Examining the Viability of Net-Negative Carbon Removal Techniques in Limiting Global Warming to 1.5 Degrees Celsius: An Economic and Environmental Evaluation

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Background

1.1 The necessity of Carbon Dioxide Removal

Bergman and Rinberg (2021) estimate that human activities have caused 2500 Gt[1] of carbon emissions into the atmosphere since 1850. This has caused the atmospheric concentration of CO_2 to rise from 278 ppm before the beginning of the industrial era to over 410 ppm in 2021 (Friedlingstein et al., 2022, p. 5). Anthropogenic global warming already reached 1 degree Celsius in 2017 (IPCC, 2018, p. 6), and the UNEP (2022, p. 30) estimates that even in the most optimistic scenarios, the peak warming will likely exceed the 1.5-degree target. [2] Similarly, a report by the NAS (2018, p. 9) concludes that to meet the goals of the Paris Agreement, negative emissions of 10 Gt/y CO_2 by 2050 and 20 Gt/y CO_2 by 2100 are required.
Additionally, while for most sectors and industries the cost of CO_2 abatement through emission avoidance or capture is significantly lower than the projected cost of most CDR strategies, there are some hard-to-avoid emissions, e.g. from agriculture and air transportation. This means that even after an atmospheric concentration of CO_2 in accordance with the goals of the Paris Agreement is reached, some carbon removal will be required to offset the remaining emissions and ensure the concentration of CO_2 remains stable (NRC, 2015).[3]

1.2 Definition of Carbon Dioxide Removal

There are a number of different definitions of Carbon Dioxide Removal (CDR), all of which are broadly equal, but slightly differ in the scope of strategies and technologies they include. For example, the IPCC (2018, p. 544) defines CDR as "anthropogenic activities removing CO_2 from the atmosphere and durably storing it in geological, terrestrial or ocean reservoirs, or in products", which suggests that any kind of carbon capture or storage constitutes CDR, given that the carbon was

[1] 1 Gt = 1 billion (metric) tons

[2] The Mercator Institute estimates that as of May 8, 2023, the remaining carbon budget to stay below the 1.5-degree goal is roughly 262Gt CO_2, which at the current pace will be exceeded in the next seven years. The current numbers can be found at: https://www.mcc-berlin.net/en/research/co2-budget.html

[3] The amount of CDR required depends on the definition of *hard-to-avoid emissions*. Although many definitions include any emissions for which their high financial cost makes CO_2 abatement unviable, Bergman and Rinberg only include emissions that cannot be avoided for physical reasons or whose avoidance would cause unacceptable social injustice, and warn against using proposed future CDR strategies as an argument to avoid emission reduction in the present.

taken from the atmosphere and not from a single point source. The NAS (2018, p. 1) use the term Negative Emission Technologies (NETs) instead, which they define as strategies "which remove carbon from the atmosphere and sequester it." More recently, Smith et al. (2023, p. 11) argued that CDR must follow the three principles (1) of removing carbon from the atmosphere, (2) using durable[4] storage, and (3) being the result of active human intervention. All these definitions imply that CDR can be divided into approaches that capture CO_2 from the atmosphere, such as Direct Air Capture, approaches that store CO_2, such as geological storage or in-situ mineralization, and approaches that capture and store CO_2, such as land management or afforestation and reforestation. This thesis focuses only on strategies and technologies that capture or capture and store carbon, excluding storage-only strategies.

1.3 Natural and technological CDR strategies

CDR strategies can be grouped into biological capture, geochemical capture, both of which mostly rely on using or enhancing natural (i.e. biological or chemical) processes, and chemical approaches, which uses technological processes involving chemical solvents (Smith et al., 2023).
Biological capture processes include land-management strategies that aim to increase the amount of CO_2 stored in e.g. agriculturally-used soil and afforestation and reforestation, as well as some ocean-based processes.
Geochemical capture processes are based on using natural weathering and mineralization processes, artificially fertilizing the oceans or increasing their alkalinity to boost their ability to absorb CO_2.
Chemical processes use novel, technological processes that involve solid or liquid solvents, which absorb CO_2 from the atmosphere and release it in concentrated form for storage.
The various approaches differ greatly in their CO_2 removal potential, their feasibility on a larger scale, their energy requirements, the durability of the storage they use, and their cost (NAS, 2018, Chapter 8).The approaches discussed in this thesis are largely those that were considered by the National Academies in their 2018 research agenda.

[4]Smith et. al define durable storage as storage that "has a characteristic timescale on the order of decades or more".

1.4 Current State of CDR research and development

In the past years, the investment into CDR research and development of CDR projects has increased substantially (Smith et al., 2023, p. 11). However, the development of the various CDR strategies is currently in very different stages. Biological processes have a large literature, are well understood, and are cheaper to deploy at the present time, but are less durable and face greater limitations in their total potential due to natural constraints (Fuss et al., 2018). In comparison, chemical processes are still in their infancy and are only deployed on a small scale (Smith et al., 2023, p. 24).

Uncertainty also exists about the contribution CDR can make to climate change mitigation efforts in general. While some reports (e.g. NAS (2018)) include the use of large amounts of CDR in the future as a necessity to reach the goals of the Paris Agreement, Fuss et al. (2018) argue that CDR is no alternative to rapid and sustainable reductions in carbon emissions and warn against over-reliance on CDR, citing the uncertainty and risks involved in its large-scale deployment.

1.5 Economic viability of CDR

Since carbon removal is generally (with some exceptions) costly and does not have immediate benefit for its producer, the economic viability of CDR depends on a carbon price instituted by systems such as the European Emissions Trading System (EU-ETS), which requires companies in some industries to buy carbon certificates and allows trading between companies, or a government-enforced carbon tax. Currently (May 2023), the price for one ton of carbon dioxide produced in the EU-ETS is 88 € (97 US$), after exceeding 100 € for the first time in February of this year. Other definitions of carbon costs include the total cost of social damage caused by carbon emissions, with different models proposing prices in a wide range between 50 US$ and 5000 US$ (Kikstra et al., 2021, pp. 1, 7). This thesis uses the definition instituted by Griscom et al. (2017, p. 3), who define a price of 100 US$/t CO_2 as cost-effective based on the costs to society avoided if global warming is kept below two degrees Celsius.

Biological Strategies

2.1 Afforestation and Reforestation

Trees store CO_2 by converting it into plant biomass by photosynthesis. Crowther et al. (2015) estimate that there are approximately three trillion trees worldwide, and forests make up 38% of all habitable land area (Ritchie & Roser, n.d.). Despite significant deforestation in the past, forests sequester 7.6 Gt of CO_2 annually, removing nearly 20% of anthropogenic carbon emissions from the atmosphere (Harris et al., 2021).

Potential

Afforestation refers to the cultivation of forests in areas that were recently deforested, whereas reforestation occurs on lands that did not grow forests in the recent past.[5] The total potential for carbon sequestration through afforestation and reforestation (AFRF) depends on three factors: (1) the amount of land available, (2) the amount of carbon that trees can sequester, and (3) the environmental climatic conditions. The IPCC 2000 report estimates that trees in boreal regions sequester up to 1.2t CO_2/ha/y, while trees in temperate regions can store 4.5t CO_2/ha/y, and trees in tropical rainforests can store up to 8t CO_2/ha/y. These differences are explained primarily through the different lengths of the growing season, which only lasts a few months in boreal climates but spans almost the entire year in tropical regions (Watson et al., 2000). Other reports assume higher storage potential, with the NAS (2018) claiming an upper bound of 30t CO_2/ha/y. Overall, the IPCC report estimated that an additional 87Gt could be sequestered using AFRF between 1995 and 2050, resulting in an annual uptake of 1.58Gt CO_2, 75% of which would be stored in tropical rainforests. More recent reports, such as Fuss et al. (2018) and Griscom et al. (2017) use higher theoretical estimates of up to 10Gt/y.
In addition to carbon removal, AFRF can bring benefits such as increased biodiversity, reduced land erosion and desertification in dry areas, and protection of watersheds. (Watson et al., 2000)

[5] 'Recent past' is typically defined as the last 30 - 50 years.

