for instance, forest or agricultural residues (Table A3.1; Wiltshire and Davies-Barnard, 2015; Smith *et al.*, 2016). At the same time, residues may have a lower environmental impact and may be cheaper because they are side products coming from industrial forestry and food production. Soil depletion is another critical aspect of large biomass supply. To be sustainable, the type of feedstock provided is preferably selected in correspondence with existing land conditions.

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[23] Using switchgrass, 200 million hectares of land could remove 1 GtC/year but would require 20% of current global fertilizer production, and water demand equivalent to 4% of the world's renewable water resources. Such rates of fertilisation will also release nitrous oxide. A process flow analysis showed that for every 1 tonne of carbon sequestered, 2.11 tonnes of carbon in the original feedstock needed to be grown.

Annex 4 Enhanced weathering

The natural carbon cycle includes processes that remove CO_2 from the atmosphere over various timescales through inorganic chemistry. Primary mechanisms include the following:

- CO_2 dissolves in seawater and is mineralised slowly, ultimately descending to deep ocean sediments (2000–8000 years is needed for this system to reach equilibrium). The critical factor is calcium (or magnesium) carbonate minerals entering the ocean after weathering on land where their alkalinity compensates for the initial acidification when CO_2 dissolves. Accelerating this could thus increase the rate of CO_2 absorption by the oceans.

- Weathering of silicate minerals and entry of calcium (or magnesium) silicate into the oceans can also affect marine chemistry in a similar way by reacting with CO_2 to produce (biogenic, amorphous, or dissolved) silica and (soluble) bicarbonate. This is twice as effective in removing CO_2 as calcium (or magnesium) carbonate but on a much slower timescale (typically hundreds of thousands of years). CO_2 can also react directly with calcium (or magnesium) silicate to produce a solid calcium (or magnesium) carbonate, a key reaction of the long-term carbon cycle (Berner, 2004).

These processes involve mineral carbonation and accelerating such natural processes offers a potential means of increasing the removal rate of CO_2 from the atmosphere at a large scale. Indeed, mineral carbonation in economically viable industrial processes was first proposed in 1990, as offering a means of trapping CO_2 into carbonates which are stable for thousands of years (Zevenhoven and Romão, 2017). The potential for CO_2 sequestration via minerals is huge as the amounts of suitable and readily available mineral silicates (suitable minerals include feldspar, serpentine, pyroxene and olivine) far exceed requirements for sequestering all conceivable anthropogenic CO_2 emissions (Lackner *et al.*, 1995; Lackner, 2003). The minerals react with CO_2 to form a carbonate through simple chemical reactions, but recreating the natural weathering on an industrial scale is challenging owing to the slow kinetics, although in aqueous solutions microbial reactions could significantly accelerate the process (Bennett *et al.*, 2001; Yao *et al.*, 2013). Nevertheless, much research has allowed a range of alternatives to be characterised, often with the benefit that a separate CO_2 capture step can be avoided while producing solid materials with commercial value.

Although the permanence of the mineralisation process is attractive, it would require large amounts of material. The inherent difference in atomic masses means that the weight of silicate mineral required will be between 1.3 and 3.6 times that of the CO_2 removed, although olivine may offer ratios approaching 1 (National Research Council, 2015). Deploying such methods to remove the gigatonnes of CO_2 required in negative emissions scenarios would thus involve mining many gigatonnes of rock. If these were used in industrial removal processes, in some cases very large quantities of water would be required to provide the dilute solutions in which the enhanced weathering reactions take place. Equally, the very large quantities of carbonate and other solids produced would also need to be transported and disposed of. Other *ex situ* routes for CO_2 mineralisation are being considered. Since reaction kinetics can be significantly speeded up if the material is ground to small grain sizes, one approach would be for grinding (see, for example, Schuiling, 2012; Hartmann *et al.*, 2013) before spreading magnesium silicate powders over large areas of agricultural land or perhaps desert. This is estimated to require 1–5 kg/m^2 of silicate rock to be applied each year to 15–45% of the Earth's land area (Taylor *et al.*, 2016) to remove the gigatonnes of carbon necessary. In addition to the sheer scale of enhanced weathering and the need for the associated energy demand to be from zero carbon sources, there are questions over the degree to which the weathering process can be controlled once the material has been dispersed.

Alternatively, dispersal into the ocean on a large scale to increase alkalinity and speed the natural weathering reactions has been proposed—particularly to high-energy shallow marine environments, and an organisation in the Netherlands has been established to promote the use of olivine (Schuiling and Krijgsman, 2006; Schuiling and de Boer, 2011). However, these applications would again require grinding, transport and dispersal with associated energy demands and raise questions over the environmental impact of such large-scale dispersal (Köhler *et al.*, 2010, 2013). The potential of carbon removal by enhanced weathering (including adding carbonate and silicate minerals such as olivine to both oceans and soils) has been estimated to be perhaps 1 GtC/year by 2100 (Köhler *et al.*, 2010) at a cost of US\$50/tCO_2 to US\$100/tCO_2 (McLaren, 2012; Rau *et al.*, 2013).

