Chapter 7

Bridging the Gap – Carbon dioxide removal

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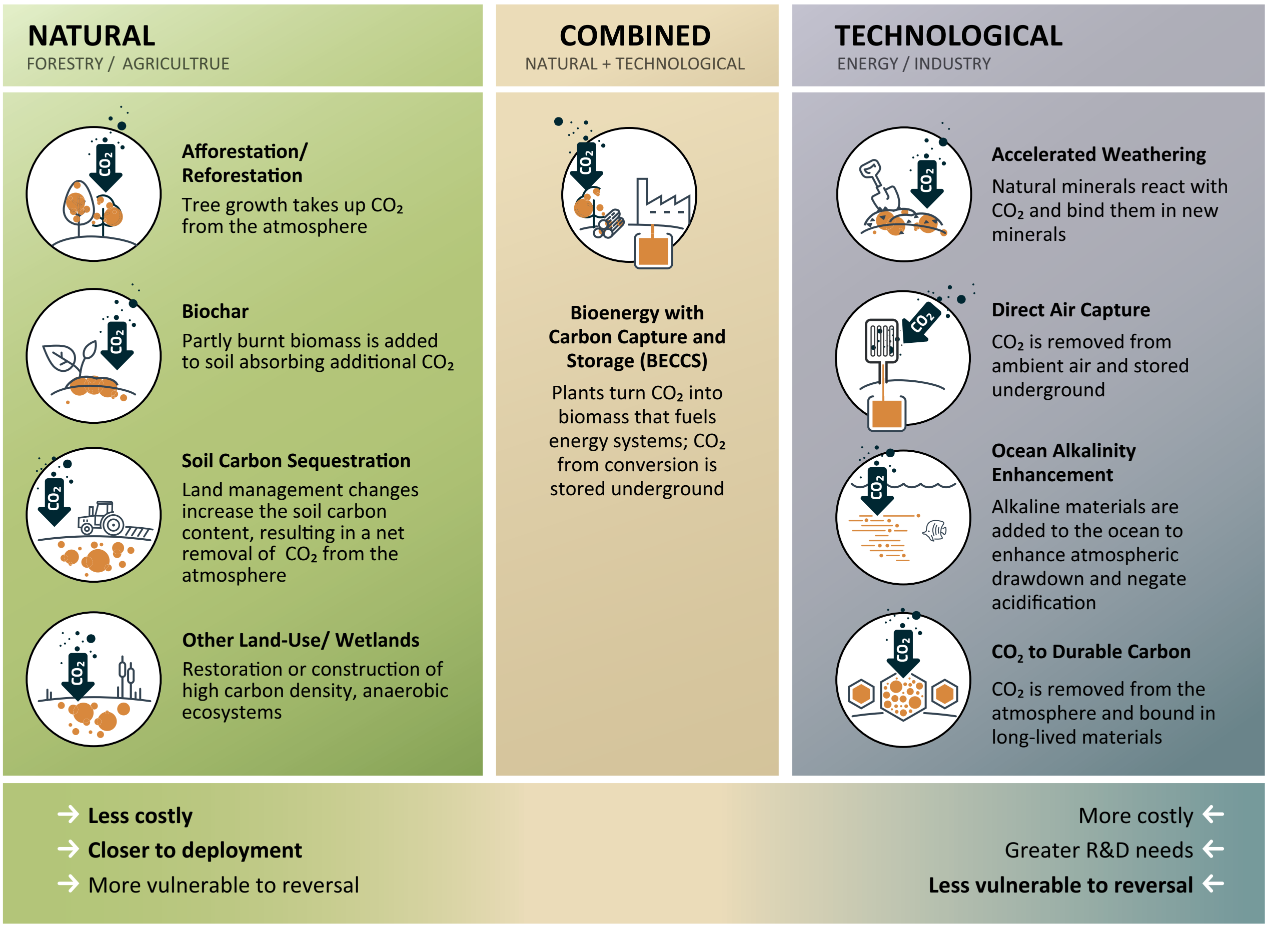
7.1 Introduction

Carbon dioxide removal (sometimes called carbon removal or CDR) refers to a cluster of technologies, practices and approaches that remove and sequester carbon dioxide from the atmosphere. Despite the common denominator of removing carbon dioxide, these technologies can be very different. To put it simply, one can distinguish between biological and engineered options. For some of the

Figure 7.1: Major strategies for negative emission technologies.



Note: This figure includes the major strategies that have been discussed in the literature so far (Minx *et al.,* 2017).

former (such as afforestation, reforestation or soil carbon management), experience has been accumulated over decades. Conversely, experience is limited with regard to the latter (notably direct air capture, or bioenergy combined with carbon dioxide capture and storage). Some approaches would be more difficult to implement than others, for example, using the ocean as a common-pool resource, which would require coordination on an international scale. The leading technologies and approaches considered here are shown in figure 7.1.

Importantly, carbon dioxide removal is not the same as solar radiation management (Royal Society, 2009). This distinction is critical and was emphasized by the United States National Academy of Sciences, which has reviewed approaches to solar radiation management (USNAS, 2015a) and to carbon dioxide removal (USNAS, 2015b). While solar radiation management may prove important for mitigating climate change in the future (Keith *et al.*, 2017), it is not the subject of this chapter. Instead, this chapter focuses on reducing carbon dioxide concentrations in the atmosphere through active management.