Limitations

Carbon removal through AFRF comes with extensive land requirements. At a storage rate of 10t CO_2/ha/y, sequestering 1Gt CO_2/y would require 100 million hectares of additional forests.[6] Cultivating ecologically sustainable forests can also prove to be difficult. Creating vast monocultures of a single species of trees or turning previous grasslands into forests can present unforeseen dangers and negatively impact ecosystem diversity. This also raises the question of durability. Compared to other, more durable carbon removal strategies, forests are vulnerable to wildfires, pests, and other disturbances that can cause rapid loss of stored carbon. Therefore, using forests as carbon storage requires ongoing fire management, e.g. by removing deadwood and intentional limited-scale fires, and pest management (Watson et al., 2000). Depending on the region, other factors, such as surface albedo and evapotranspiration, can also play a role and significantly reduce the effectiveness of carbon storage. Forests generally have lower albedo rates than grasslands, meaning that they reflect a lower portion of the incoming sunlight and therefore trap a larger amount of heat. This effect is especially strong in high-latitude forests. In comparison, evapotranspiration occurs mainly in tropical rainforests, where large amounts of water evaporate and, while cooling the surface, can act as a potent greenhouse gas and cause atmospheric warming. (NRC, 2015). Finally, the net additionally of AFRF also depends on what the land was previously used for. If farmland is converted to forests, then it is likely that, considering the increasing food demand worldwide, forests elsewhere will be cut to ensure sufficient supply. This would significantly reduce or fully eliminate the net effect of AFRF. The same is true if forests are planted on lands that would naturally have regrown forests anyway (Gates, 2021, p. 128).

Carbon storage by trees is also limited by their growth rate and natural lifecycle. Carbon uptake is generally the highest during the growth phase, which can be between 20 and 200 years depending on the species, but slows down afterward (Watson et al., 2000). The highest uptake rate is usually reached after 30 - 40 years, depending on environmental factors (NRC, 2015). Watson et al. (2000) propose using non-organic nitrogen fertilizers to increase growth rates and carbon uptake. However, a study by Crutzen et al. (2008) has shown that nitrogen fertilizer is partially converted to nitrous oxide, whose greenhouse potential is 300 times greater than CO_2. The assumed amount of nitrogen fertilizer required ranges from 24kt/y (Rau et al., 2013) to 500kt/y (Dipple et al., 2021) for 1Gt CO_2/y stored and in a worst case scenario could create more CO_2e than the tree growth removed (NRC,

[6] For comparison, Germany has a total surface area of about 36 million hectares.

2015).
Finally, climate change itself is strongly affecting forest ecosystems. While increased levels of atmospheric CO_2 and warmer temperatures can increase tree growth, an increase in the frequency of droughts, wildfires, and other extreme weather events disturbs forest growth and negatively affects plant and animal life (EPA, 2015), making AFRF efforts more difficult. The verification of the effects of AFRF is also an issue. Although it is possible to measure forest growth using a land-based approach, the accuracy of such measurements can be limited, and the measuring capabilities can vary by country. (Watson et al., 2000).

Cost

The cost of AFRF is largely dependent on the cost of land, the terrain and the type of trees that are planted. According to Gorte (2009), the cost of reforestation after severe wildfires in the United States in 2002 ranged between 200 and 2000 US$/acre[7], and the average cost was 523 US$/acre in 2007. At a storage rate of 10t CO_2/ha/y, this suggests costs between 49 US$/ton CO_2 and 494 US$/ton CO_2, and an average of 129 US$/ton CO_2.
Other studies resulted in slightly lower cost estimates, with a lower limit of 1 US$/ton CO_2, a cost of 7.5 - 22 US$/ton CO_2 for sequestration of 1Gt CO_2/y, and half of the total sequestration potential being available below 55 US$/ton CO_2. However, it remains questionable whether these estimates adequately account for the possible risks of fires, pests, or other disturbances that could lead to the release of sequestered carbon (NRC, 2015, pp. 41–42).
Additional cost reductions could be achieved by using and systematizing agroforestry, an approach that integrates trees into crop pastures and comes with numerous co-benefits that can offset the cost of tree cultivation, and is useful especially in economically disadvantaged regions and dry climates (Reij, 2014).

2.2 Soil Sequestration

According to the 2000 IPCC report, soil cultivation can result in the release of more than half of the carbon stored in it into the atmosphere. The NRC (2015) estimates that in the last ten thousand years agricultural activities have caused a net release of up to 840 Gt of CO2. Despite this loss, soils are still an important carbon storage, containing up to 10% of the global carbon stocks.

[7] 1 acre = 0.405 hectares

Potential

Using a number of improved land management techniques, such as conservation tillage practices, planting cover crops, and optimizing crop types and fertilization practices, the loss from agricultural use can be partially reversed and the amount of organic matter in soils, more than half of which is typically stored not above ground, but in roots, dead leaves, and wood litter, can be increased (Ontl & Schulte, 2012; Watson et al., 2000, p. 192). This increased sequestration serves both economic and environmental purposes, as it increases the amount of carbon stored while potentially increasing crop yields and promoting soil health. (Dipple et al., 2021)
Improved-land management practices are well-understood techniques and have been in use in the United States since the 1950s and have since seen increased adoption in Asia and parts of South America (Watson et al., 2000, p. 202). Compared to forest-based carbon removal approaches, carbon sequestered in soils is less vulnerable to fires and other diseases, making soil sequestration a more reliable form of carbon storage (Dipple et al., 2021). The theoretical potential of soil sequestration for carbon storage is determined by the historical stock before the beginning of agricultural use, which caused much of the degradation of the ecosystem and the resulting loss of soil carbon (NAS, 2018). Dipple et al. (2021) estimate that soils are currently a net sink of CO_2, with an annual uptake of 1 - 2Gt CO_2, mostly caused by the increased CO_2 concentration in the atmosphere itself.[8] However, the use of optimized land management practices can significantly increase carbon uptake. Conservation tillage is one of the most effective techniques. It involves a reduction or complete elimination of tilling to prevent soil disturbance, while also leaving at least 30% of the residual crop biomass from agricultural use in the field. Originally developed to reduce soil erosion, studies found that by minimizing soil disturbance and maintaining crop residues, organic matter aeration and decomposition is reduced, leading to increased soil organic carbon (SOC) and prolonged carbon storage. Studies estimate that an average of 1.2t of CO_2 could be stored per hectare of farmland annually through conservation tillage in approximately 60% of the total arable land. With a total cropland area of approximately 1.5 billion hectares worldwide, conservation tillage has the potential to sequester a total of 0.33 to 4.3Gt CO_2/y[9] (NRC, 2015; Watson et al., 2000). Another promising method of soil carbon sequestration is the use of cover crops, which are planted between cash crop seasons to protect and improve soil quality. These crops provide continuous soil cover, thus reducing

[8] This effect is also referred to as "CO_2 fertilization".

[9] The 2000 IPCC report (p. 202) estimates carbon storage of 0.1 - 1.3t C/ha. Based on molecular mass, this is equal to 0.37 - 4.9t CO_2/ha; applying that to 60% of 1.5Gha worldwide yields these results.

erosion, promote biological activity in the soil and supply organic matter to the soil through roots and biomass, while increasing nitrogen content and serving as natural fertilizers (Dipple et al., 2021; Ontl & Schulte, 2012). In total, studies estimate that in feasible scenarios soils could sequester between 3.3Gt and 5.2Gt CO_2/y globally (Bossio et al., 2020; Dipple et al., 2021; NRC, 2015).