Potential substitutes for natural carbonates or silicates can include industrial by-products such as fly ash, cement kiln dust, and iron and steelmaking slag. These have been shown to offer net savings in terms of the quantities of CO_2 removed relative to that emitted in operating the removal process (reactant transportation, chemical conversion and product treatment). For instance, cement kiln dust requires processes that emit approximately 150 tCO_2 for every

1000 tCO_2 stored. In the USA, fly ash is most abundant (130 million tons/year), followed by cement kiln dust (~18 million tons/year), steelmaking slag (~8 million to 10 million tons/year), and red mud (<5 million tons/year) (Gadikota *et al.*, 2014). Overall, Kirchofer *et al.* (2013) found that US industrial alkaline by-products have the potential to mitigate about 7.5 MtCO_2/year: just 0.1% of US CO_2 emissions.

Although not deployed as a NET, *ex situ* mineral carbonation has been demonstrated on pilot and demonstration scales, and the technology has been proposed as a means of removing CO_2 from flue gases from small and medium emitters (<2.5 MtCO_2) while CCS (Annex 7) is focused on the larger emitters (Sanna *et al.*, 2014). However, its application is currently limited by its high costs, which range from US$50 to US$300 per tonne of CO_2 sequestered. Energy use, the slow reaction rate, material handling and the lack of a market for the large quantities of the product (calcium carbonate and magnesium carbonate) are key factors restricting this technology's application. Current costs are too high for a widespread deployment of this technology, whether for flue gas removal or extracting CO_2 from the air (Sanna *et al.*, 2014).

In situ carbonation involves injecting CO_2 into silicate rock formations underground where the gas reacts to form stable carbonates. This is being evaluated in a project in Iceland (see Box A7.2).

Annex 5 Direct air capture and carbon storage (DACCS)

Approximately half of current anthropogenic GHG emissions are from distributed sources such as transport and residential heating (IPCC, 2014a). Capturing these emissions at the source is often impractical. It is, however, possible to capture this CO_2 by collecting it directly from the ambient air. This is called 'direct air capture' (DAC). The possibility to capture the CO_2 in principle anywhere holds the promise of flexibility. It may, for instance, be captured close to CO_2 storage sites, thereby minimising transport costs (even capture on offshore platforms is conceivable). On the other hand, DACCS needs a carbon-neutral energy and/or heat source to operate, which may limit the choice of a suitable location to those where such a source is available.

DAC (Figure A5.1) is similar conceptually to the first capture stage of CCS (Annex 7) and uses a solid or liquid sorbent to bind the CO_2. There are, however, some important differences due to the low concentration of CO_2 in air versus the concentration in flue gas. After binding the CO_2, the sorbent is regenerated releasing high purity CO_2 that can be safely stored (Sanz-Perez *et al.*, 2016).

Important DACCS processes include the following.

Absorption using a strong base solution, typically sodium hydroxide (NaOH). This sorbent is different from the amine solutions that are commonly used for CO_2 capture from point sources, which are too expensive considering the large air volumes that have to be processed in DACCS. The resulting sodium carbonate (Na_2CO_3) solution has to be treated to recover the NaOH, which can be done with the Kraft process whereby lime is used to causticise the Na_2CO_3 back to NaOH, producing $CaCO_3$. The limestone is then treated at high temperatures to release the CO_2 (calcination) and regain the original lime.

The need for high temperature heat is clearly a drawback of this process. For the process to be sustainable, waste heat or heat from renewable sources would be necessary. The process also requires heat integration between solid particulate streams, which may require advanced engineering solutions. Operating issues include water loss, scaling and corrosion. Currently, improved contactor designs and NaOH regeneration strategies are being considered, since the price for the contactor and the energy requirement for the calcination contribute heavily to the overall cost of the process (Sanz-Perez *et al.*, 2016).

Adsorption using a solid sorbent. Typically, chemically based sorbents such as immobilised amines on porous support structures are used. In contrast to the physical sorbents commonly used for capture from point sources, they feature a high selectivity for CO_2 even in the presence of water vapour. Research on sorbent materials such as ion-exchange resins, solids with multiple amine sites to adsorb CO_2, and metal-organic frameworks is ongoing. Sorbent regeneration is commonly done through an increase in temperature and/or a decrease in pressure. Additionally, some anion-exchange resins have been developed that absorb CO_2 when dry and release it when moist; a so-called humidity-swing. The latter has the potential to reduce the energy requirements of regeneration. (Lackner *et al.*, 2012; Sanz-Perez *et al.*, 2016). Overall, the possibility of using low-grade waste heat for sorbent regeneration (~100 °C) makes adsorption processes a promising alternative to absorption processes. In addition, the much simpler process configuration may favour adsorption over the absorption process.