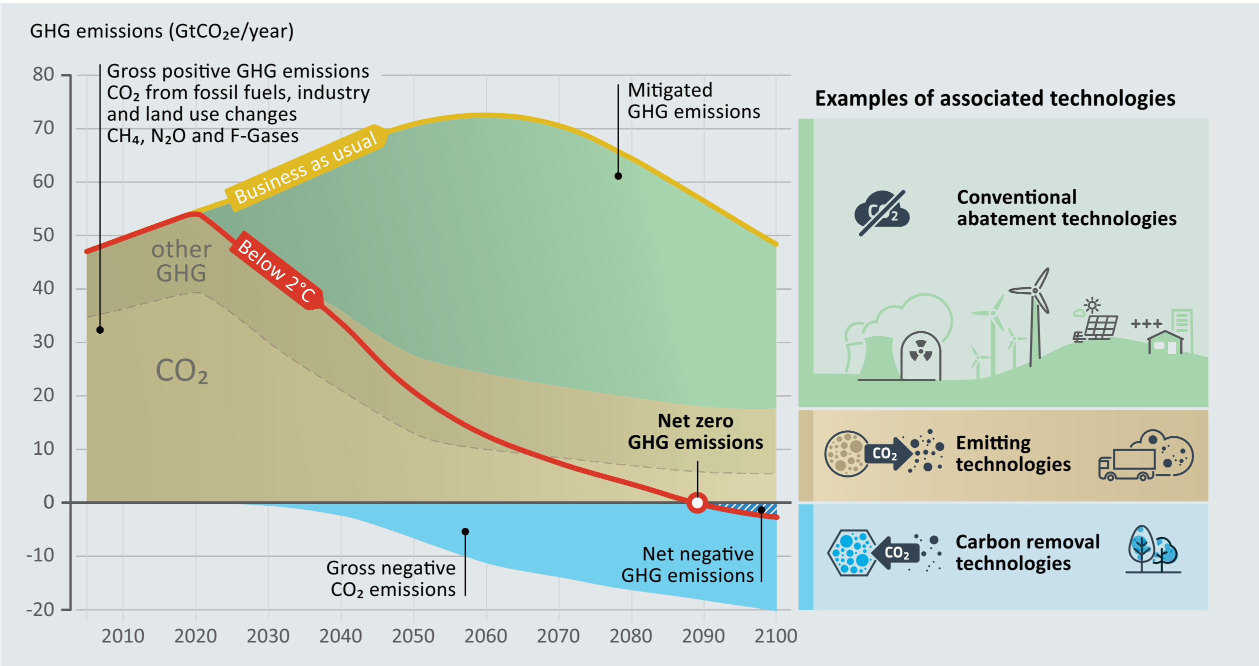
Carbon dioxide removal options have become a common feature in climate change mitigation scenarios that are consistent with the goals of the Paris Agreement (Clarke *et al.*, 2014; van Vuuren *et al.*, 2013; Fuss *et al.*, 2014). Given that carbon budgets are tight and rapidly being depleted (Rogelj *et al.*, 2016; IPCC, 2014), carbon dioxide removal options are more widely used to compensate for temporary budget overshoot.

Carbon dioxide removal and the deployment of negative emissions approaches must be employed *in addition* to other mitigation options (such as those discussed in Chapter 4). Stated differently, carbon dioxide removal is concerned with the management of overshoot, even in the event that all mitigation options are pursued. For example, limiting deforestation and improving forest management are key undertakings to reduce current emissions and avoid future emissions. However, necessary as they are, these practices are quite different to afforestation, which is the practice of adding forests to areas where there are none today.

In many scenarios, *net* negative emissions occur in the second half of the 21st Century. However, negative emissions are introduced much earlier, and to a greater extent, in those scenarios. This is done to compensate for residual emissions that are too difficult or too expensive to reduce at the level of climate policy ambition that the scenario seeks to characterize. Taken together, both climate dioxide removal options represent the total or gross negative emissions required in a particular scenario (figure 7.2).

From a wider portfolio of mitigation options, integrated assessment models select negative emissions technologies based on cost-minimization considerations[1]. Naturally, the deployment of negative emissions technologies varies

Figure 7.2: The role of carbon dioxide removal in climate change mitigation.



Note: This figure shows emission reductions from conventional mitigation technologies combined with carbon dioxide removal. This exemplary scenario is consistent with an at least 66 percent chance of keeping warming below 2°C relative to pre-industrial levels. Emission reductions are shown against a business-as-usual scenario without any additional climate policies. Global net emissions levels turn to net negative towards the very end of the century, but carbon dioxide removal is already being deployed much earlier. Some residual greenhouse gas emissions remain at the end of the century, as they are too difficult to mitigate in the scenario. Note that the scenario used is different from the scenarios used in Chapter 3, which leads to small variations in emission levels and timing of negative emissions.
Source: Jérôme Hilaire (Mercator Research Institute on Global Commons and Climate)

1 Specifically, integrated assessment models determine the least-cost pathway for the global economy to meet a given climate target (before additional benefits are accounted for). They do so on the basis of assumptions about technology costs and availability, alongside other macroeconomic factors (for example, demand for energy and food).

greatly from one scenario to the next, due to differences in scenario design and the specifications of the particular model. Nevertheless, some robust patterns emerge across clusters of scenarios:

- Scenarios consistent with the 1.5°C target depend on the large-scale availability of negative emissions technologies. There are no scenarios available that can keep warming below 1.5°C by 2100 without removing carbon from the atmosphere via negative emissions technologies (Fuss, 2017; Minx *et al.*, 2017).
- In general, the deployment of negative emissions technologies in the second half of the century occurs on a large scale, and with a very rapid scale-up to 8 $GtCO_2$ per year by 2050 (range 5–15). By 2100 the median (2010–2100) removal of carbon dioxide via negative emissions technologies is 810 $GtCO_2$ (range 440–1,020). This corresponds to about 20 years of global emissions at current emission rates.
- In the 2°C scenarios with immediate climate action, the median (2010–2100) deployment of negative emissions technologies is considerably lower: 670 $GtCO_2$ (range 320–840). In addition, the scale-up towards mid-century is much slower.
- Delay in adequate near-term climate action swiftly locks 2°C pathways deeply into negative emissions. To limit warming to 2°C, current Nationally Determined Contributions lead to pathways that are fundamentally dependent on the large-scale availability of negative emissions technologies (like 1.5°C pathways today, and with similar deployment rates and technology upscaling requirements).
- Compared to emissions pathways that are less efficient in energy use, 1.5°C and 2°C emissions pathways that feature aggressive energy savings are less dependent on negative emissions technologies.

It is worth noting that a few scenarios can meet the 2°C target without the deployment of negative emissions technologies. If the models select these technologies, it is because they represent a cheaper mitigation option overall. This means that even in scenarios that are consistent with the 2°C target, there is scope to considerably limit the deployment of negative emissions technologies, compared to what we see in economic optimization scenarios.

7.2. Land-based carbon dioxide removal options

Land-based carbon dioxide removal involves technologies, practices and approaches that harness the carbon removal potential of land-based ecosystems, including forests, wetlands, agricultural land and soils. As these systems have been managed by humans for many years, there is a wealth of knowledge that can be readily applied today with confidence. In addition, these approaches present opportunities to meet other global sustainability goals, such as improved water quality, ecosystem restoration, biodiversity preservation, food and nutrition security, job creation and improved crop yields.

For these land-based options to contribute to carbon removal at the scale of gigatonnes, new management approaches that impact large land areas and ecosystems will be required in some cases. In others, traditional, sustainable practices such as agroforestry may need to be applied[2].

Many substantial uncertainties exist regarding effective carbon dioxide removal rates, the volumes stored, the duration of effective sequestration under a changing climate and the implications for ecosystem services provided by the land in question. In this regard, carbon dioxide removal in these systems may prove very different to other current efforts. Ultimately, each option has its strengths, uncertainties and constraints.

7.2.1 Afforestation and reforestation

Afforestation refers to planting trees on land not afforested in recent history (usually 50 years or longer), while reforestation refers to the replanting of trees on more recently deforested land (Hamilton *et al.*, 2010). Agroforestry practices entail the integration of trees into agricultural systems, in combination with crops, livestock or both. Afforestation, and reforestation, and agroforestry projects form part of several voluntary and mandatory carbon-offset trading schemes worldwide (Diaz *et al.*, 2011; Miles and Sonwa, 2015).

Globally, the carbon dioxide removal potential for afforestation and reforestation options is quite significant—it has been estimated at between 4 and 12 $GtCO_2$ per year (Smith *et al.*, 2016), with other recent estimates even higher, at up to 28 $GtCO_2$ per year (Griscom *et al.*, 2017). Preparation and deployment can be done at a relatively modest cost[3], with the potential for co-benefits. The existence of various projects today, and the experience of forest managers worldwide, provide a high level of technical readiness for afforestation and reforestation options[4]. As such, afforestation and reforestation are considered established carbon dioxide removal options and projects could feasibly be launched soon.

Ultimately, achieving large carbon removal rates and volumes would require very large tracts of land (Houghton *et al.*, 2015; Kriedenweis et al. 2016) and potentially huge volumes of water (Trabucco *et al.*, 2008), although vegetation density is positively correlated with the strength of precipitation sheds and has a moderating effect on the volatility of water availability—in this regard, distant effects might be different and as such, more research is required. Competition for land and water used for food production is a development concern, but could be minimized through agroforestry[5] or careful selection of appropriate land areas for afforestation and reforestation. There are significant uncertainties around

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2 While agroforestry is widely present in the tropics, there are many agroforestry systems in temperate and even boreal regions. For example, according to Aertsens *et al.* (2013), 90 percent of Europe's mitigation potential in the agriculture sector stems from agroforestry.

3 For example, Nielsen *et al.* (2014) report that, within the United States of America, up to 730 $MtCO_2$ per year might be sequestered at a carbon price below US$50 per tonne of carbon.

4 Political and planning readiness varies between countries.

5 Such competition is avoided in agroforestry systems, which allow integrated management of agricultural landscapes for food production and the delivery of ecosystem services (Zomer *et al.,* 2016; Kimaro *et al.,* 2011; Williams-Guillén *et al.,* 2008).

the impacts on non-carbon dioxide greenhouse gases (Benanti *et al.*, 2014), albedo (Kirschbaum *et al.*, 2011; Zhao and Jackson, 2014), evapotranspiration, emissions of volatile organic compounds and other issues[6]. Obstacles may also arise with regard to monitoring, sustaining sequestered carbon in the long term due to sink saturation, changing practices among forest managers and farmers, and creating market and policy contingencies. Despite these uncertainties and obstacles, experience with managing forests stands in our favour for adopting these options, which, as previously mentioned, also have the potential to contribute to other global sustainability goals.

7.2.2 Other 'natural', land-based solutions

Other natural, land-based carbon dioxide removal solutions rely on the restoration or construction of high carbon density, anaerobic ecosystems, including "inland organic soils and wetlands on mineral soils, coastal wetlands including mangrove forests, tidal marshes and seagrass meadows, and constructed wetlands for wastewater treatment" (IPCC, 2014). Hereinafter, these solutions are referred to as wetlands. It is increasingly critical to not only preserve existing wetlands, but also to restore and construct these ecosystems for use as carbon dioxide removal solutions.