Limitations

The two biggest limitations facing soil sequestration through improved land management are the limited potential for carbon absorption per hectare of agricultural land and the need for permanent maintenance. Naturally, the amount of carbon that soil can absorb is limited. P. Smith (2016) estimates that soil saturation will occur after 10 to 100 years, depending on the type of soil and environmental conditions, and that it will be slower in colder climates. The 2000 IPCC report estimates that on average, sequestration reaches its highest annual potential within the first 5 to 20 years after adopting conservation tillage approaches and then declines to near-zero after 50 years. Consequently, if started globally today, soil sequestration would not be available as a sink for the second half of the 21st century. This problem is increased by the fact that, while uptake is limited, it is also easily reversible, meaning that a return to previous, standard land use and management techniques would release the carbon stored previously. This means that improved land management techniques will have to be used indefinitely and the costs that could be associated with them will have to be paid continuously. (P. Smith, 2016, p. 9). Therefore, the use of optimized land management techniques faces not only technical, but also socioeconomic problems (Dipple et al., 2021). Zelikova et al. (2020) argue that to increase the incentive for farmers to implement better land management, demonstration projects should be conducted and the support for farmers should increase.

Cost

Due to the wide range of different agricultural processes involved and the difficulty in measuring their exact costs, the economic feasibility of soil carbon sequestration techniques such as conservation tillage and cover cropping is difficult to quantify. Bossio et al. (2020) expects that half of the total soil sequestration potential is available below 100\$/t CO_2, while one-fourth is available below 10\$/t CO_2, based on the available marginal abatement cost curves. A study by McKinsey (2009) reaches a similar conclusion. However, these estimates include sequestration not only on agricultural land, but also in forests. Bossio et al. (2020) also note that, based on the co-benefits of improved soil health and reduced inputs, some soil sequestration can be cost-effective, i.e. have negative costs. Yet, Zoebisch et al. (2022) remark that these co-benefits can take some years to become effective, while the initial costs of implementing new practices can be high. Chambers et al. (2016) used the subsidies paid to farmers in the US for the adoption of such practices as a reference point and found costs to be between 3.44 - 11.34 US$/t CO_2 sequestered. However, this estimate is based on a small-scale study, only includes the sum paid to farmers by the government, and may not be representative of the costs associated with the broader implementation of these measures.

2.3 Summary of Biological Strategies

Overall, since biological carbon removal technologies are based on the usage and enhancement of natural processes that have occurred for millions of years, they are well understood and have a theoretically large carbon removal potential in the range of 5 - 10 Gt CO_2/y. Their implementation is very straightforward, and mostly an issue of deploying them on a large-enough scale. The biggest advantage of biological carbon removal is that most of the costs are incurred during the initial implementation, i.e. for planting trees and adapting to new land management processes, while the operating costs, under ideal circumstances, could be relatively low. However, there is relatively little experience with the dedicated application of these methods for carbon removal purposes. While studies generally point to the costs being below 100 US$/t CO_2, which would make biological strategies economically viable, the vast land requirements, the limited amount of carbon that biomass and soil can sequester, and the risk of natural disasters such as wildfires and pests impacting the permanence of carbon storage cast doubt on whether these strategies can be used for long-term, large-scale carbon removal operations.
Additionally, it should be noted that with an ever-increasing world population, the demand for food will continue to rise, thus potentially creating competition for land or forcing farmers to choose between using long-term, sustainable farming techniques (i.e. those that also allow enhanced carbon sequestration) and maximizing shorter-term yields.

Geochemical Strategies

3.1 Enhanced Mineralization

Carbon mineralization is a chemical process in which alkaline materials such as magnesium and calcium silicates react with water and carbon dioxide to produce stable and solid carbonates. Similarly to the aforementioned biological processes, it has occurred naturally for millennia, albeit at a very slow rate.

Potential

Mineralization strategies include enhanced weathering (EW), which involves the spread of finely ground alkaline minerals on large land surfaces to naturally react with atmospheric CO_2, in-situ processes, for which concentrated CO_2 streams are injected into geological formations containing appropriate minerals, and ex-situ processes, which involve the extraction and processing of alkaline materials to improve their reactivity with CO_2. All of these processes fixate carbon dioxide in stable carbonate minerals, which can be stored for hundreds or thousands of years and avoid the risk of leakage. Alkalinity sources are typically minerals such as peridotites and serpentinites, which are abundantly available (Lackner et al., 1997), and industrial by-products of high mineral content such as waste materials produced during resource extraction, construction and manufacturing, which are highly reactive and available at little cost (NRC, 2015). Since 38% of all global land areas are croplands or pastures, which are ideal for spreading rock dust (Almaraz et al., 2022), EW theoretically has a huge potential for carbon sequestration. Beerling et al. (2018) estimate that if two-thirds of the most productive cropland worldwide (a total area of 900 million hectares) were treated with rock dust at a rate of 20-30 t/ha/y, a sequestration potential of 0.5 - 4Gt CO_2/y could be achieved. They also argue that treating cropland with basalt has been shown to have significant co-benefits, including increased soil fertility and crop yields, and an increased amount of organic material in soils. Combined with the previously mentioned improved soil management techniques, this could make EW an attractive strategy from both a carbon removal and agricultural productivity perspective. Another study by Goll et al. (2021) proposes spreading a single dose of 5t of basalt dust per hectare on 5500 million hectares of unpopulated land, and based on a land surface model that uses experimental weathering data, estimates a sequestration potential of 2.5Gt CO_2/y over the next 50 years.

For ex-situ approaches, Lackner et al. (1997) propose an exothermic chemical process that uses a reactor vessel and concentrated CO_2 atmosphere to carbonize alkaline minerals under pressure without requiring large additional energy inputs. For in-situ processes, proof-of-concepts that inject carbon-rich liquid into underground basalt formations are currently underway, with one experimental plant in Iceland sequestering about 12Kt CO_2/y. In optimistic estimates, both of these processes could also sequester multiple gigatons of CO_2 per year if deployed on a large scale (Dipple et al., 2021).

Limitations

The primary issue of enhanced mineralization is that it requires a constant supply of fresh rock and large amounts of energy to mine, grind and transport rock dust. For EW, Schuiling and Krijgsman (2006) estimate that about 2 tons of olivine rock dust are required per tonne of CO_2 removed, based on a calculation of the amount of rock required per square meter to absorb all atmospheric CO_2, which was estimated at 5kg/m^2 of surface area.[10] If basalt is used, the amount of rock dust required is even greater, with Beerling et al. (2018) estimating that up 6.75t of basalt per tonne of CO_2 could be needed. On a global scale, this would require between 9 and up to 27 Gt of basalt to remove a maximum of 4Gt of CO_2 annually. The study by Goll et al. (2021) arrived at a more optimistic estimate of 5.5Gt of rock dust needed to remove 2.5Gt CO_2/y, albeit on unpopulated land.[11] Extracting, processing, and transporting such large amounts of rock dust would require significant energy and resource input, which would not only be costly, but also offset between 10 and 30% of the sequestered carbon. Large-scale mining operations also necessarily disrupt ecosystems and have negative ecological impacts (Beerling et al., 2018). Almaraz et al. (2022) note that there is little experience with the ecological impact of rock dust application, and warn that heavy metal contents in rock material could accumulate in the soil and then be introduced into the food chain.

