Carbon Dioxide Removal (CDR) Technologies

An overview of the different methods for capturing and storing carbon dioxide from the atmosphere

April 2025

Carbon dioxide removals (CDR) are one of several necessary levers to achieve net-zero CO_2 emissions from air transport. This report looks at the most common CDR technologies currently deployed, their relative costs, technological readiness, and associated co-benefits and risks.

FACTS

Executive Summary

For air transport to reach net zero CO_2 emissions by 2050, market-based measures (MBMs) such as carbon dioxide removals (CDR) will be key to address any leftover CO_2 emissions, as emission reductions from in-sector solutions like sustainable aviation fuel (SAF) are not expected to be able to address all of the CO_2 emissions from the air transport sector in 2050. MBMs such as CDR will be necessary to address these CO_2 emissions, and while these emissions do not need to be addressed until 2050, it's important to start thinking about how to scale up nascent markets like CDR from the present day. CDR is defined by the International Panel on Climate Change (IPCC) as a cluster of technologies, practices, and approaches that remove and sequester carbon dioxide from the atmosphere and durably store the carbon in geological, terrestrial, or ocean reservoirs.

CDR technologies can be divided into conventional and novel CDR technologies, referring respectively to whether a CDR technology is already mass commercially deployed or whether there is still further work to be done in research, demonstration, pilot testing or commercial deployment. CDR technologies can be branched into various categories: technological, biological, and ocean-based CDR, depending on the mechanisms of CO_2 capture and storage, and each CDR technology can belong to more than one category. Considerations for CDR technologies can include its techno-economic aspects like technological readiness level (TRL) and costs as well as co-benefits and risks of each technology beyond its CO_2 removal potential.

In general, the techno-economic considerations will play a big role in determining the viability of these technologies in the short to long term. Co-benefits and risks play a big role in determining whether there are other gains to using CDR other than the CO_2 removal that it achieves. Ultimately, all CDR technologies will be key pieces to achieve net zero CO_2 emissions in the air transport sector in 2050, and continued investment into technologies that are developed today and those that will be developed in the future are essential for the growth of this industry. The key findings of the CDR technologies based on the assessed criteria of TRL, cost, co-benefits, and risks, as well as what is required for these technologies to grow and develop are summarized:

- Nature-based conventional CDR solutions such as AR and SCS have the lowest costs and highest TRL among all CDR solutions. They also have high co-benefits, but much higher risks, particularly having relatively lower durability of CO_2 storage compared to other CDR methods.
- Nature-based novel CDR solutions, such as biochar have relatively moderate costs and high TRLs, and offer greater certainty compared to conventional nature-based solutions. Mixed nature-based and technological solutions such as BECCS also benefit from relatively moderate costs, high TRL, and moderate risk.
- Novel CDR solutions such as ERW require somewhat longer investment horizons as technologies mature and important risk considerations, including MRV, need to be resolved.
- DACCS, also a novel technological solution, has high costs even at technological maturity. Investors must be interested in the longer-term potential and willing to enable economies of scale to progressively deliver commercial availability. Further funding for research into less technologically developed DACCS approaches, including humidity swing and cryogenic separation, would be welcome.
- Other novel CDR approaches mainly include ocean-based CDR approaches, which are mostly on the lower end of the TRL scale and are costly, with the exception of CBC. The priority for these technologies should be to gain public and private funding and support to lift technological readiness and commercial viability and address the need for robust MRV frameworks to quantify carbon flux between the ocean and the atmosphere.

1. Introduction

1.1. Definition and history of CDR

According to the IPCC, carbon dioxide removals (CDR) refer to a cluster of technologies, practices, and approaches that remove and sequester carbon dioxide from the atmosphere and durably store the carbon in geological, terrestrial or ocean reservoirs, or in products.[1]

Net emissions accounting, or methods to track and account for greenhouse gas emissions and removals, was first introduced in the United Nations Framework Convention on Climate Change (UNFCCC) in the 1990s, mainly by industrialized States with an interest in forestry. Carbon sinks were eventually included in the Kyoto Protocol[2], enabling the utilization of human-induced emission reduction or removal activities related to land use, land-use change, and forestry (LULUCF)[3] to meet State's decarbonization commitments under the Protocol.[4] There was much scientific and political debate regarding the significant uncertainties of carbon uptake via LULUCF activities, including risks of CO_2 leakage and assigning baselines to calculate carbon uptake via these activities. This eventually paved the way for more research and thought to be put into the permanence of CO_2 sequestration in biological carbon sinks and how to address anthropogenic i.e. fossil-origin CO_2 emissions. More novel technologies such as direct air capture (DAC), bioenergy with carbon capture and storage (BECCS), enhanced rock weathering (ERW), ocean fertilization, etc., emerged which aimed to address some of the challenges posed by the initial LULUCF-based activities. These novel technologies, together with the conventional LULUCF-based CO_2 removal methods, have come to be known as CDR.[4]