Peatlands and coastal wetlands store up to 44 to 71 percent of the world's terrestrial biological carbon pool (Zedler and Kercher, 2005). While the carbon stocks in peatlands and coastal wetlands are now vulnerable to reversal (Parish *et al.*, 2008), these ecosystems also have significant carbon sequestration capacity (Page and Hooijer, 2016).

Compared to afforestation and reforestation options, much less is known about wetlands. Roughly one third of global wetland ecosystems had been lost by 2009 (Hu *et al.*, 2017), suggesting there are a number of locations where work could begin. Long-term sequestration rates in wetlands range from 0.1 to 5 tonnes of carbon per hectare and per year, a rate that significantly improves when emissions avoided from (previously degraded) restored wetlands are counted (Parish *et al.*, 2008; Mitsch *et al.*, 2012; Smith *et al.*, 2008). However, estimating global rates and volumes is challenging. Carbon dioxide abatement costs for wetland restoration range from US$10 to US$100 per tonne of carbon dioxide (Worrall *et al.*, 2009), suggesting potential low-cost options for projects.

Little is known about the total land and water requirements needed to achieve substantial and sustainable levels of carbon dioxide removal through wetlands. However, non-carbon dioxide greenhouse gases represent a substantial risk. While wetlands store significant amounts of carbon in above- and below-ground biomass, and in soil, they have also historically been a significant source of methane, with estimates ranging from 20 to 25 percent of global methane emissions (Mitsch *et al.*, 2012). As such, restoring some wetlands could induce a short-term net warming effect (Mitsch *et al.*, 2012) due to increased emissions of methane and nitrous oxide[7]. In addition, while some sites may be suitable for early remediation, in other instances, sites of former wetlands have been converted to ports, industrial sites and other high-value capital assets, which limits the extent to which they can be used for carbon dioxide removal. Griscom *et al.* (2017) estimate that avoided coastal wetland impacts, avoided peat impacts and peat restoration could deliver 0.3, 0.7 and 0.8 $GtCO_2$ per year, respectively, by 2030. As with forest management, wetlands and peatlands have been managed by humans for many years, which provides an opportunity to capitalize on existing knowledge and on the readiness to implement measures (Griscom *et al.*, 2017). There is also the added potential to contribute to other global sustainability goals such as improved water quality, ecosystem restoration, biodiversity preservation and job creation.

7.2.3 Soil carbon sequestration

Soil carbon sequestration occurs when a change in land management practices increases the carbon content of soil, thus resulting in a net removal of carbon dioxide from the atmosphere. Since the level of carbon in the soil is a balance of carbon inputs (for example, from litter, residues, roots or manure) and carbon losses (mostly through respiration, which is increased by soil disturbance), practices that either increase inputs or reduce losses can promote soil carbon sequestration. Lal (2011, 2013) and Smith *et al.* (2008, 2014) cite a large number of land management practices that can promote soil carbon sequestration, some of which can also promote carbon sequestration in above-ground biomass.

Soil carbon sequestration uses agricultural and land management practices that are generally well known by farmers and land managers, and for the most part, does not require additional machinery or infrastructure. It therefore represents a readily available option to be implemented.

Rates for soil carbon sequestration vary considerably, depending on land management approaches, soil type and climate region (Smith, 2012; Lal, 2013). When scaled globally, the technical potential for soil carbon sequestration is estimated at 4.8 $GtCO_2e$ per year (Smith, 2016)[8]. Assuming unit costs between US$20 and US$100 per tonne of carbon, the global carbon emissions mitigation potential of soil carbon sequestration ranges between 1.5 and 2.6 $GtCO_2e$ per year (Smith *et al.*, 2008; Smith, 2016). It is worth noting that for some systems, such as croplands and grazing lands, soil carbon sequestration costs range from minus US$45 to plus US$10 per tonne of carbon (Smith, 2016), suggesting there are revenues and cost savings to be made from some of these practices[9]. Smith (2016) estimated that carbon dioxide removal through soil carbon sequestration at a rate of

6 These uncertainties could be reduced or better characterized through a dedicated science programme aimed at understanding the issues across ecosystems, latitudes and climate zones.

7 Dedicated and sustained research is needed to resolve or reduce these uncertainties.

8 Other estimates range between 0.4 $GtCO_2e$ per year (Powlson *et al.,* 2014) and 11.4 $GtCO_2e$ per year (Lal, 2011; Lal, 2013; Minasny *et al.,* 2017).

9 Most of the annual estimates are based on sequestration values calculated over 20 years. Given that sinks saturate, annualized sequestration estimates should be multiplied by 20 to derive the total cumulative sequestration potential.

2.6 $GtCO_2e$ per year would save US$7.7 billion, comprising US$16.9 billion of savings and US$9.2 billion of costs.

Although the apparent energy costs for soil carbon sequestration appear low, and in many cases, soil carbon sequestering practices would benefit soil ecosystems and agribusinesses, implementing these practices involves a significant range of potential land requirements (Smith *et al.*, 2010). While emissions from methane may be limited, soil carbon sequestration may result in emissions of nitrous oxide (Smith, 2016). As for wetlands, dedicated and continued research on these uncertainties and challenges could help reduce risks and improve performance.