The second issue is the land requirement: Due to relatively slow weathering, it could take years to decades to fully mineralize the rock dust. Weathering speed also heavily depends on environmental circumstances. Although acid rain with pH values around 4, which occurs, for example, in Europe and North America, can mineralize the proposed rock dust layer in 30 years, an increase in pH of just 0.3 units could double the required time (Schuiling & Krijgsman, 2006). This means that a large

[10]The full calculation is as follows: Schuiling et al. estimate that a rock dust layer of 0.4 cm would be required on all global land areas to remove the entire CO_2 content from the atmosphere. This equals 0.004m^3 of rock dust per m^2 of surface area, which at a density of about 2500kg/m^3 results in a requirement of 10kg of olivine dust.

[11]For comparison, about 8Gt of coal and 2.5Gt of iron ore are mined globally per year.

percentage of the total land area would have to be treated, and although rock dust application does not generally compete with other land uses such as agriculture and forestry, it would still be a significant logistical challenge (Dipple et al., 2021). Another issue is the question of how the mineral dust would be spread. For farmland application, small-scale experiments in Germany by the Carbon Drawdown Initiative (2022) have shown that the use of existing agricultural spreaders, such as manure spreaders or fertilizer spreaders, is the only method that can effectively and efficiently distribute rock dust, with the spread of 40t on one hectare of farmland taking a little more than 30 minutes. However, this process requires the use of larger-grained rock instead of superfine dust, which results in a less homogeneous rock layer and makes monitoring the results more difficult. On the other hand, the Goll proposal includes the use of spreader aircrafts for distribution, which would require significant resources and infrastructure to operate, further adding to implementation costs. Lastly, it should be considered that for ex-situ processes, the study by Lackner et al. (1997) admits that to accelerate mineralization to complete in hours instead of days, high-pressure and high-temperature reactors are required, which could result in significant energy requirements. Also, both in-situ and ex-situ reaction processes (excluding EW) strictly speaking are not carbon removal processes, but carbon storage processes, since they require the usage of pre-concentrated CO_2, e.g. from DAC or point sources in industrial plants.

Cost

The costs associated with the implementation of enhanced mineralization are somewhat difficult to calculate, considering the number of steps involved in the process, from mining to spreading (or mineralizing) the rock dust. While Almaraz et al. (2022) argue that EW can be economically viable for farmers due to the previously mentioned co-benefits, they do not provide specific numbers. These benefits also do not apply to other in-situ or ex-situ mineralization processes. Overall, the largest share of costs would come from the extraction, processing, and transportation of large amounts of rock dust. Studies by Beerling et al. (2018) and Fuss et al. (2018) provide wide-range estimates for EW, with a minimum of 50 US$/t and a maximum of 578 US$/t of CO_2 removed, mostly based on the cost to grind the basalt rock and transport the dust to its destination. The study by Goll et al. (2021) comes to a similar conclusion, stating that 0.2Gt CO_2/y should be available below 100 US$/t CO_2, and up to 2.5Gt/y below 500 US$/t CO_2, based on the logistics cost of application in uninhabited areas. The study by Lackner et al. (1997) estimates that raw materials costs will be between 40 and 100 US$/t CO_2 removed for ex-situ mineralization, and argue that they could be further reduced once large-scale production begins. However, this estimate does not include the costs of energy required or the cost of building and maintaining the infrastructure and industrial-scale processing plants required. If energy requirements were included, Lawler and Knops (2021) argue that costs could be as high as 600 US$/t CO_2 removed for ex-situ mineralization, but do not provide a detailed basis for this calculation. They also argue that ex-situ mineralization could be cost-effective, albeit at a limited scale, if the mineralization byproducts were sold to e.g. the paper industry as a replacement for lime. For in-situ mineralization, even less data is available. CarbFix, the company currently running one of the largest in-situ mineralization projects, estimated their costs to be around 25 US$/t CO_2 sequestered (Lawler & Knops, 2021). While this relatively low estimate is promising, it is important to note that it only accounts for the costs of carbon sequestration, while the costs for capturing it using e.g. DAC technology are not included.

3.2 Ocean Fertilization

During its growth, phytoplankton absorbs solved carbon dioxide from the surface ocean through photosynthesis. When it dies, it falls to the ocean floor, taking the CO_2 it absorbed with it. There, it is consumed by fish and other animals, which respire and convert organic carbon back into CO_2. This cycle is called the biological carbon pump (BCP). The idea of ocean fertilization is to stimulate phytoplankton growth and strengthen the BCP to sequester more carbon in the oceans.

Potential

In most oceans, the growth of phytoplankton is limited by the availability of nutrients such as iron, nitrogen and phosphorus. The first step of ocean fertilization (OF) is to supply these nutrients, either by adding the micronutrient iron (Ocean Iron Fertilization, OIF) or the macronutrients nitrate and phosphate (Ocean Macronutrient Fertilization, OMF) (NAS, 2022, p. 77). OIF was first popularized by John Martin ("Give me half a tanker of iron, and I will give you the next ice age.") and is proposed for regions where macronutrients are high, but phytoplankton content is low (i.e. iron where iron is the limiting factor). These high-nutrient, low-chlorophyll (HNLC) regions are found mainly in the Southern Ocean, the Equatorial Pacific, and parts of the North Atlantic. On the other hand, OMF would be applied to low-nutrient, low-chlorophyll (LNLC) regions (Chisholm et al., 2001). In the second step, stimulated phytoplankton growth takes up CO_2 from the surface ocean, converting it into organic matter through photosynthesis. Once this organic matter falls to the ocean floor, its carbon content are incorporated into sediment and

sequestered for hundreds of years or even millennia. (Fuss et al., 2018; S.F. Jones, 2014)
OIF has shown promising results in increasing phytoplankton growth and CO_2 uptake in HNLC. It is also favored due to the low ratio of iron required to sequestered carbon of approximately 1:1000 (NAS, 2022, p. 99). The study by Hauck et al. (2016) found that the global sequestration potential of OIF is 113Gt CO_2 per century based on an ecosystem model that includes nitrate, silicic acid and iron, but does not account for potential sea-air backflow of carbon. At an average rate of 1.1Gt CO_2/y, they require an input of 2.3Mt Fe/y into the oceans. They also proposed coupling OIF with EW, since the olivine minerals used in EW release iron that can be used for OIF. Keller et al. (2014) give a more optimistic estimate of up to 15Gt CO_2/y, based on a scenario in which the entire southern ocean would be continuously fertilized, but admit that this number would quickly decrease to a maximum 5Gt CO_2/y as the large reservoir of available macronutrients is used up. Overall, the NAS (2022, p. 87) found a realistic potential for OIF in HNLC regions of 1Gt CO_2/y.
For OMF, Harrison (2017) estimates a one-off potential of 3.6Gt CO_2, with about 0.7Gt CO_2/y afterwards if only nitrate is added. Their estimate is based on the quantity of phosphate (which would be the limiting factor) available in the oceans and the amount of nitrogen needed to "use up" that phosphate, combined with the expected efficiency in boosting phytoplankton growth. In a second scenario, they consider the addition of both nitrate and phosphate, increasing the annual potential to 1.5Gt CO_2, with only the amount of phosphate extracted being the limiting factor.

Limitations

OF is limited to specific regions of the oceans that present ideal conditions for fertilization (i.e. HNLC for OIF and LNLC for OMF). This largely limits OIF to the Southern Ocean that surrounds Antarctica. For OMF, viable oceanic regions are easier to access as large parts of the global oceans are LNLC, however, the amount of material (nitrate and phosphate) required is huge in comparison, based on the Redfield ratio[12] and calculations by S.F. Jones (2014) and Harrison (2017), and in addition to the required logistics it would represent a significant share of the total phosphate produced worldwide.
The biggest concern however is that only a small fraction of organic carbon is transferred to the deep ocean and buried. When phytoplankton dies and starts sinking

[12] The Redfield ratio of 106:16:1 describes the ratio of carbon to nitrogen to phosphorus (C:N:P) found in phytoplankton.

to the ground, most of it is consumed by zooplankton, microbes, and other animals within 100 meters of the photic zone. Their respiration releases carbon, which quickly returns to the surface ocean and eventually the atmosphere (NAS, 2022, pp. 82, 84). Zeebe (2005) estimates a sedimentation rate of only 10 - 25% based on ocean carbon cycle models. This means that of 1Gt CO_2 absorbed by phytoplankton, only 0.1 - 0.25Gt are incorporated into the bottom sediment while the rest are quickly returned to the surface. Furthermore, Harrison (2013) estimates that even under optimal conditions, only 8.3% are sequestered and stored for more than 100 years, the average being a mere 0.4%.