CDR is expected to play a major role in decarbonizing the air transport industry, with an estimated 500 million tonnes (Mt) of residual CO_2 emissions to be compensated for via CDR and other market-based measures in 2050, according to the IATA Net Zero Roadmaps.[5] CDR is still a nascent industry. The supply of CDR today is far below the demand of the airline industry and all other sectors of the economy. Before discussing how CDR can be scaled-up, it is important to understand how CDR technologies work, what the high-level techno-economic characteristics are, as well as the associated potential risks and co-benefits beyond the CO_2 removal potential.

This paper provides insight into the techno-economics characteristics and co-benefits/risks outside of CO_2 removal regarding some of the key CDR technologies present in the market today, as well as technologies that are expected to play a bigger role in the medium to long term, and technologies that are still developing but that have a high potential to remove CO_2 in the longer term.

1.2. Scope

The technologies presented in this paper can be divided into two main categories, novel and conventional. Novel CDR refers to technologies that have not yet undergone commercial deployment while conventional CDR refers to methods and technologies that have high technological readiness levels and commercial deployment today. These latter technologies can be sub-categorized into nature-based, technological and ocean-based CDR.

Biological-based CDR refer to CDR methods and technologies that use biological carbon sinks for CO_2 sequestration, utilizing or enhancing natural sequestration processes. Technological CDR refers to CDR

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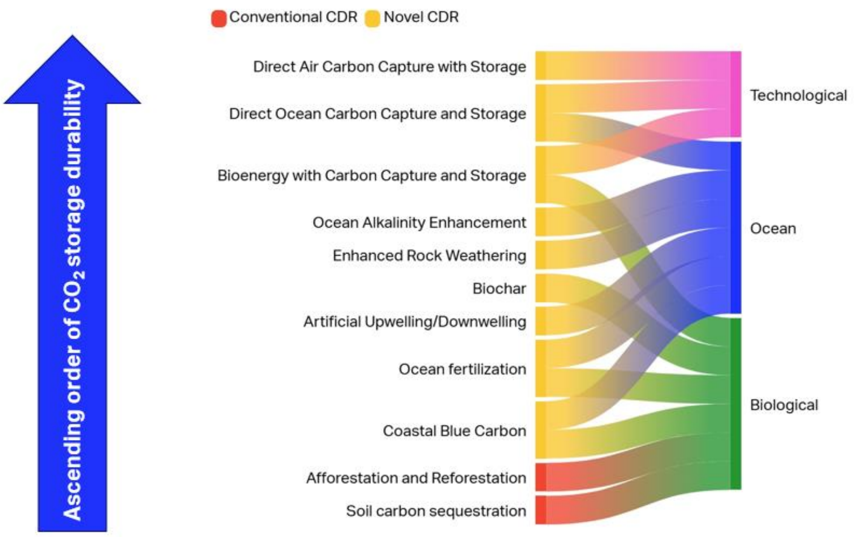
[1] **IPCC (2022). *Climate Change 2022: Mitigation of Climate Change*. [online] IPCC. Available at: https://www.ipcc.ch/report/ar6/wg3/.**
[2] **The Kyoto Protocol operationalizes the UNFCCC by committing industrialized countries and economies to limit and reduce GHG gas emissions in accordance with agreed individual targets.**
[3] **Under the Kyoto Protocol, Parties reported CO_2 and other greenhouse gas emissions and removals from land-use, land-use change and forestry, or LULUCF, activities such as afforestation, reforestation, deforestation, forest management and cropland management.**
[4] **Carton, W., Asiyanbi, A., Beck, S., Buck, H.J. and Lund, J.F. (2020). Negative emissions and the long history of carbon removal. *WIREs Climate Change*, 11(6). DOI: https://doi.org/10.1002/wcc.671.**
[5] **IATA (2024). *Net Zero Roadmaps*. [online] Iata.org. Available at: https://www.iata.org/en/programs/sustainability/roadmaps/.**

methods and technologies that capture and store CO_2 from the atmosphere via human-engineered technologies. Ocean-based CDR is a suite of methods and technologies which utilize and enhance ocean carbon sinks to capture and store CO_2 from the atmosphere.