Barriers to implementation include lack of knowledge among farmers, lack of policy incentives, monitoring and verification of practices and costs and crucially, reversibility of stored carbon. Dedicated pilot projects and programmes could help to identify the measures required to overcome these barriers, with an emphasis on learning-by-doing and resolving key uncertainties through data acquisition and development of practices. Since soils have been managed for millenniums, there is a high level of knowledge and readiness, with the potential to contribute to other global sustainability goals such as improved water quality, ecosystem restoration, biodiversity preservation, job creation and increased yields and food security.

7.2.4 Biochar

Biochar is produced through pyrolysis of biomass into a stable, long-lived product, such as charcoal. Biochar is resistant to decomposition (Lehmann *et al.*, 2015) and can stabilize organic matter added to soil (Weng *et al.*, 2017). It can form long-term carbon pools in the soil and provide a range of soil fertility and soil quality co-benefits, such as improved water and nutrient retention, increased soil porosity and higher crop yields.

While biochar can be applied at high rates (Genesio *et al.*, 2012; Zhang *et al.*, 2010), the net benefits of biochar are likely to be higher if applied in low volumes in the most responsive soils[10]. The carbon dioxide removal potential through biochar is high: it has been estimated at between 1.8 and 3.3 $GtCO_2e$ per year (Woolf *et al.*, 2010). However, the efficacy of biochar for carbon dioxide removal is disputed[11]. Costs range between US$18 and US$166 per tonne of carbon dioxide-equivalent per year (Woolf *et al.*, 2010), although economic benefits and revenues could offset part of this cost.

Although biochar is an established technology, it is not yet widely applied, in part due to costs and the (limited) availability of infrastructure. Additional infrastructure (namely pyrolysis facilities) would be required for large-scale implementation. Indeed, the quantity of biomass available for biochar production is a key factor limiting the global potential for carbon dioxide removal through biochar. Energy and water are also required to produce the crop feedstocks, although producing biochar can also produce power and fuels[12]. While the land use for carbon dioxide removal through biochar appears relatively modest (between 26 and 95 million hectares), estimates are dependent on land and crop quality. Not least, carbon dioxide-reduction benefits may be mitigated by albedo reduction (Bozzi *et al.*, 2015). Although the risks of reversibility and difficulty of monitoring are lower than for soil carbon sequestration, barriers such as limited knowledge of practice or policy support remain.

7.3 Combined land/technology-based option: bioenergy with carbon dioxide capture and storage

Bioenergy with carbon dioxide capture and storage removes carbon dioxide from the atmosphere through the cultivation of biomass (bioenergy), and stores carbon dioxide from energy generation in deep, geological formations (carbon dioxide capture and storage), providing net carbon removal. So far, this is the carbon dioxide removal technology that has featured most prominently in the mitigation scenarios by the Intergovernmental Panel on Climate Change (Fuss *et al.*, 2016; Fuss, 2017).

Many integrated assessment models estimate the availability of sustainable bioenergy at 100 exajoules per year (Creutzig *et al.*, 2015; Slade *et al.*, 2014)[13]; fewer models accommodate estimates above 300 exajoules per year.

With regard to carbon dioxide capture and storage, estimates for geological storage capacity are well above 5,000 $GtCO_2$. However, the estimated capacities are not viable in all locations (Scott *et al.*, 2015; De Coninck and Benson, 2014; Lassiter and Misra, 2016; Global CCS Institute, 2016).

The combined potentials of bioenergy and carbon dioxide capture and storage in 2050 are estimated at between 2 and 18 $GtCO_2$ per year (Kemper, 2015; USNAS 2015a; McLaren, 2012). To achieve this scale, the demands on land use are significant: a level of carbon dioxide removal consistent with average 2°C emissions pathways would require between 0.38 and 0.7 billion hectares of crops purpose-grown for bioenergy with carbon dioxide capture and storage (Smith *et al.*, 2016)[14]. Under more conservative assumptions, the demands on land use would be even higher (Monfreda *et al.*, 2008).

Use of agricultural and forest residue as a feedstock for bioenergy does not require competition for land, although its extraction can adversely impact soil carbon stocks (Smith *et al.*, 2016). The potential competition for land from widespread use of bioenergy with carbon capture and

10 Notably after enhancement through co-composting or nutrient addition (Joseph *et al.,* 2013).
11 Interestingly, biochar can reduce non-carbon dioxide greenhouse gases, notably nitrous oxide (Cayuela *et al.,* 2015).
12 Net energy balances remain controversial and dependent on process, feedstock and products.
13 Roughly, this represents 15 percent of global primary energy consumption today.
14 For comparison, global agriculture today, including both farming and grazing, requires roughly 5 billion hectares of land.

storage remains a major issue for large-scale bioenergy with carbon capture and storage deployment and policymaking.

In a scenario consistent with the 2°C target, infrastructure investment costs associated with bioenergy with carbon dioxide capture and storage in 2050 are estimated at US$138 billion per year for power and US$123 billion per year for fuels (Smith *et al.*, 2016). Nonetheless, there are significant variations in unit costs for bioenergy and with carbon dioxide capture and storage, depending on assumptions about feedstock, technology, supply chains and logistics[15].

For a level of bioenergy with carbon capture and storage deployment consistent with a 2°C target, 170 exajoules per year of energy would be generated from bioenergy with carbon capture and storage by 2100 (Smith *et al.*, 2016).

Bioenergy with carbon dioxide capture and storage could have a large impact on water use, requiring about 720 km^3 per year or roughly 3 percent of the fresh water currently appropriated for human use (Smith *et al.*, 2016). Non-carbon dioxide greenhouse gas impacts are value-chain specific and uncertain, as are global albedo effects (Bright *et al.*, 2015; Jones *et al.*, 2015). Taken together, these considerations suggest that (i) over the next 10 to 20 years, carbon reduction using combined land- and technology-based options will be challenging; and (ii) there are risks associated with large-scale implementation of these options.