Other issues include (1) the fact that OF is a geoengineering technique with global implications and, as such, can negatively impact ocean food webs and alter biochemical cycles (Chisholm et al., 2001; Zeebe, 2005), (2) the potential for OIF to cause "nutrient robbing", which means that macronutrients are drawn from other areas of the ocean, reducing the amount of biomass growth there, and leading to limited additionality (Zeebe, 2005), and (3) the emission of N_2O (which is a potent greenhouse gas) caused by the use of nitrate fertilizer. All of these issues have the potential to severely limit the net carbon removal effect of OF and cause unintended consequences for the ocean ecosystem. Finally, measuring the effect of OF is difficult (NAS, 2022, p. 87). Although surface waters can be sampled for nutrients and phytoplankton growth and monitored using satellite imaging, measuring sequestration rates in the deep ocean is more challenging and requires highly advanced sensors and instruments (Chisholm et al., 2001; NAS, 2022).

Cost

Optimistic estimates for OIF claim costs as low as 2 US$/t CO_2 removed (Fuentes-George, 2017), however, these estimates are at least partially influenced by the commercial and marketing interests of the companies involved. A more realistic estimate by Harrison (2013), based on previous OIF experiments, includes the losses mentioned above and places the cost of OIF at 18 US$/t CO_2 in the best case, but admits that at the average long-term storage rate, they could be as high as 457 US$/t CO_2. For OMF, a detailed economic analysis by S.F. Jones (2014) concluded that if only nitrogen fertilization is required, costs could be as low as 20 US$/t CO_2 removed, including the cost to produce and transport nitrate. However, this study does not take into account the low long-term sequestration rate. All things considered, Gattuso et al. (2021) expects the average cost per ton of CO_2 sequestered to be 230 US$ across both approaches.

3.3 Summary of Geochemical Strategies

Geochemical CDR (gcCDR) strategies are based on the enhancement of natural geological carbon sinks on land and in the oceans on a global scale. Proponents of these strategies promise cheap large-scale carbon removal. Their greatest advantage is the safety and durability of storage as solid rock or sequestered in the ocean floor, which makes them less prone to leakage and requires less long-term care than the biological approaches discussed in Chapter 2. In combination, their sequestration potential could be between 5 and 10Gt CO2/y at proposed costs as low as 50US$/t CO_2 for EW and 20US$/t CO_2 for OF.
However, gcCDR strategies suffer from the global scale of deployment required to realize a significant impact, which presents logistical and environmental challenges. Enhanced weathering requires large-scale mining operations and large amounts of energy for processing and transportation, which is counterintuitive to climate protection and would probably face opposition due to the impact on local ecosystems and communities. Also, as Goll et al. (2021) conclude, it would only be viable if sufficient renewable energy was available to maintain carbon neutrality of the supply chain. Ocean fertilization is highly dependent on uncontrollable factors such as ocean currents and ecosystem response and suffers from uncertain effectiveness for long-term sequestration and potential nutrient robbing. Therefore, more research is needed on the real durability and additionality depending on the specific conditions of the ocean. From an economic perspective, the existing estimates for both approaches are highly uncertain and vary widely. They are mostly based on small-scale experiments and ecosystem models, making it difficult to accurately predict the cost and efficacy of large-scale implementation. The necessary mining and transportation also mean that the ongoing operating costs would be significantly higher compared to biological approaches. In a worst-case situation, if required investments and potential negative impacts are included, the cost per ton of CO_2 could exceed 400US$. Lastly, the global scale of these approaches, especially OF, requires international cooperation and a framework that governs who can deploy them in which locations and ensures proper accountability for the potential long-term consequences.

Chemical Strategies

4.1 Direct Air Capture

In contrast to biological and geochemical approaches, which are based on enhancing natural processes, Direct Air Capture (DAC) is a novel approach to carbon dioxide removal that utilizes engineered chemical reactions to remove CO_2 directly from the ambient air. DAC uses a filtration system to capture CO_2 molecules and generate a concentrated stream of CO_2 for sequestration or industrial use as a commodity. This process can use liquid solvents, such as calcium hydroxide (LDAC) or solid sorbents, such as amines (SDAC). The solvent or sorbent is then regenerated using heat to release captured CO_2 in concentrated form for further processing or storage (Gorman et al., 2021; Mulligan et al., 2020).

Potential

The main advantage of DAC over the approaches discussed above is that it does not require large amounts of land or continuous supplies of reactive material (IEA, 2022; Mulligan et al., 2020). Generally speaking, LDAC is more suitable for continuous operations in large-scale industrial settings, and the proposed facilities are comparable in size to power plants. SDAC is more suitable for smaller-scale batch applications due to its modular nature and the need to remove sorbents for regeneration (IEA, 2022, pp. 22–23). The efficiency and amount of (IEA, 2022; Mulligan et al., 2020) removed through DAC is easy to measure and quantify, as it produces a highly concentrated stream of CO_2. The global potential of DAC as a CDR technology is significant, as it is limited only by the available funding to construct and maintain the facilities. The IEA (2022) expects an initially slow scale-up, with only 85Mt/y in CO_2 removal capacity deployed by 2030, but a significant increase in pace throughout the next decades. By 2050, most studies believe that 1-2 Gt/y could be in operation, and by 2100, DAC could account for 10-15 Gt/y (IEA, 2022; Mulligan et al., 2020), providing a substantial portion of the total required annual negative CO_2 emissions. The highest hypothetical calculations even assume that up to 40Gt/y are possible (Fuss et al., 2018). Due to its independence from any space or material requirement, DAC is inherently flexible and can be placed anywhere, making it suitable for various industrial or geographical contexts. For example, DAC plants could be placed close to the cheapest available energy sources, leading to reduced energy costs and increased economic viability. Other proposals include the conversion of old industrial plants, such as refineries, into DAC facilities to use the existing energy and pipeline infrastructure. In cities, skyscrapers could be fitted with DAC technology due to their large surface area and the potential to realize co-benefits by, for example, using filters to also remove air pollution or capture water from the air (Lawler et al., 2022). Some studies also argue that CO_2 captured by DAC can be provided at any desired concentration and could be used in various commercial applications, such as carbonation of beverages and enhanced oil recovery. However, the commercial potential is limited, and the use of CO_2 removed from the atmosphere to extract more oil would ultimately be counterproductive in terms of mitigating climate change (Erans et al., 2022).