Other concepts. Besides absorption and adsorption, Eisaman *et al.* (2012) proposed the possibility of extracting CO_2 from seawater using **membranes**, which then reabsorbs CO_2 from the atmosphere. Additionally, Agee and Orton (2016) studied the possibility of removing CO_2 from air by dry ice deposition using a laboratory prototype, **cooling** the air to the point where CO_2 solidifies and can be separated.

Given that the concentration of CO_2 in the atmosphere is relatively low (about 400 ppm, equal to 0.04%), the minimum theoretical work to separate the CO_2 is significantly higher than for capture from point sources

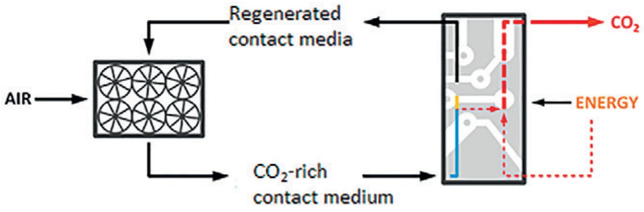

Figure A5.1 Basic principles of DAC.

(~20 kilojoules per mole (kJ/mol) CO_2 for DAC compared with 8.4 kJ/mol for aqueous amine-based flue gas capture) (Sanz-Perez *et al.*, 2016). This comparison of the theoretical minimum work suggests that the *real* energy requirement for DAC will also exceed the energy requirement for CO_2 capture from point sources. In addition to the high energy requirement, the low CO_2 concentration also increases the size of the treated gas stream, which can be a factor of 100–300 larger than post-combustion capture options. Very large contactors are required, which leads to issues such as land availability, public acceptance and construction material availability. Long-term geological storage of the captured CO_2 raises the same challenges for DACCS as for normal CCS (see Annex 7).

Absorption processes using aqueous solutions can involve substantial evaporative losses, possibly making water supply an issue in some areas (Smith *et al.*, 2016). This is, however, not a limitation if solid sorbents are used. Adverse effects on nearby vegetation from the reduction of CO_2 levels in the atmosphere are also conceivable, but likely to be local, and highly uncertain. Because of the need for large equipment and the high energy demand, the cost of capturing CO_2 from ambient air is inevitably substantially more expensive than from more concentrated point sources. APS (2011) calculated the cost of a DACCS system to be of the order of US$600 or more per tonne of CO_2. Lackner *et al.* (2012) cite estimates from US$30 to US$1,000 per tonne CO_2. In the work of Mazzotti *et al.* (2013), capture and regeneration costs are estimated to be between US$400 and US$600 per tonne CO_2 captured. Solid sorbent systems have been estimated at US$200 t/$CO_2$, with prospects of reducing this to US$30 t/$CO_2$. Sanz-Perez *et al.* (2016) conducted an extensive review of DAC technology where costs ranged from US$200 to US$1000/tCO_2 compared with US$30–100/t$CO_2$ for CO_2 capture from flue gas.

In addition to academic research and development, several commercial parties are developing and/or commercialising different variations of DAC (Table A5.1 and Figure A5.2). At the current stage of development, commercial operation is focusing on CO_2 utilisation instead of storage. Even though this does not lead to negative emissions, it is an important driving force for the development of DAC technology. The possibility of generating the CO_2 directly where it is used makes DAC particularly suitable for utilisation applications.

Figure A5.2 Climeworks DAC Facility in operation in Switzerland (source: www.climeworks.com).

Table A5.1 Status of some DAC technology providers

Company	Technology	Status	Notes
Carbon Engineering	Liquid alkali solution	1 tCO_2/day demonstration plant	Pilot demonstration of captured CO_2 to fuels planned by 2018
Infinitree	Ion-exchange resin	Research and concept	CO_2 enrichment for plant cultivation in greenhouses, humidity-swing
Climeworks	Solid sorbent	Commercial operation at 990 tCO_2/year	Regeneration at 100 °C, waste heat used for regeneration, modular approach
Global Thermostat	Ceramic-attached amine	Pilot and commercial demonstration	Regeneration at 85–100 °C using waste steam, modular approach

Recent energy–economy–climate analyses from Chen and Tavoni (2013) and Marcucci *et al.* (2017) assessed the role of DAC in limiting global warming to well below 2 °C. They found that large-scale deployment of DACCS in the second half of the 21st century (scenarios of up to 38.3 GtCO_2 (10.4 GtC) captured in 2100) may be promising to contribute to the 1.5 °C target. DACCS becomes more important and economic the later strong emission reductions take place, because then more CO_2 is present in the atmosphere.

Annex 6 Ocean fertilisation

The oceans currently provide one of the largest natural sinks for CO_2, via the so-called 'solubility pump' (since CO_2 is slightly soluble in seawater), and the 'biological pump' (since microscopic plants take up CO_2 to make organic matter constituting the base of the ocean food web). Both of these sinks could potentially be enhanced. The possibility of encouraging uptake through dissolution and mineralisation was included in Annex 4; this annex considers enhancing the sink as a result of biological activity.