The technologies discussed in this document can also belong to more than one sub-category. There are a total of 11 technologies discussed in this paper, chosen on the basis of high market activity currently and high-potential technologies that can generate more market activity in the future. However, this is not an exhaustive list, as other CDR technologies exist in the current market, and novel ones will emerge in the future (Chart 1).

Chart 1: Categorization of CDR technologies



This document aims to provide an overview of how major CDR technologies function, their techno-economic capabilities at present, as well as the associated co-benefits beyond the direct benefit from removing CO_2 from the atmosphere. Risk factors are also discussed regarding the use and implementation of CDR technologies.

2. Methodology

The methodology used in this paper assesses technologies based on two broad criteria:

1) Techno-economic: This assesses the **technological readiness level (TRL)** of the technology and the **relative cost** of the technology. TRL is measured on a scale of TRL 1 to 9, and the relative cost is divided into low, moderate, and high, typically using US dollars (USD) per tonne of CO_2 captured as the main cost metric. The assessment can guide investors with respect to their wish to focus on short-term technologies, technologies which have high potential in the long-term but might be costly in the short-term, and technologies which are not currently viable and likely costly in the short-term, but that are expected to have high potential in the long-term.

2) Co-benefits and risks: This evaluates the **relative co-benefits and risks** associated with a CDR technology beyond its capability to capture and store CO_2. The potential co-benefits and risks of the technology with respect to the broader economy, society, and the environment beyond the direct climate impact of CO_2 sequestration, are assessed. Both relative co-benefits and risks are categorized on a low, moderate, and high scale. The full methodology can be found in Appendix 1, and a summary of key takeaways in Section 5.

3. CDR technologies with active market participation

Some of the most significant transactions in CDR credits in the market are mainly voluntary purchases from the voluntary carbon market (VCM), that involve both conventional and novel CDR credits. This includes afforestation and reforestation (AR), soil carbon sequestration (SCS), direct air carbon capture and storage (DACCS), bioenergy with carbon capture and storage (BECCS), enhanced rock weathering (ERW), and biochar (Table 1).

Table 1: Summary of CDR technologies with the highest transactions in the Voluntary Carbon Market (VCM)

Technology	TRL	Cost	Type of storage	Durability in years[1]	Co-benefits	Risks
AR	8-9	Low to moderate	Soil and vegetation	10s to 100s	High	High
SCS	8-9	Low	Soil and vegetation	10s to 100s	High	High
Biochar	8-9	Moderate	Soil and vegetation	100s to 1000s	High	Moderate
BECCS	9	Moderate	Geological storage	10,000 +	Low	Moderate
DACCS	2-8	High	Geological storage	10,000 +	Low	Moderate
ERW	4-6	Moderate	Dissolved minerals in water bodies	10,000 +	Moderate	Moderate

Note: SCS= Soil Carbon Sequestration, AR= Afforestation and Reforestation, DACCS = Direct Air Carbon Capture and Storage, BECCS = Bioenergy with Carbon Capture and Storage, ERW= Enhanced Rock Weathering

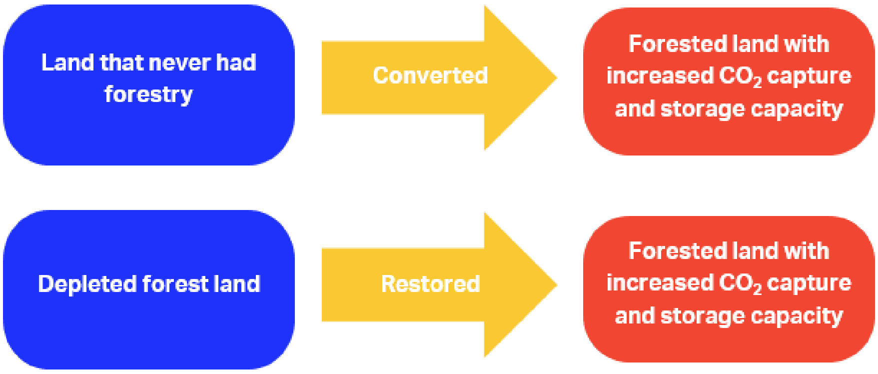
3.1. Conventional CDR technologies

3.1.1. Afforestation and Reforestation (AR)

AR are methods that allow the growth of new forests in historically unforested land or the regrowing of forests in areas that were previously forested through human intervention. Forests act as natural biogenic sinks for CO_2 sequestration from the atmosphere through photosynthesis. Increasing the forested land area will allow more CO_2 to be sequestered from the atmosphere.[6]

[6] Chan, L. (2024). ***Industry Report / Catalyzing Carbon Dioxide Removal at Scale***. **[online] B.C. Centre for Innovation and Clean Energy. Available at: https://cice.ca/knowledge-hub/catalyzing-carbon-dioxide-removal-at-scale-report/ [Accessed 28 Feb. 2025].**