Three main barriers stand out with regard to large-scale implementation of bioenergy with carbon dioxide capture and storage. Firstly, carbon dioxide capture and storage and bioenergy enjoy little public acceptance (Benson *et al.*, 2012; Upham and Roberts, 2011; Wallquist *et al.*, 2012; de Best-Waldhober *et al.*, 2009). Secondly, whether there are substantial, or even any carbon reductions when accounting for displaced activities is unclear (Havlík *et al.*, 2011; Frank *et al.*, 2013; Searchinger *et al.*, 2009; Plevin *et al.*, 2010, Creutzig *et al.*, 2015; Popp *et al.*, 2012). Thirdly, the lack of economic incentives and the regulatory barriers related to underground storage hamper large-scale implementation (De Coninck and Benson, 2014)[16].

McLaren (2012) reports a technological readiness level of 4 to 6 for bioenergy with carbon dioxide capture and storage from combustion and co-firing, and a technological readiness level of 5 to 6 for bioenergy with carbon dioxide capture and storage from ethanol fermentation (technological readiness level 6 corresponds to "prototype demonstration in the 'relevant' real-world environment" and technological readiness level 4 to the stage of "component validation"). Although individually, both bioenergy and carbon dioxide capture and storage are relatively mature technologies, in combination they have seen very little demonstration and deployment, especially at a large scale. Whether bioenergy with carbon dioxide capture and storage can thus be scaled up in the manner required to achieve ambitious climate change targets remains questionable, given the lag in actual carbon dioxide capture and storage deployment, compared to the requirements associated with emissions pathways that are compatible with the 2°C target (Peters *et al.*, 2017; Peters and Geden, 2017).

7.4 Technology-based carbon dioxide removal options

Man-made technologies to remove carbon dioxide from the air have been in use for many years, mostly in submarine, aerospace and medical applications. Consideration of them as global-scale carbon removal agents is recent (USNAS, 2015a). They offer specific benefits in that they use very little land or water, they do not emit non-carbon dioxide greenhouse gases and they have very high levels of certainty regarding the flux and long-term fate of the carbon dioxide removed. Some approaches also produce materials that can be used commercially, for example, cements and aggregates.

However, many approaches are expensive. Most have not been deployed at scale and have a low level of technical readiness. Investment in developing these options will likely yield breakthroughs in material science and manufacturing, and could spur new industries and a circular carbon economy (McDonough, 2016; Center for Carbon Removal, 2017), as was true for lithium-ion batteries 25 years ago (The Economist, 2017). Nonetheless, among the 23 countries committed to undertaking large-scale research and development programmes in this and related areas, only the United Kingdom has financed technology-based carbon dioxide removal programmes, and at a modest level of £8.6 million (approximately US$11.3 million) per year (NERC, 2017).

Each option has strengths, uncertainties and constraints. The low level of readiness facing many technologies is perhaps the most pressing issue.

7.4.1. Direct air capture

Direct air capture is the practice of separating carbon dioxide from ambient air, typically through chemical or physical separation (Lackner *et al.*, 1999; Sanz-Peres *et al.*, 2016). Early approaches to this process have been applied in aerospace and submarine settings, to provide environmental controls (Keith *et al.*, 2006). To achieve carbon removal and negative emissions, direct air capture would have to be combined with carbon-dioxide capture and storage or carbon dioxide conversion to long-lived materials (see below)[17].

To yield negative emissions, direct air capture combined with carbon dioxide capture and storage must be powered predominantly by zero-carbon energy sources (wind, solar,

15 Estimates of cost per tonne of carbon dioxide range from US$60–250 (Kemper, 2015), to US$70–250 (McLaren, 2012), to as little as US$15–45 for bioenergy and carbon dioxide capture and storage from ethanol fermentation.

16 Current low carbon prices deter investments in bioenergy with carbon dioxide capture and storage. The withdrawal of public support for these technologies (as was the same effect.

17 Several companies have fielded direct air capture units (Marshall, 2017; Lassiter and Misra, 2016). Most of these produce fresh water as a by-product (American Physics Society, 2011). Niche applications could include the food and beverage industry, semiconductor manufacturing and remote sites for enhanced oil recovery (Lassiter and Misra, 2016).

geothermal, hydro and nuclear). Although this approach has a technical potential above 20 $GtCO_2$ per year, actual global deployment is likely to result in reductions of between 2 and 5 $GtCO_2$ per year (USNAS, 2015a).

Cost remains the largest barrier to deployment. Since direct air capture involves separating carbon dioxide from air, and the partial pressure of carbon dioxide in air is low, costs can be between US$200 and US$600 per tonne (American Physics Society, 2011)[18]. Like bioenergy with carbon dioxide capture and storage, direct air capture combined with carbon dioxide capture and storage would require functional scale deployment of carbon dioxide capture and storage, which represents both a potential limit and cause for renewed commitments to the technology (Center for Carbon Removal, 2017).

It is worth noting that it is possible to directly separate dissolved carbon dioxide from ocean water and from air. This could provide an additional benefit as a local or global countermeasure to ocean acidification. However, research on dissolved ocean carbon dioxide is very recent and at very low technical readiness levels (Willauer *et al.*, 2014)[19].