The rate of phytoplankton production is limited in many parts of the oceans by nutrient availability, and enhancing this has long been seen as a potential route for increasing the rate of CO_2 uptake. The biological pump could therefore be enhanced by ocean fertilisation, i.e. by providing additional essential nutrients where these are in short supply, to allow greater production of the biological material which is food for other organisms. Much of the carbon so fixed will be released again through grazing by other marine organisms and respiration, but a small proportion of the particulate matter will ultimately settle into the deep ocean where it may be retained for centuries as remineralised dissolved organic carbon, or sequestered in sediments as particulate material. This natural process is reasonably well understood although measurements of the fluxes of organic material are difficult to make and sparsely sampled.

Ocean fertilisation using macro-nutrients such as nitrogen and phosphorus is feasible, but unlikely to be practicable owing to the high cost of the large quantities required (the amount of nitrogen in the fertiliser required would be 10–20% of the extra carbon to be removed). With limiting micro-nutrients such as iron, however, the amount of carbon fixed can be substantially higher than the micronutrient quantity involved. For instance, in those areas where iron is a limiting nutrient, supplying this will promote the consumption of 1000–100,000 times the amount of carbon. OIF has thus been explored as a means of ensuring that waters with surplus nitrogen and phosphorus present may increase their primary productivity and ultimately increase the transfer of organic carbon to the deep ocean (Wallace *et al.*, 2010). In some areas (e.g. large areas of the southern oceans) there appear to be adequate macro-nutrients but phytoplankton growth is limited by low concentrations of iron. Other iron-limited regions include the subpolar North Pacific and eastern Equatorial Pacific. Field experiments undertaken to understand the biological system (see, for example, Boyd *et al.*, 2007) have shown that adding iron can induce a rapid growth in phytoplankton, causing blooms over considerable areas. However, to be effective in removing carbon, a significant fraction of the material needs to sink and reach the deep ocean, and it has proved to be difficult to make the measurements necessary to demonstrate and quantify this.

Once the plankton growth has been stimulated by the addition of iron, much of the additional organic matter will be remineralised and returned to CO_2, nutrients and dissolved iron by the metabolism of bacteria and zooplankton in the upper few hundred metres of the water column. Thus much of the CO_2 taken up initially is likely to be returned to the atmosphere on relatively short timescales (Robinson *et al.*, 2014). Recapturing such released CO_2 may require additional iron, so the fate of the original iron is important: whether it remains in a soluble form and available for subsequent growth or is immobilised as particulate material and removed to the sediment. Iron is scarce because it is normally rapidly scavenged in the ocean, so iron fertilisation may need to be continued indefinitely to support continuation of enhanced planktonic growth.

Uncertainties over this continue but the National Research Council (2015) estimate that there is a potential upper limit for a sustained ocean iron fertilisation CO_2 sink of 1.0–3.7 $GtCO_2$/year (0.3–1 GtC/year) and that the total ocean sequestration capacity until the end of the century is 85–315 $GtCO_2$, assuming continuous iron fertilisation of the entire iron-limited Southern Ocean, Equatorial Pacific and subpolar North Pacific. If the iron is fully used in increased plankton growth, cost estimates can be quite low (<US\$10/tCO_2; ~US\$35/tC). However, if the rate of remineralisation through respiration is significant, Harrison (2013) estimated that the biological efficiency of the process becomes much lower and the costs higher at approximately US\$450/tCO_2 (US\$1650/tC).

The types of plankton stimulated by OIF cannot be controlled and will depend on other factors (such as the availability of silicon necessary for some species). Iron addition may stimulate the growth of diatom species, some of which are associated with toxic algal blooms. Ecological impacts on the marine food web and fisheries, and downstream effects on nutrient supply, productivity and food web dynamics are also difficult to predict. Disruption of the natural ocean ecosystem and food web on such a large scale can also be expected to bring with it some unpredictable risks (Williamson *et al.*, 2012). Ocean fertilisation (whether by iron or other nutrients) involves a major modification of the plankton community and its composition (the carbon sequestration is a small side effect), which is likely to affect higher trophic levels, including fish, seabirds and marine mammals. Also, some iron fertilisation experiments have demonstrated that toxin-producing algae may be stimulated (‘harmful algal blooms’; Moore *et al.*, 2008). Effects on ocean biogeochemistry may also influence the production and fluxes of trace gases such as dimethylsulfide, and methane and nitrous oxide (Barker *et al.*, 2007), which are GHGs that could reduce the benefits derived from increased uptake of CO_2. These issues require considerable further research and field trials to be clarified, before OIF could be regarded as a potential contributor to achieving negative emissions.