Chart 2: How CO_2 is captured and stored via AR



Technology level

AR is a well-established method of CDR **with a maturity equivalent to TRL 8 to 9**, that is commercially deployed today.[1]

Cost

The cost of AR varies but typically falls within the **low to moderate** range. AR is a well-established method, requiring minimal resources to implement and has low capital expenditures. Costs are a function of the type of trees planted, the climate conditions where AR is implemented, and the location in which AR is conducted, which can affect factors such as land leasing costs of private land.[7]

Co-benefits

- AR on agricultural land can improve biodiversity, increase primary production, reduce the vulnerability of exotic species invasion, and fortify ecosystems against climate change.[8]
- AR can improve soil quality and carbon stock compared to agricultural soils.[8]
- AR can enhance the water quality of freshwater streams as fewer agricultural pollutants are used on land, such as pesticides and fertilizers, which would have eventually entered water streams.[8]

Risks

- Forests can be highly vulnerable to weather events and conditions such as storms, wildfires, changes in temperatures, and soil pH. This can reverse CO_2 storage.
- The net amount of CO_2 being sequestered is difficult to measure due to uncertainties in the Monitoring, Reporting, and Verification (MRV) frameworks.
- It takes time for trees to grow before the benefits of AR can be fully realized.
- Reforestation on agricultural land can lead to loss of nitrogen.[8]
- Widespread reforestation of agricultural land can reduce water catchment.[8]

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[7] Summers, D.M., Bryan, B.A., Nolan, M. and Hobbs, T.J. (2015). The costs of reforestation: A spatial model of the costs of establishing environmental and carbon plantings. *Land Use Policy*, 44, pp.110–121. DOI: https://doi.org/10.1016/j.landusepol.2014.12.002.

[8] Cunningham, S.C., Mac Nally, R., Baker, P.J., Cavagnaro, T.R., Beringer, J., Thomson, J.R. and Thompson, R.M. (2015). Balancing the environmental benefits of reforestation in agricultural regions. *Perspectives in Plant Ecology, Evolution and Systematics*, [online] 17(4), pp.301–317. DOI: https://doi.org/10.1016/j.ppees.2015.06.001.

3.1.2. Soil Carbon Sequestration (SCS)

SCS is a set of CDR methods which aim to enhance the soil organic carbon content of soil through changes in farming practices. These practices can include but are not limited to.[9]

1) Planting of perennial crops, which do not perish every year and have deep roots that help soils store more carbon.

2) Planting cover crops, which are planted after the main crop is harvested, ensures soils can take in carbon throughout the year.

3) Reducing tilling, which normally breaks up soil to prepare land for new crops and minimize weed growth, but also releases a lot of carbon contained within those soils.

Technology level

SCS is a well-established method of CDR with **TRL 8 to 9** and has seen widespread use today. SCS can be implemented as a standalone solution for sequestering CO_2 from the atmosphere but also in conjunction with existing farming practices to make farming less carbon intensive. Further mass commercial deployment of SCS will be required to achieve significant climate benefits.[1]

Cost

The cost of SCS is **low** and requires minimal resources to implement. The cost depends on the method used to implement SCS, and other factors such as labor cost, degree of mechanization,[10] and the cost of MRV to quantify the net amount of CO_2 sequestered.[11] Estimates in literature quantify the cost of SCS to be between USD 20 to 100 per tonne of CO2 removed.[10]

Co-benefits

- SCS improves soil health and agricultural productivity.[12]
- SCS reduces fertilizer dependence as soil health improves via SCS methods.[12]
- Healthier soils via SCS become more resilient against harsh climate conditions such as droughts and heavy rainfall.[12]

Risks

- Rising global temperatures can speed up soil decay, which increases the probability of CO_2 storage reversal.[13]
- The amount of CO_2 sequestered can be highly variable to factors such as temperature and soil pH.[14]
- There are high uncertainties in current MRV methods to determine the amount of net CO_2 being stored via SCS.[12]

[9] https://climate.mit.edu/explainers/soil-based-carbon-sequestration

[10] Fuss, S., Lamb, W.F., Callaghan, M.W., Hilaire, J., Creutzig, F., Amann, T., Beringer, T., de Oliveira Garcia, W., Hartmann, J., Khanna, T., Luderer, G., Nemet, G.F., Rogelj, J., Smith, P., Vicente, J.L.V., Wilcox, J., del Mar Zamora Dominguez, M. and Minx, J.C. (2018). Negative emissions—Part 2: Costs, potentials and side effects. *Environmental Research Letters*, 13(6), p.063002. DOI: https://doi.org/10.1088/1748-9326/aabf9f.