Limitations

DAC is currently deployed only on a very small scale. In total, 18 facilities of varying sizes and capacities from 1t/y to 4kt/y are in operation globally, with a total capacity of 8kt/yr (IEA, 2022, p. 18). The largest single plant is the "Orca" facility run by the Swiss company Climeworks in Iceland, which removes 4kt/y of CO_2 from the air using a combination of renewable energy and solid sorbent technology. This means that the feasibility and potential problems of large-scale deployment are not yet fully understood. Despite the promising potential of DAC as a CDR approach, there are several limitations to its implementation. The root cause of these limitations lies in the low concentration of CO_2 in the ambient air, compared to point sources such as fossil fuel power plants, which makes capturing CO_2 more difficult and requires highly binding solvents or sorbents. In turn, regenerating liquid solvents requires extremely high temperatures of around 900°C (IEA, 2022, p. 23). Solid sorbents require less heat or can even be regenerated by vacuum or pressure swing adsorption, but often have lower capture efficiencies than liquid solvents (NAS, 2018, p. 192). LDAC requires approximately as much energy to remove 1t CO_2 as was made usable when 1t CO_2 was released during the burning of fossil fuels. SDAC is less energy intensive, but still requires a considerable amount of energy (Linow et al., 2022). For both technologies, the largest fraction of the required energy is the heat required to regenerate the solvent or sorbent, while most of the remainder is used to operate the fans that pump ambient air through the contactors (NAS, 2018, p. 203). Based on the study by House et al. (2007), between 3181 and 5226 kWh of electricity is required to capture one ton of CO_2[13]. More recent reports by NAS (2018) and Mulligan et al. (2020) conclude that about 5 to 10 GJ of energy is required per ton of CO_2, which converts to a more optimistic 1389 to 2778 kWh of electricity.

[13]House assumes that 500 - 800kJ are required for 1 mol of CO_2. The result is calculated based on a molar mass of CO_2 of 44.01g and 3600KJ being equal to 1kWh

However, these results assume that only renewable electricity is used to power the DAC process. However, most of the heat demand is currently met using natural gas, resulting in an efficiency penalty of around 30% due to emissions caused by gas combustion (Fuss et al., 2018). If coal is used to power the process, DAC would be completely unviable, since the burned coal releases more CO_2 than is captured (Erans et al., 2022; NRC, 2015).

The large amount of renewable energy required raises the question of land requirements. For DAC facilities, the NAS (2018) report estimates that about 38000m^2 of contactor surface area is required to absorb 1Mt CO_2/y. Using the contactor design proposed by Holmes and Keith (2012), 10 contactors of size 20x8x200m would be sufficient, with a total land area needed of 0.4 to 1.7km^2 (IEA, 2022, p. 23). This is only a fraction of the land used by e.g. AFRF or the mining operations required for EW. However, to remove 1Gt CO_2/y, about 1.4TWh of electricity is required, compared to the 1Twh of renewable energy produced in the US in 2022. At an average production of 174kWh/y/m2 of solar PV (footnote about location here), this implies a need of 8000km^2 of solar PV to satisfy the entire energy requirements of a 1Gt/y operation. Furthermore, a recent study by An et al. (2022) revealed that environmental conditions can impact the efficiency of DAC more than previously expected. They observed that capture rates in hot, humid climates can be increased by a factor of 2 compared to dry and cold climates. Other issues that must be considered are the rapid degradation of the sorbent material used for SDAC Lawler et al. (2022) the significant water requirement of LDAC of approximately 5t/t CO_2 IEA (2022) and the somewhat counterintuitive side effect of local CO_2 depletion, which can lead to lower photosynthesis rates in the direct vicinity of DAC plants (NAS, 2018, p. 230).

Cost

DAC generally requires high investment in building capture facilities and significant ongoing expenditures to cover the energy requirements for capture and regeneration. For the cost of CO_2 removal, the literature gives a wide range of estimates from 100 to 1000 US$/t. The upper end is based on thermodynamic considerations, while the lower end is proposed by authors closer to industry (Ishimoto et al., 2017; NRC, 2015). For LDAC, Carbon Engineering, the first company to commercialize this technology, estimates costs between 168 and 232 US$/t for their plant currently under construction in Texas (McQueen et al., 2021). For SDAC, Climeworks estimates that their current costs are around 600 US$/t (NAS, 2018, p. 220). In the long term, many studies expect costs to fall in the range of 100 - 300 US$/t based on assumed learning effects during the ongoing deployment (McQueen et al., 2021;

Mulligan et al., 2020; NAS, 2018). Lackner and Azarabadi (2021) argue that DAC, especially SDAC, is in principle similar to solar PV in that it is a modular technology manufactured in small units. McQueen et al. (2021) believe that learning rates of 10 - 20% are realistic. Based on an initial facility of 1Mt/y capacity for 600 US$/t and a learning rate of 20%, the 100$/t mark could be reached after the deployment of 260Mt, requiring a total investment of 37.5B US$. At a 30% learning rate, this would decrease to 33Mt and 5.5B US$.[14] Further cost reduction could also be achieved by developing improved solvents or sorbents with higher useful life and optimizing the materials used for contactors. Overall, the NAS (2018) estimates costs between 89 and 877 US$/t.

4.2 Bioenergy with Carbon Capture and Storage

Bioenergy with Carbon Capture and Storage (BECCS) is a CDR strategy that combines bioenergy production with carbon capture and storage (CCS). The concept involves growing biomass such as crops or trees and using it to generate energy through combustion or other conversion methods while capturing the resulting CO_2 emissions. The captured CO_2 is then transported and stored typically in geological formations, resulting in a net-negative effect.

Potential

Due to the concentration of CO_2 emissions when using biomass as a feedstock, capturing CO_2 using CCS is easier compared to capturing it from the ambient air using DAC. BECCS can use several different conversion processes such as combustion, biochemical, or thermochemical conversion, depending on the feedstock used. Feedstock can consist of biomass from agricultural waste or municipal solid waste (MSW), forestry, or purpose-grown energy crops (Dipple et al., 2021). Depending on the combination of feedstock and conversion process, the total potential and efficiency can vary greatly, with the literature giving estimates ranging from 1 to 85 gigatons of CO_2 removal per year (IPCC, 2018, p. 342). Based on a model that includes conversion efficiency, energy penalties and CO_2 capture rates, GGarcía-Freites et al. (2021) estimate that 1.1t CO_2 can be captured per MWh of energy produced with BECCS, which suggests a total global capacity of 790Mt CO_2/y if all current bioenergy electricity generation was converted to BECCS.[15] In the long term, Fuss et al. (2018) estimate that 0.5 - 5Gt CO_2/y could be sequestered using

[14]For a detailed discussion of learning effects, see appendix A.

[15]The IEA estimated a global bioenergy electricity generation of 718TWh in 2020 (https://www.iea.org/reports/bioenergy-power-generation)

BECCS by 2050, with the lower end using waste biomass only and the upper end requiring vast amounts of dedicated energy crops. Pour et al. (2018) estimate that looking at the growing amount of organic municipal waste, BECCS could remove 2.8Gt CO_2/y from MSW alone by 2100. Hanssen et al. (2020) argue that theoretically, 40Gt CO_2/y are possible by 2100, but concede that this estimate relies on an unrealistic assumption of land availability. The IPCC 2018 report projects a realistic range of 3 - 11Gt CO_2/y in the long term. In addition, BECCS has the potential to produce excess energy that can be used for other purposes Fajardy and Mac Dowell (2017), such as cross-deployment with DAC, or displacing some fossil fuels. However, the main motivation for BECCS is generally the CDR aspect, not electricity generation Klein et al. (2014).