Annex 7 Carbon capture and storage (CCS)

Current status

Visions of a low carbon energy future have long seen CCS as an essential component given the current high level of dependency on fossil carbon fuels, and the inertia resulting from the long lifetime of fossil fuel infrastructure. Indeed, the more demanding climate goals under the Paris Agreement make it even less likely that renewables and energy efficiency alone could achieve the necessary reduction in emissions without at the same time containing emissions from the embedded fossil fuel base in the power and EII sectors. The scale of the problem can be understood by the fact that

- currently two-thirds of global electricity production remains from fossil fuels;
- in addition to existing stock, many coal-fired power stations are either under construction or planned around the world, and some countries (e.g. Australia and USA) are seeking to expand their coal production;
- around one-quarter of global emissions come from industry where fossil fuels are an essential input to the production process in many sectors (including iron and steel, cement and chemical production);
- there is the challenge of meeting future demands for heat in northern countries where winter demand for heat is currently met by gas, oil or coal, although increasingly through the use of heat pumps and biomass fuels.

CCS was duly recognised as an essential component of emission reductions in an IPCC Special Report (IPCC, 2005). Since then the presumption that CCS will be deployed on a large-scale is included in future scenarios that allow the objectives of avoiding dangerous climate change to be met. The latest IPCC assessment report (IPCC, 2014b) analyses suggest that limiting atmospheric concentrations to around 450 ppm CO_2eq by 2100 is either not possible or would be much more expensive without deploying CCS. Placing a figure on the amounts of CO_2 that CCS is expected to remove, IEA (2016) calculate that a least-cost pathway to achieving a scenario in which average warming is restricted to 2 °C above pre-industrial levels would require the capture and storage of almost 4000 million tonnes (4 Gt) of CO_2 per annum by 2040. The critically important role of CCS in any strategy to limit temperature rises to 2 °C (and even more so for 1.5 °C) has been more recently emphasised by Ekins *et al.* (2017).

Such considerations have led the EU to include CCS in its low carbon strategy since the early 2000s. Early EU projections for CCS deployment (EC, 2009) contained estimates that (provided CCS obtained private, national and community support and proved to be an environmentally safe technology) 7 Mtpa (million tonnes per annum) of CO_2 could be stored annually by 2020, and up to 160 Mtpa by 2030, reducing the EU's CO_2 emissions by 15%. Without CCS, the costs of GHG reductions required could be up to 40% higher than with CCS, and projections envisaged CO_2 storage of 800–850 Mtpa by 2050 (EC, 2008).

The European strategy for CCS has been reviewed by EASAC (2013). At that time, enabling commercial use of CCS through demonstration at industrial scale was seen as one of the key technology challenges over the next 10 years required to meet the EU's climate change mitigation targets. There were six demonstration plants planned to be operational by 2015, and technology roadmaps had identified steps needed to develop and deploy CCS technologies that would be cost-competitive at a carbon price anticipated to be €30–50 per tonne by 2020–2025. The six demonstration plants (supported initially in the European Energy Programme for Recovery) were to demonstrate integrated operation of CCS for all three main CO_2 capture technologies (post-combustion, oxy-combustion and pre-combustion), and the main storage options (onshore as well as offshore saline aquifer and depleted hydrocarbon fields) (EC, 2010). However, this and other initiatives (e.g. the New Entrants Reserve of the EU Emissions Trading Scheme to support demonstration of CCS and innovative renewables) failed to deliver the required support of Member States to attract EU funding, and progress has been much slower than anticipated. Currently only two projects are in operation in Europe, both offshore of Norway involving injection of CO_2 separated from natural gas into offshore sandstone reservoirs. Sleipner has been in operation since 1996 and injects 1 Mtpa, while Snøhvit has operated since 2008 at an injection rate of 0.7 Mtpa. Other projects within the EU have proceeded to design stage (in some cases funded by the European Energy Programme for Recovery), but none are currently being implemented. The latest CCS Institute database cites only one advanced development activity in Norway, plus two *early development* activities, both in the UK (Table A7.1).[24]

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[24] Very recently two new proposals for CCS projects in Europe have emerged. One (in Ireland) is to capture CO_2 from gas-fired power stations and store it in the nearby Kinsale gas field. A second (in Merseyside, UK) is to convert methane to hydrogen and capture the CO_2. See http://www.powerengineeringint.com/articles/2017/10/cork-forcarbon-capture-and-storage.html; https://cadentgas.com/About-us/Innovation/Projects/Liverpool-Manchester-Hydrogen-Cluster

Table A7.1 Large-scale CCS Projects under consideration in Europe (Global CCS Institute, December 2017)

Name	Country	Planned start operation	Capacity (Mtpa)	Industry	Capture type	Transport type	Storage type
Norway Full Chain CCS	Norway	2022	1.3	Various (cement, ammonia, waste incineration)	Various industrial separation	Various	Dedicated geological storage
Teesside Collective	UK	2020s	0.8	Various	Various industrial separation	Pipeline	Dedicated geological storage
Caledonia Clean Energy	UK	2024	3.0	Power generation	Post-combustion capture	Pipeline	Dedicated geological storage