[11] Agroscope (2023). *Soil carbon sequestration in Switzerland: Analysis of potentials and measures (Postulate Bourgeois 19.3639).* [online] Agroscope.ch. Available at: https://link.ira.agroscope.ch/en-US/publication/53606 [Accessed 4 Feb. 2025].

[12] https://www.american.edu/sis/centers/carbon-removal/fact-sheet-soil-carbon-sequestration.cfm

[13] Hopkins, F.M., Torn, M.S. and Trumbore, S.E. (2012). Warming accelerates decomposition of decades-old carbon in forest soils. *Proceedings of the National Academy of Sciences of the United States of America*, [online] 109(26), pp.E1753–E1761. DOI: https://doi.org/10.1073/pnas.1120603109.

[14] Min, K., Lehmeier, C.A., Ballantyne, F., Tatarko, A. and Billings, S.A. (2014). Differential effects of pH on temperature sensitivity of organic carbon and nitrogen decay. *Soil Biology and Biochemistry*, [online] 76, pp.193–200. DOI: https://doi.org/10.1016/j.soilbio.2014.05.021.

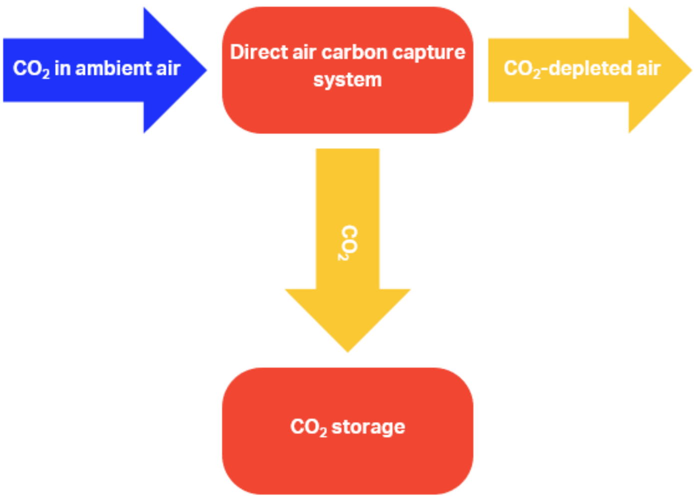
3.2. Novel CDR technologies

3.2.1. Direct Air Carbon Capture and Storage (DACCS)

DACCS uses engineered systems to pull ambient air from the atmosphere and capture CO_2 via chemical interactions with a suitable sorbent or solvent. The captured CO_2 is then stored in geological reservoirs or other suitable storage medium, such as CO_2-containing materials. The CO_2-depleted air is subsequently released back into the atmosphere.[6]

Traditional Carbon Capture and Storage (CCS) captures CO_2 from flue gases emitted from industrial sources, which typically have CO_2 concentrations of 3-14% by volume, depending on the emission source (e.g., coal, natural gas) and costs around USD 70-100 per tonne of CO_2 captured.[15] DACCS captures and stores CO_2 directly from the air, which contains only 0.04% of CO_2 by volume. As a result, DACCS capture systems have a much lower capture efficiency than CCS from flue gases and require about 2-4 times the energy, leading to greater cost per tonne of CO_2 captured and stored.[16] The International Energy Agency (IEA), for example, assessed the levelized cost of DACCS was between USD 134-342 per tonne of CO_2 captured.[17]

Chart 3: How DACCS system captures and stores CO_2



Technology level

There are several subsets to DACCS technologies, depending on the systems used to capture CO_2 from the atmosphere. These systems also have varying techno-economic characteristics, with some technologies still in the lab scale, while others are already commercially viable, given that they have undergone all other stages of the TRL assessment as outlined in Appendix 1.

The most technologically advanced DACCS technologies are those that capture CO_2 using solid structured sorbents with low-temperature (LT) regeneration[18] and liquid sorbents with high-temperature (HT) regeneration. These technologies are in **TRL 9 and 7** respectively, indicating that they are ready for commercial deployment. They have had ample time to develop thanks to the resources of the companies using these technologies today,

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[15] Wang, X. and Song, C. (2020). Carbon Capture From Flue Gas and the Atmosphere: A Perspective. *Frontiers in Energy Research*, 8. DOI: https://doi.org/10.3389/fenrg.2020.560849

[16] Fasihi, M., Efimova, O. and Breyer, C. (2019). Techno-economic assessment of CO2 direct air capture plants. *Journal of Cleaner Production*, [online] 224, pp.957–980. DOI: https://doi.org/10.1016/j.jclepro.2019.03.086.