7.4.2. Accelerated weathering of minerals

It has long been known that natural weathering of most rocks (silicates, carbonates and oxides) binds carbon dioxide from the atmosphere (Chamberlain, 1899; Raymo, 1991). Accelerated weathering has been proposed as a means of either drawing carbon dioxide from the air, binding it permanently, or both (Lackner *et al.*, 1995; Chiang and Pan, 2017). Much of this research proposes using rocks that are very rich in iron, calcium and magnesium (ultramafic rocks) as the primary feedstock, and reacting these in situ or ex situ with carbon dioxide to form carbonate rocks and minerals, locking away atmospheric carbon dioxide in the process (Kelemen and Matter, 2008).

While the technical potential of accelerated weathering is, in theory, unlimited (IPCC, 2005), the *effective* technical potential is not. This is due to the kinetics of most carbon dioxide mineral reactions, which are slow and limit the viable rates for carbon dioxide removal. Not least, the technical potential can be limited by the rate at which the ground material can be applied to land (Smith *et al.*, 2016, Taylor *et al.*, 2016). Global estimates of potential for accelerated weathering of minerals are in the range of 0.7 and 3.7 $GtCO_2$ per year (Lenton, 2014; Smith *et al.*, 2016).

While kinetics can be improved by grinding, drilling and deep, in situ injection, adding heat or other energy sources, or adding chemicals (such as strong acids), these approaches dramatically increase costs and can increase the carbon intensity of the overall process[20]. These estimates are poorly represented in the literature, thus necessitating additional research in this area.

Since carbon dioxide is bound indefinitely in chemical form, there is both high confidence in carbon dioxide retention for many years, and robustness in accounting and validation of carbon storage and removal. For ex situ approaches, revenues from product sales, including agricultural inputs or aggregate and cement for construction offer an additional benefit (Monkman and MacDonald, 2015; CO_2Sciences, 2016)[21].

7.4.3. Ocean alkalinity enhancement

The addition of alkaline materials to sea water enhances the amount of carbon stored in the ocean. It draws carbon dioxide from the atmosphere by shifting the equilibrium between atmospheric carbon dioxide and dissolved inorganic carbon in the ocean, which also serves to counter ocean acidification. While ocean alkalinity enhancement has received very little attention, compared to other carbon dioxide removal options, it has the potential "to sequester hundreds of billions to trillions of tonnes of [carbon]" (Renforth and Henderson, 2017).

Ocean alkalinity can be enhanced in a number of ways:

- Weathering of silicate and carbonate minerals on land, resulting in the introduction of calcium and magnesium ions into ocean waters (Hartmann *et al.*, 2013; Rau *et al.*, 2007).
- Introducing calcium ions into ocean water by adding calcium oxide or calcium hydroxide to sea water, a procedure often referred to as ocean liming (Kheshgi, 1995; Renforth and Kruger, 2013).
- Electrolysis of sea water, often referred to as electrochemical splitting, to increase aqueous sodium hydroxide (House *et al.*, 2007) or to accelerate the dissolution of calcium carbonate (Rau *et al.*, 2004).

Few techno-economic assessments of these approaches exist. Preliminary estimates range from US$10 to US$600 per tonne of carbon dioxide for weathering of silicate and carbonate minerals, US$72 to US$159 per tonne of carbon dioxide for ocean liming and US$14 to US$190 per tonne of carbon dioxide for electrochemical splitting (Renforth and Henderson, 2017).

The availability of suitable minerals close to oceans would limit deployment. Notwithstanding, environmental concerns and governance considerations may prove to be the primary barrier to implementation. Regarding the former, the consequences of increased alkalinity on marine ecosystems are poorly understood (Henderson *et al.*, 2008)[22]. Regarding the latter, the addition of alkaline materials to the ocean would fall within the remit of the International

18 Specialized companies claim much lower prices today (a maximum of US$500 per tonne) and cost reductions of about 50 percent in the next 10 years.
19 Nonetheless, the United States Senate recently asked the National Academies to undertake an assessment on the matter (Whitehouse, 2017).
20 Costs would range between US$20 and US$1,000 per tonne of carbon dioxide (USNAS, 2015a).
21 Early niche applications are likely at diamond, base-metal and asbestos mines with tailings of carbon dioxide-reactive rocks that have already been processed for primary mineral extraction.
22 Note that the addition of alkaline materials would counteract ocean acidification.

Maritime Organization, through the London Protocol to the "Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter" (also known as the "London Convention")[23].

7.4.4. Conversion of carbon dioxide to long-lived products

The concept of using carbon dioxide to produce chemicals and materials was already being developed in the context of chemical research in the 1970s, long before climate change and the possibilities for removing CO_2 from the atmosphere entered the public debate (Aresta, 2010; Bruhn *et al.*, 2016). Most of these technologies have not been developed with long-term storage of carbon dioxide in mind. In addition, most materials based on captured carbon dioxide (for example, polyurethane foams or fuels such as ethanol) only have limited lifetimes in the context of the timescales that are relevant to climate change (Aresta, 2013; CLCF, 2011). An exception to this is carbonates, which are used to produce cement-like construction materials in which long-term (decades to centuries) sequestration of carbon dioxide can be achieved (von der Assen, Jung *et al.*, 2013; Bruhn, 2016), as noted above.

Recently, there has been new research and commercial activity focused on converting carbon dioxide directly to other long-lived materials, including polymers, carbon fibre composites, graphene, carbon black and even diamond (ICEF, 2017). Although these companies and research efforts are in their infancy, they have attracted substantial commercial interest. Due to the early stages of development, it is difficult to estimate the upscaling potential of the various approaches. A recent estimate puts the annual market for these materials between 1 and 7 $GtCO_2$ per year, although this is contingent on policy- and market-support actions (CO_2Sciences, 2016).