Globally, the 2016–2017 Global CCS Institute inventory identifies 17 large-scale operational CCS projects with a CO_2 capture capacity nearing 35 Mtpa in operation by early 2017. Of these, however, 13 (10 of them in North America) involve use of the captured CO_2 for enhanced oil recovery, which is increasingly seen as CO_2 capture and utilisation rather than a NET (Armstrong and Styring, 2015). Moreover, only two of the 17 operational facilities operate on a flue gas from power generation (Boundary Dam in Canada and Petra Nova in the USA[25]). The presence of oxygen presents a challenge for conventional CO_2 capture using amine solvent, resulting in significant degradation at typical capture process temperatures which, besides a need for solvent make-up, gives rise to generation and release of hazardous nitrous decomposition products (see, for example, Mazari *et al.*, 2015). For CO_2 capture applied to flue gases, chilled ammonia shows better stability against degradation while membrane separation methods also offer increasing potential (see, for example, Khalilpour *et al.* 2015). CCS applied to power station emissions must therefore be seen as at the demonstration stage to develop solutions to technical problems and to reduce as far as possible the 'parasitic' energy costs (reduced overall efficiency in the conversion of coal to electricity), in contrast to the proven and more mature technology applied to oil and natural gas fields.

Projects in Australia and Canada should raise the number of large-scale operational CCS projects to 21 by the end of 2017, with a CO_2 capture capacity of approximately 40 Mtpa. However, there is little additional capacity in the pipeline and, even to 2024, anticipated capacity remains just 1% of the 4,000 Mtpa envisaged in the 2040 scenario above. The roadmap for the IEA scenario envisaged 100 plants by 2020 and 3000 by 2050 with required investments of US$5 billion to US$6 billion per year between 2010 and 2020 (IEA, 2009).

As pointed out by Reiner (2016), the difference between the earlier ambitions expressed by governments and achievements to date is stark. As shown in Figure A7.1, rather than already being through the first tranche of demonstration and into the commercial stage leading to large-scale rollout from 2025, very few plants have come online or are in the pipeline, so that there is little learning underway between different technological options (learning through diversity) or in cost reduction within a single technology (learning by replication).

Barriers to implementation

Given the critical role identified for CCS in reducing CO_2 emissions from fossil fuels and that CCS is a precondition for BECCS (and carbon storage for DACCS), the substantial delays in deploying this technology threaten the ability to meet the Paris targets. Installing the capacity required to capture and store the quantities of CO_2 envisaged comprises a huge engineering challenge, so inevitably will have the long planning times associated with other major societal infrastructure projects. If CCS is to make a significant contribution to climate change mitigation by 2030–2040 therefore, transport and storage infrastructures required to support individual carbon capture projects need to be under development now. Several companies (e.g. MHI, Fluor, Aker Solutions and Cansolv) currently offer CCS technology commercially, and therefore the lead time to develop the capture part of CCS is expected to be shorter (less than 5 years).

EASAC's 2013 analysis concluded that, '*… If CCS is to make a significant contribution in Europe to climate change mitigation, technologies, capacity and infrastructure need to be developed steadily and with greater urgency than currently prevails. CCS is not a tap that can simply be turned on, if and when suitable financial conditions emerge*

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[25] This is currently extracting approximately 1 million tonnes per annum of CO_2 and is supported by a grant of US$160 million from the US Department of Energy Clean Coal Power Initiative.

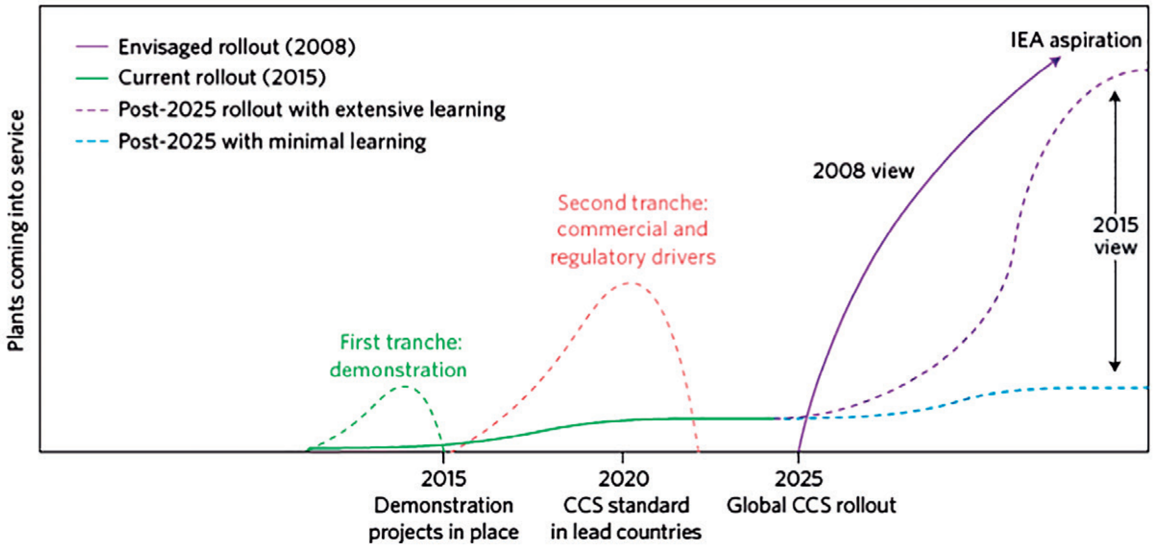

Figure A7.1 Comparison of development of CCS technology envisaged in 2008 with achievements to 2015 and implications for future rollout (Reiner, 2016).