[17] https://www.iea.org/data-and-statistics/charts/levelised-cost-of-co2-capture-by-sector-and-initial-co2-concentration-2019

[18] After CO_2 capture, these sorbents/solvents need to be regenerated by removing the CO2 that was absorbed/adsorbed on then via change in temperature or some other mechanism.

they have been brought to near or full technological maturity. Carbon Engineering (using liquid sorbents with HT Regeneration, founded in 2009) and Climeworks (using solid structured sorbents with LT regeneration, founded in 2009) are examples of companies which have allocated extensive resources to developing their technologies from scratch to the high TRL levels seen today.

Other, newer DACCS technologies that utilize liquid sorbents with low-temperature regeneration, solid unstructured sorbents, electrochemical solid sorbents, liquid solvents with electrochemical regeneration, humidity swing separation, membrane separation, or cryogenic separation for CO_2 capture, have **TRLs between 2 and 6.**[6] Further development and resources will be necessary to reach technological maturity.

A table summarizing these different DACCS technologies is presented under Appendix 2.

Box 1: Commercial DACCS projects across the globe

There are few commercial DACCS projects worldwide, though more are expected to be operational by 2030 when a total capacity of about 6 to 11 million tonnes (Mt) of CO_2 removed per year is expected. The largest commercial DACCS plant operating today is Climeworks' Mammoth plant in Hellisheidi, Iceland, with a maximum capture capacity of 36,000 tonnes of CO_2 per year.[19] The largest planned commercial DACCS plant currently is the 1PointFive's STRATOS plant in Texas, USA, using technology developed by Carbon Engineering, with an expected capture capacity of 500,000 tonnes of CO_2 per year starting from mid-2025. It is expected to remove up to 1 Mt of CO_2 per year by 2030.[20]

Many commercial DACCS projects still face techno-economic barriers to become operational. In 2024, a planned commercial plant in Wyoming by CarbonCapture, expected to remove 5 Mt of CO_2 per year from 2030, was paused due to the lack of renewable electricity in the location to power the plant. Other DACCS projects utilizing systems of low TRLs are still in the demonstration or pilot phase.[21] Countries must continue to decarbonize their grids and expand the supply of low-cost renewable energy to maximize the potential of DACCS.

Costs

The costs of building and operating a DACCS plant are relatively **high**. Most of the operating costs are attributed to the energy required for operation and the cost of storage. DAC technologies with high TRLs (liquid solvents with high-temperature (HT) regeneration and structured solid sorbents with low-temperature (LT) regeneration) use more energy in the process. This is mainly because of the high amount of energy required to regenerate the solvent or sorbent used for capture.

One study[22] assessed that for HT regeneration using liquid solvents, the total heat demand accounted for about 1390-2500 KWh per tonne of CO_2 removed, and the total electricity demand accounted for 350 to 770 kWh per tonne of CO_2 removed, with the highest energy demand coming from the sorbent regeneration process. For LT regeneration using structured solid sorbents, heat demand amounts to about 200-300 kWh per tonne of CO_2 captured on the fans and control systems and an additional 1,500-2,000 kWh per tonne of CO2 captured for the regeneration of the sorbent. Estimated costs for DACCS today are around USD 500 to 600 per tonne of CO_2 removed.

[19] https://climeworks.com/plant-mammoth
[20] https://www.1pointfive.com/projects/ector-county-tx
[21] https://carbonherald.com/carboncapture-inc-pauses-development-of-project-bison-in-wyoming/
[22] **Omnya Al Yafiee, Mumtaz, F., Kumari, P., Karanikolos, G.N., Alessandro Decarlis and Dumée, L.F. (2024). Direct air capture (DAC) vs. Direct ocean capture (DOC)–A perspective on scale-up demonstrations and environmental relevance to sustain decarbonization. *Chemical Engineering Journal*, 497, pp.154421–154421. DOI: https://doi.org/10.1016/j.cej.2024.154421.**

Lack of scale also contributes to the high costs, as there are few commercial plants, and most are first-of-a-kind (FOAK). Some key areas where the cost of DACCS could be reduced include air contractors, sorbents/solvents, and regeneration methods. For example, the deployment of modular units can help reduce the capital cost through learning curves. Passive air contractors[23], and advances in sorbent chemistry for more effective CO_2 can reduce operational costs.[24] Costs can be expected to decrease as other more efficient and cost-effective DACCS technologies mature, and low-cost renewable energy becomes more abundant and accessible.[22]