Limitations

The greatest limitation of BECCS is, similar to AFRF, the vast land required for growing the necessary biomass feedstock. The IPCC (2018) estimates that to sequester 1t CO_2/y, between 0.03 and 0.5ha of land are required. This means that for sequestering 1Gt CO_2/y, up to 500Mha of land would be required, which is a significant portion of the world's total arable land.[16] At this scale, BECCS would compete with food crops for land, which poses significant ethical concerns regarding the potential impacts on global food security, since rural communities and people in the poorest countries of the world are often impacted the most by increased food prices. (Anderson, 2017; Hanssen et al., 2020).[17] BECCS also favors the use of fast-growing monoculture plantations of energy crops such as switchgrass or miscanthus (Fajardy & Mac Dowell, 2017). This decreases the land requirement but leads to a loss of biodiversity, disrupts local ecosystems, and can increase the risk of pest and disease outbreaks. Competition for land also puts the additionality of BECCS into question. If vast amounts of agricultural land are used to grow energy crops, increased deforestation and land-use change might be necessary to compensate for the decreased land available for food production. This, in turn, would cause the release of more CO_2 from soils, and offset at least parts of the sequestration effects of BECCS (Chatham House, 2020; Muratori et al., 2016). It also means that BECCS is in direct competition with other CDR approaches such as AFRF and soil sequestration. Furthermore, depending on the regions used to grow en-

[16]The total global cropland area amounts to about 1.5Bha (Source: https://www.worldometers.info/food-agriculture/cropland-by-country/)

[17]However, Muratori et al. (2016) note that if bioenergy alone was used to replace fossil fuels without using CCS, the negative impact would be even higher, because the use of BECCS reduces carbon prices, which allows the higher continued use of fossil fuels, leading to less demand for biomass and therefor also less competition for land and less upward pressure on food prices.

ergy crops, other side-effects such as a decreased surface albedo rate could reduce the net effect of BECCS (Hanssen et al., 2020). Growing vast quantities of energy crops also requires high inputs of fertilizers, which are associated with significant GHG emissions, and fresh water. Fajardy and Mac Dowell (2017) estimate that to sequester 3.3Gt CO_2/y, at least 3.6 billion m^3 of water and 21Mt of fertilizers would be required, which would release large amounts of N_2O.[18] They also note that emissions along the supply chain can be significant, for example if large amounts of biomass had to be transported from agricultural lands to the location of power plants. Using biofuels for transport vehicles and renewable electricity for processing plants would thus be necessary to reach the maximum potential of BECCS. If BECCS was to only utilize waste biomass, most of these negative effects could be avoided or significantly decreased, however, the amount of CO_2 removed would also be limited to about 1Gt/y at present, and 2.8Gt/y by 2100, based on the amount of waste available (Pour et al., 2018).

Cost

For the cost per ton of CO_2 removed using BECCS, the literature provides a range of estimates from 50 to 250 US$, based on different levels of efficiency and the revenue generated from excess electricity produced. Overall, most estimates are below 200 US$ (IPCC, 2018, p. 343). Fuss et al. (2018) estimate a more narrow range of 100 to 200 US$ and argue that the lower-end estimates generally assume an optimal conversion efficiency and abundantly available biomass. Langholtz et al. (2020) focused on the United States only and concluded that the realistic range should be between 42 and 137 US$ based on a scenario analysis that includes different biomass supply, logistics, and power generation approaches.

4.3 Summary of Chemical Strategies

[18] The negative impacts of reduced surface albedo and increased fertilizer use were discussed in the chapter on AFRF.

Conclusion

Technology	Afforestation / Reforestation	Soil Sequestration	Enhanced Mineralization
Potential	1.2 - 10 (Avg.: 5.8)	1.2 - 3.57 (Avg.: 2.4)	2.5 - 10 (Avg.: 4.9)
Cost (USD/t CO2)	1 - 494 (Avg.: 97)	10 - 100 (Avg.: 45)	24 - 600 (Avg.: 225)
CAPEX	Low - Medium	Medium	Medium - High
OPEX	Low	Low	High
Cost drivers	Land required, management cost	Cost of adapting to new land management techniques	Construction of infra-structure,processing and transportation
Resource requirements	Land, water	None (doesn't prevent land use)	Rock, energy
Durability	Medium	Medium	Highest
Risks to durability	Fires, pests	None, but requires continuous and permanent usage	None
Additionality	Medium, converting farmland back into forests may result in forest removal in other locations	High	High
Co-Benefits	Can be used with agroforestry	Improved soil quality, reduced land erosion	Can improve soil fertility, reduce ocean acidity
Negative side effects	Possible competition for land	none	Possible release of toxic metals to the food chain
Verification	Somewhat difficult, but possible based on forest area	Difficult, land-based	Difficult, land-based

Technology	Ocean Fertilization	DAC	BECCS
Potential	0.3 - 5 (Avg.: 2)	1.2 - 15 (Avg.: 5.8)	0.3 - 12 (Avg.: 5.85)
Cost (USD/t CO2)	20 - 457 (Avg.: 115)	60 - 1000 (Avg.: 352)[a]	42 - 300 (Avg.: 147)[a]
CAPEX	Low - Medium	High	Medium - High
OPEX	Medium	High	Medium
Cost drivers	Cost of mining and spreading nutrients	Construction of facilities, energy requirements	Land required, fertilization, processing, construction of bioenergy plants
Resource requirements	Rock	Vast amounts of energy	Land, water, fertilizer
Durability	Questionable	Depends on storage approach	Depends on storage approach
Risks to durability	None if sequesterd on ocean floor, but most CO2 captured is respired back to surface quickly	-	-
Additionality	Questionable, due to possible nutrient robbing	Highest	Medium, possibly high competition for land
Co-Benefits	Phytoplankton can increase oxygen content of oceans	Can be used to clear air from pollution or draw water from the ambient air	Electricity production, displacement of fossil fuels
Negative side effects	Nutrient robbing, acidification of deep ocean	CO2 depletion of local ecosystems	Risk of disease for mono-cultures, threat for food security
Verification	Very difficult, requires measuring of carbon content of deep ocean	Simple	Simple

[a] The cost for DAC and BECCS does not include the cost of storage or sequestration, which is considered to be around 20 US$/t.

Appendix A

Learning effects of DAC

Learning effects (sometimes called "learning-by-doing") refer to the phenomenon that individuals or organizations become more efficient or effective at a task over time as they gain experience and knowledge, which can result in significant cost decreases. This effect was first described by Wright (1936) in the manufacture of aircraft. He observed that with each doubling of the quantity of aircraft produced, the cost per unit dropped to about 80% of the previous cost. Since then, learning effects have been observed in a number of manufacturing processes, most prominently in the manufacturing of solar photovoltaic modules. Between 2010 and 2020, the cost of solar PV decreased by a factor of five, from approximately 4700 USD/kW to below 900 USD/kW, while the installed capacity increased from 222GW to 1448GW globally. Similar effects, although not of the same magnitude, were observed for wind turbines (Shrestha, 2022). Mathematically, the experience curve that represents the relationship between the increase in quantity and the reduction in costs is described by

$$cost_{new} = cost_{old} * \left(\frac{quantity_{new}}{quantity_{old}} \right)^{-b} \tag{A.1}$$

where b is defined as

$$-b = \frac{\log PR}{\log 2} \tag{A.2}$$

with PR being the progression ration, that is, the percentage of the original cost remaining after doubling the quantity (Fasihi et al., 2019).

The literature expects similar learning effects to occur for DAC, based on the similarity of DAC module manufacturing and solar PV module manufacturing. The graph below illustrates possible price decreases, starting with a cost of 600 US$/t CO_2 for an initial 1Mt/y DAC plant. If a 20% learning rate, that is, an 80% progress ration, can be achieved, the cost of DAC would decrease to below 100 US$ after the deployment of 260Mt/y. If an even higher learning rate of 30%, similar to solar PV, is assumed, this point would be reached at only 33Mt/y. Using the integral of the experience curve, the necessary investment can be calculated. For a 20% learning curve, an investment of 37.5B US$ is required to deploy 260Mt/y, while for a 30% learning curve, an investment of 5.5B US$ would be sufficient to deploy 33Mt/y.