or future policy makers decide that CCS is a crucial component of Europe's energy strategy.' This analysis also noted that allowances in the Emissions Trading Scheme would have to be around €50/t CO_2 to make carbon capture from coal-fired power plants economically attractive, well above the then market price of €8/t. These comments seem particularly pertinent today with the lack of any firm new projects and a carbon price of €5–6/t expected for 2017–2018. Critical to addressing this challenge is to recognise that each of the individual components of the CCS production chain (capture from the original source, transport of captured CO_2 and long-term storage) are distinct and require different technologies, skill sets and infrastructures. Integrating these elements into project structures and identifying the responsibility for risk at each stage has proved extremely difficult (especially for applications outside the oil/gas sector, notably the electric power sector) and, along with uncertainties over government funding, led to the withdrawal of many projects.

Several studies (see, for example, Herzog, 2011; ETI, 2014; Oxburgh, 2016; Reiner, 2016) have identified barriers that have contributed to this lack of progress. One key factor is that the carbon price has been persistently below expectations, thus weakening the business case for private investment in CCS, requiring government intervention to provide the necessary environment for private investment (this includes taking on the responsibility for post-monitoring geological storage sites after the CO_2 injection site was closed, releasing the CCS actor from this burden). Such investments are critical to delivering economies of scale and triggering cost-reducing innovation cycles through learning (Reiner, 2016).

A recent analysis of how to provide a viable business framework was conducted in the UK following a failure to follow through on previous commitments to CCS demonstrators[26]. Analysing the reasons for this failure, Oxburgh (2016) pointed to the length and complexity of the competition, priority on allocating risks away from government towards CCS developers, and requirement on projects to provide their own transport and storage infrastructure funding. This was judged to have led to over-engineering of projects, a need to fund oversized CO_2 transport infrastructure, and demanding complex and unfamiliar business partnerships which led to greatly inflated costs.

To overcome such barriers, the study advocated that government should see the necessary transport and storage facilities as essential societal infrastructure. Transport and storage infrastructure (CCS hubs) would then provide the essential services for producers of CO_2 to dispose of the CO_2 captured from individual sources (see Box A7.1). As in all large-scale engineering projects, implementation has to be phased in over an extended period and thus requires early and consistent planning. Full-chain CCS costs of about £85/MWh (€95) were estimated, so that CCS projects can compete on price with other forms of clean electricity.

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[26] The UK Government's own Committee on Climate Change had concluded that '*CCS is very important for reducing emissions across the economy and could almost halve the cost of meeting the 2050 target in the [UK's] Climate Change Act*' (CCC, 2015). The incoming Government after the 2015 election had also specifically promised to invest £1 billion in CCS demonstration in its pre-election manifesto. Despite this, the competition was cancelled in November 2015.

The above analysis is consistent with the latest analysis from the CCS Institute (2016) which also saw barriers as institutional and organisational rather than technological (see Box A7.2). Globally, CO_2 capture technologies have progressed significantly in the past decade, costs have reduced and efforts are underway on second-generation and transformational technologies to further reduce costs. The transportation of large volumes of CO_2 has been practised for decades under internationally adopted standards and codes of practice. Similarly, the storage technology is already available to select, characterise, safely operate, complete and close storage sites, with secure CO_2 geological storage demonstrated at several locations. At the same time, geological assessments suggest that storage resources to support CCS development are sufficient to meet projected capacity demands.

The main issues standing in the way of development are thus seen as

- acquiring the scale up and process development experience required to reduce costs, stimulate innovation and establish the most efficient capture technology;

- how to support or incentivise investment in CO_2 transport and storage solutions that will accommodate widespread CCS deployment.

In summary, there is no technical reason why, after a promising start in 1996 with the Sleipner facility, a larger effort should not be made on implementing CCS at scale today to provide experience in producing and handling the large amounts of materials such as solvent/sorbent for CO_2 capture, and defining energy requirements. The reason why it has not been done is that for industry it is more expensive than business as usual, and governments have yet to choose to use either regulation or financial incentives to change the situation.

Box A7.1 Infrastructure for CCS

Around the world, clustering of industries sharing common characteristics has been observed, including many clusters of EIIs. Such clusters bring together petrochemicals, chemicals, cement, plastics and other large sources of emissions currently dominated by fossil fuels. Envisaging effective CCS infrastructure for such clusters requires diverse stakeholders to work together, and for the business case for CCS to meet individual company needs, where ability to absorb additional costs is always limited by the possibility that affected companies may simply move away from the area in which CCS is applied.