Co-benefits

- Minimizing land-use and land-use change emissions as non-arable land can be used for deployment, unlike CDR methods utilizing biomass.[22]
- Certain DACCS methods that use saltwater as a capture solvent can also co-produce freshwater, hydrogen, chlorine, and other useful chemicals from the desalination process.[25]

Risks

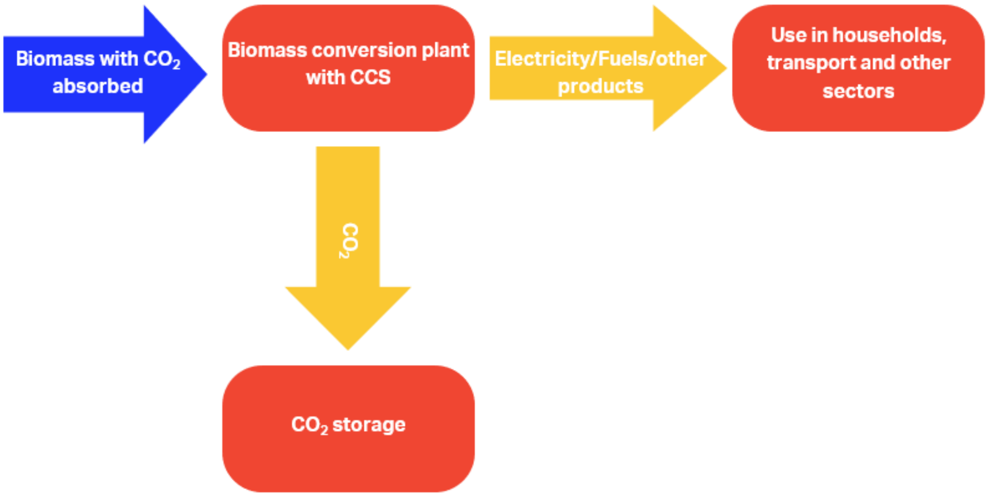
- CO_2 stored via geological storage may be subject to leakage. This can contaminate groundwater sources and pose other environmental risks.[26] Before the construction of the storage well, due diligence must be exercised to identify potential areas of leakage such as faults along the well. During injection and post-injection monitoring, pressure increases due to CO_2 in the storage reservoir can cause the CO_2 plume to move and therefore it is also important to monitor this to prevent potential leakages.[27]
- For offshore geological storage under the seabed, leakage can lead to ocean acidification among other adverse effects.[28]
- For sorbent-based DACCS technologies, the sorbents deteriorate over time after loading and unloading, reducing their ability to capture CO_2 over time.[22]
- Developing infrastructure for CO_2 transport and storage may cause environmental and societal damage if proper protocols are not followed.[29]

3.2.2. Bioenergy Carbon Capture and Storage (BECCS)

Biomass has a natural ability to sequester and store CO_2 from the atmosphere. Biomass can be utilized to generate electricity, produce fuels, or other useful products. When used in such ways, the CO_2 originally contained within the biomass feedstocks is released. BECCS utilizes point source[30] CO_2 capture methods to capture these CO_2 emissions before they are released back into the biosphere and store the CO_2 in either geological formations or in other suitable storage mediums. Biomass feedstocks used to produce energy can be regenerated and continue to sequester CO_2 from the atmosphere. Hence, using BECCS can result in net negative CO_2 emissions.

[23] Unlike traditional air contractors, passive air contractors are devices that draw in air from the atmosphere towards the DACCS system using passive means such as through wind patterns.
[24] Ozkan, M., Nayak, S.P., Ruiz, A.D. and Jiang, W. (2022). Current Status and Pillars of Direct Air Capture Technologies. *iScience*, 25(4), p.103990. DOI: https://doi.org/10.1016/j.isci.2022.103990.
[25] https://capture6.org/our-approach/
[26] Lawter, A.R., Qafoku, N.P., R. Matthew Asmussen, Bacon, D.H., Zheng, L. and Brown, C.F. (2017). Risk of Geologic Sequestration of CO2 to Groundwater Aquifers: Current Knowledge and Remaining Questions. *Energy Procedia*, 114, pp.3052–3059. DOI: https://doi.org/10.1016/j.egypro.2017.03.1433.
[27] Gholami, R., Raza, A. and Iglauer, S. (2021). Leakage risk assessment of a CO2 storage site: A review. *Earth-Science Reviews*, 223, p.103849. DOI: https://doi.org/10.1016/j.earscirev.2021.103849.
[28] Deep Trouble: The Risks of Offshore Carbon Capture and Storage, Center for International Environmental Law, July 2024 (https://www.ciel.org/reports/deep-trouble-the-risks-of-offshore-carbon-capture-and-storage-november-2023/)
[29] von Rothkirch, J. and Ejderyan, O. (2021). Anticipating the social fit of CCS projects by looking at place factors. *International Journal of Greenhouse Gas Control*, 110, p.103399. DOI: https://doi.org/10.1016/j.ijggc.2021.103399.
[30] CO_2 captured at the point of a large emission source, like an industrial facility, rather than directly from the atmosphere.