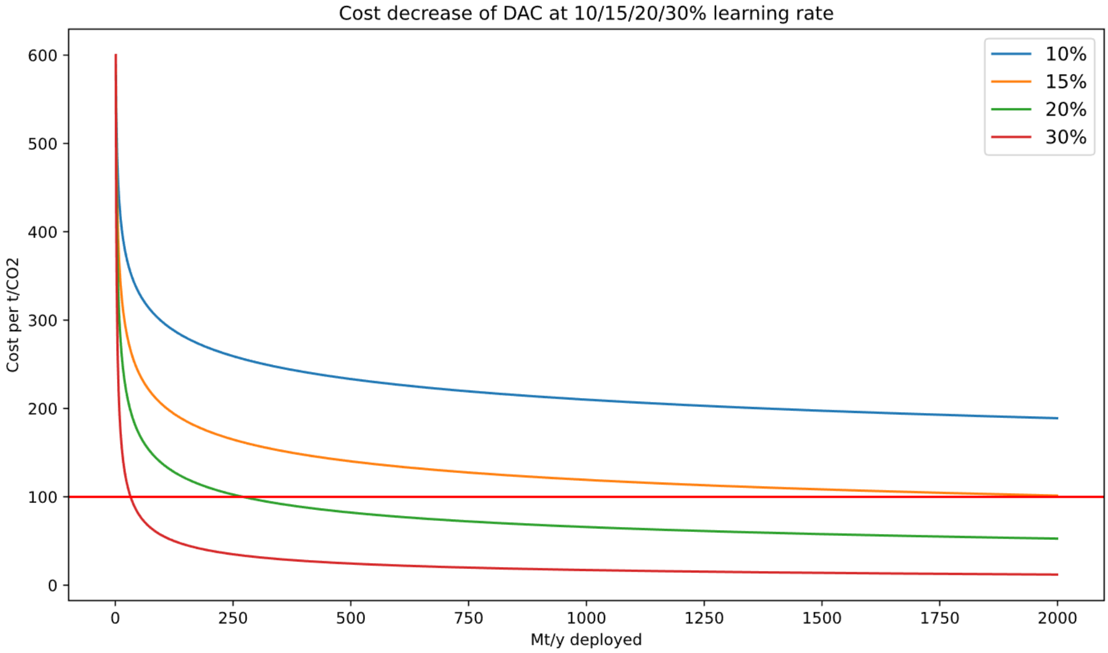

Figure A.1: The colored curves show the possible price decreases at different learning rates. The red horizontal line represents the 100 US$/t threshold that must be reached to make DAC economically viable.

From this figure it can be concluded that the learning rate will have a significant impact on the future of DAC technology. If a high learning rate is realized, DAC will become relatively cheap rather quickly as commercial deployment progresses. However, if only a low learning rate is observed, DAC may stay prohibitively expensive for the foreseeable future.

Appendix B

Overview of potential and cost estimates

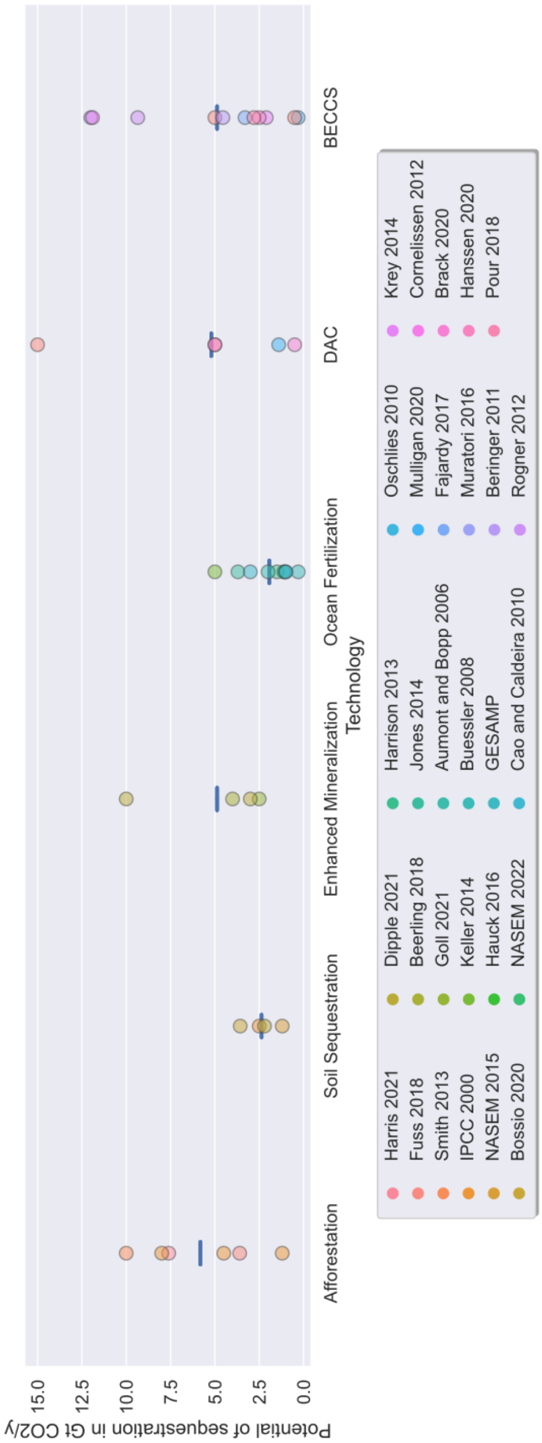

Figure B.1: Overview of the potential of CDR approaches mentioned in literature. The blue lines represent the average values.

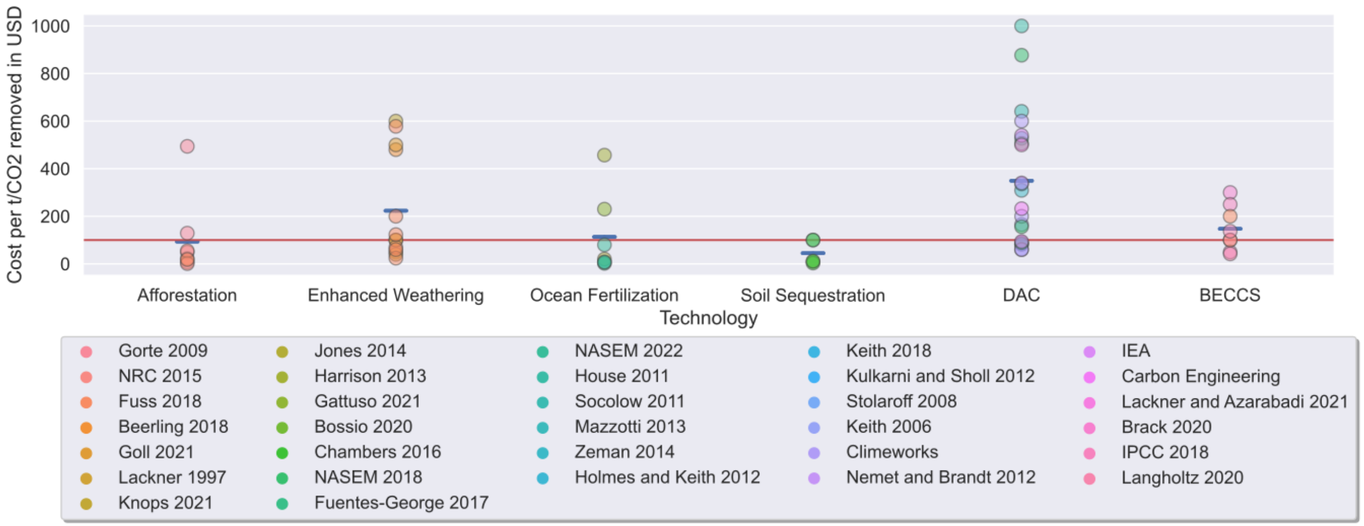

Figure B.2: Overview of the cost of CDR approaches mentioned in literature. The blue lines represent the average values. The red line represents the 100 US$ threshold.

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