A model that drives industrial CCS must thus create an attractive proposition to many stakeholders. One business plan has been developed for the Teesside industrial cluster (Pöyry, 2017) to recognise the different outlooks and success criteria of the key stakeholders, namely the following:

- EIIs need to build a sufficient case for investment; thus a business case for national or international management is needed with a reasonable rate of return and benefit in reducing carbon emissions.
- Government's industrial strategy requires measures to maintain or increase competitiveness of its industry in a carbon-constrained future.
- Government also needs to consider its role in the provision of the necessary infrastructure where value-for-money is critical.

At a national level, Norway is considering taking on the risks involved in creating a transport and storage network to accept CO_2 from Norwegian and EU countries' capture projects. This will include gas-carrying ships, subsea pipelines and a storage facility some 40 miles off the coast of Norway, in saline caverns beneath the seabed. Capital costs are estimated at €1.4 billion and the system is expected to cost €100 million a year to operate (http://www.gassnova.no/en).

Box A7.2 Current technical status

EASAC (2013) provided a detailed description of the state of the technology for capture, transport and storage up to 2012. Since then experience has been gained on all aspects.

Capture

The capture element of CCS still accounts for the largest cost in the CCS chain. In power generation, for example, 70–90% of the overall cost of a large-scale CCS project can derive from the capture and compression process. While capture technology has been successfully applied in extracting CO_2 from natural gas fields, experience of removal from power stations emissions is limited. The 110 MW (1 Mt CO_2 per year) at Boundary Dam has encountered technical problems[27] and has not delivered expected amounts of CO_2 to the related enhanced oil recovery project. In addition, possible formation of toxic chemicals (e.g. nitrosamines, nitramines and amides) through reaction of amines with oxygen in the absorber unit of a capture system continues to receive research-level attention (Mazari *et al.*, 2015; Reynolds *et al.*, 2016; Muchan *et al.*, 2017; Shreedhar *et al.*, 2017).

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[27] https://sequestration.mit.edu/tools/projects/boundary_dam.html

More cost-effective capture technologies are being developed through the following avenues:

- successful CCS demonstrations to provide design, construction and operational experience ('learning by doing' or 'learning by replication');
- research and development on a range of capture technologies (incl. solvent/sorbent development), higher efficiency power generation cycles and industrial processes ('learning by diversity');
- potential second-generation capture technologies.

Transport
Transport of CO_2 by pipelines, road, rail and ships is already standard practice in many locations; for instance, in the USA there are around 7600 kilometres of onshore CO_2 pipelines transporting roughly 68 Mtpa of CO_2 for enhanced oil recovery purposes.

Storage
There are basic technical requirements for storage sites:

1. Containment–storage sites need to be able to securely store CO_2 in subsurface reservoirs with low and manageable risks, including those associated with any potential leakage.
2. Capacity–subsurface reservoirs require the capacity to permanently store the required amounts of CO_2.
3. Injectivity–the subsurface reservoirs must be able to accept CO_2 at a rate compatible with the capture process.
4. Proximity–reasonable transport distance from capture to storage, avoiding geographically complicated or sensitive terrain and densely populated regions.

Geological storage of CO_2 has been successfully demonstrated at several pilot and large-scale sites over the past two decades in both onshore and offshore environments. Experience from four decades of CO_2 enhanced oil recovery operations (USA and Norway especially) has led to best practices and techniques established for the selection, safe operation and secure closure of CO_2 storage sites.

Regarding capacity potentially available, estimates show that geological sequestration in depleted oil and gas reservoirs, coal beds and saline aquifers has a global 'theoretical' capacity of 35,300 $GtCO_2$, an 'effective' capacity of 13,500 $GtCO_2$ and a 'practical' capacity of 3,900 $GtCO_2$ (Dooley, 2013). Benson *et al.* (2012) emphasise that environmental risks of geological sequestration appear manageable, but regulations will be required to govern site selection, operating guidelines, and the monitoring and closure of a sequestration facility. Public perception of the safety and effectiveness of geological sequestration will likely be a challenge until more projects are underway with an established safety record, especially when the storage site is onshore rather than offshore. Recent debate in Germany over the use of porous sedimentary rocks containing saltwater has focused on dangers of leakage, so that the presence of suitable impermeable strata above the reservoir, speed of carbonation into solid forms and resistance to any unexpected earthquakes become issues.

Research on *in situ* mineral carbonation has also shown that technically it is possible to mineralise the CO_2 injected into appropriate geological formations, thus removing any possibility of return to the atmosphere. Experience at an injection site in Iceland found almost complete disappearance of the injected CO_2 in less than 2 years (Snæbjörnsdóttir and Gislason, 2016). *In situ* accelerated weathering may also be able to sequester CO_2 on a large scale: Kelemen and Matter (2008) estimate that if the large deposits of peridotite could be used (in Oman), around 1 trillion tons of CO_2 could be sequestered.

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