7.5. Governance issues for carbon dioxide removal

Realizing the potential of carbon dioxide removal would require large-scale investment in research (to reduce key uncertainties), and development and deployment incentives (to reduce costs). Governments can play a key role in providing the funding and incentives needed to achieve these investments (Lomax *et al.*, 2015; Peters and Geden, 2017).

Firstly, government policy can work to protect communities from any potential, negative side-effects (environmental, economic, social, political and ethical) associated with large-scale deployment of carbon dioxide removal solutions (Buck, 2016). Secondly, governments can set consistent standards for transparency, notably with regard to the measurement and verification of carbon stored from a given carbon dioxide removal solution (Zakkour *et al.*, 2014). Thirdly, they can require that standards accept products arising from carbon dioxide-reduction approaches[24]. And finally, they would have to develop international agreements with regard to the transboundary effects of these technologies (Schäfer *et al.*, 2015).

There is currently limited discussion on carbon dioxide removal issues in most subnational and international climate policy forums. Policymakers might consider giving attention to the importance of carbon dioxide removal, the risks and challenges faced by leading carbon dioxide removal solutions and the policy options for addressing these risks and challenges (Williamson, 2016). This is because, to achieve the objectives of the Paris Agreement, mobilizing a rapid reduction of greenhouse gas emissions will be essential. Carbon dioxide removal can play an important role in meeting these objectives. However, to do so, enabling actions on carbon dioxide removal will be required, including more extensive policy discussions and focus on specific barriers to deployment (Peters and Geden, 2017).

Many key uncertainties can be explored using a learning-by-doing approach, notably by undertaking research and small-scale deployment activities (Lomax *et al.*, 2015). All of the approaches described in this chapter have initiated or can initiate small- and large-scale pilot projects, from which data on cost, performance and improvement opportunities can be drawn (IEA, 2017). Some efforts, such as afforestation or reforestation projects, have begun under the jurisdiction of United Nations programmes that could be expanded or rapidly scaled up. Scenarios that show net emissions turning negative in the second half of the 21st Century can give the false impression that there is no urgency. However, to achieve those scenarios will require significant amounts of gross negative emissions by 2030 at the latest (Rogelj *et al.*, 2015; Anderson and Peters, 2016), and advancing techniques to maturity usually takes decades.

7.6 Conclusions and recommendations

Carbon dioxide removal remains an important set of undertakings following the Paris Agreement, to supplement immediate and aggressive mitigation action. In order to achieve the goals of the Paris Agreement, to keep the global mean temperature increase well below 2°C (or even below 1.5°C), carbon dioxide removal is likely a necessary step.

Although there is much ongoing work worldwide on this topic, the field of carbon removal remains very young (particularly for technology-based solutions), with relatively little scholarship on the direct topic of carbon dioxide removal. In some cases, efforts aimed at strengthening approaches to carbon dioxide removal can build on deep understanding and experience from other industries, for example, agribusinesses or heavy industry. Nonetheless, specific questions concerning current and future costs of carbon dioxide removal options, the longevity of carbon retention, the environmental consequences of scale-level

23 The London Convention is examining ocean alkalinity enhancement.

24 For example, the International Civil Aviation Organization (ICAO) standards do not currently accept synthetic fuels made from carbon dioxide derived from direct air capture.

deployment of carbon dioxide removal and other key questions remain largely unexplored. Critically, only one country in the world (the United Kingdom) has a government programme aimed explicitly at supporting carbon dioxide removal (NERC, 2017).

In light of the above, there are four key recommendations for consideration:

- Governments around the world might carefully assess the potential role of carbon dioxide removal in achieving the goals of the Paris Agreement. They would benefit from understanding these technologies and the potential ancillary benefits they may provide to commerce and trade, such as improved crop yields.
- Governments and other stakeholders could launch joint research and development programmes on the many pathways for carbon dioxide removal. Such programmes would be appropriate, given that some carbon dioxide removal options are only at the early stages of development, and in light of the role they could play in curbing climate change. Both core scientific undertakings (for example, a decade-long science programme on the carbon cycle in soil) and technology development efforts (focused, for example, on novel materials and processes for direct air capture) could be included, possibly structured around pilot programmes and early-demonstration activities, where progress can be made quickly and early-action opportunities can be identified and investigated.
- Carbon dioxide removal presents specific challenges for life-cycle accounting, which will directly affect accounting standards, industrial standards, industrial and financial practice, and regulation. Emissions trading in particular would be complicated by carbon-negative approaches. Overt and dedicated analysis and efforts would be required to develop, refine and incorporate carbon dioxide removal approaches into these commercial and governmental endeavours.
- Some approaches raise questions around global governance in the near term (for example, ocean alkalinity enhancement vis-a-vis the London Convention). In addition, wide deployment of carbon dioxide removal raises fundamental questions about how to appropriately stabilize atmospheric carbon dioxide concentrations and how to manage interests globally and among nations. Dedicated working groups, perhaps modelled on the Climate and Clean Air Coalition and their work on short-lived climate pollutants, could be formed and begin discussing these issues.
- Since the land-based systems relevant for carbon dioxide removal have been managed by humans for many years, there is a wealth of knowledge that can be readily applied today with confidence. Furthermore, these approaches present opportunities to meet other global sustainability goals, such as improved water quality, ecosystem restoration, biodiversity preservation, food and nutrition security, job creation and improved crop yields.