Chart 4: How BECCS captures and stores CO_2 from bioenergy



Technology level

Both BECCS-to-power and BECCS-to-fuel have a **TRL 9**. This means that the technologies are well-established and ready to be deployed commercially. However, economic factors have so far curtailed commercial deployment.[6]

Costs

The cost of BECCS is **moderate** but can be highly variable depending on where and how BECCS is deployed. BECCS plants are often customized, and complexity increases in response to unique scenarios in the electricity or fuel production, such as the type of biomass used and the final product the biomass is converted into. Thanks to the elevated maturity though, the learning rates for cost reductions for BECCS are expected to remain low.[61] For electricity generation, BECCS costs can range from USD 88 to 288 per tonne of CO_2 removed. For industrial applications such as biofuel conversion, costs are lower, between USD 20 to 175 per tonne of CO_2 removed.[31]

Co-benefits

- Biomass production for BECCS could improve soil carbon, nutrient and water cycling, contribute to market opportunities, employment opportunities, economic diversification, and energy security[1].
- Biomass production for BECCS could improve Biomass production for BECCS may also improve local air quality.[1]

Risks

- BECCS requires the growth and production of biomass, which have both direct and indirect impacts on land use and can generate higher land-use change emissions.[32]
- Dedicated biomass is required for operations, potentially putting pressure on food security, biodiversity, and water resources, and increasing the usage of fertilizers.[1]

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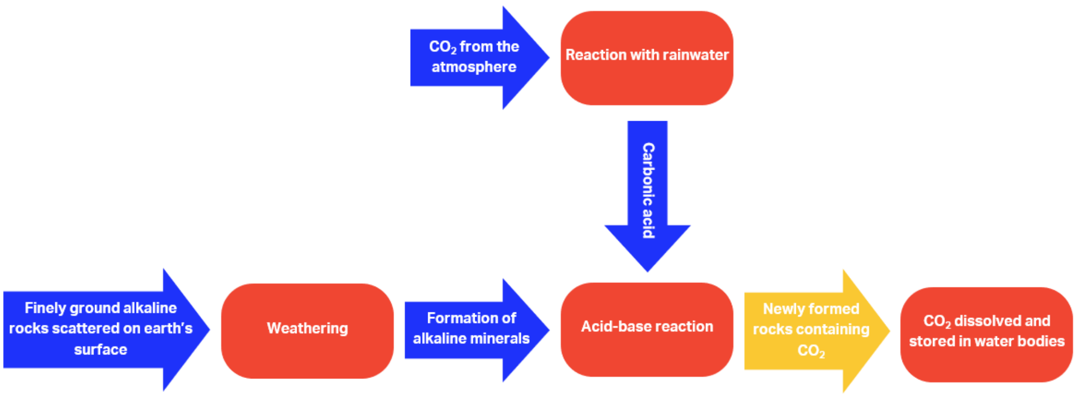
[31] potentials and side effects. *Environmental Research Letters*, 13(6), p.063002. DOI: https://doi.org/10.1088/1748-9326/aabf9f.
[32] Beuttler, C., Charles, L. and Wurzbacher, J. (2019). The Role of Direct Air Capture in Mitigation of Anthropogenic Greenhouse Gas Emissions. *Frontiers in Climate*, 1. DOI: https://doi.org/10.3389/fclim.2019.00010.

- Incomplete combustion of biomass can produce air pollutants such as aerosols and volatile organic compounds (VOCs), associated with serious indoor and outdoor air pollution, and pose subsequent health risks.[33]
- As explained in section 3.2.1, BECCS shares the same risks as DACCS using geological storage of CO_2. These risks include CO_2 leakages from the geological reservoir and environmental and social risks of developing CO2 infrastructure for transport and storage. Careful assessment of the well conditions and pressure monitoring of CO_2 must be done to minimize risks of CO_2 leakage.

3.2.3. Enhanced Rock Weathering (ERW)

ERW accelerates the natural geological weathering process through the distribution of finely ground alkaline rocks in agricultural, urban, or forest soils. When weathering occurs, these alkaline rocks are broken down into alkaline minerals that can react with acids. CO_2 in the atmosphere forms carbonic acid by reacting with rainwater, which chemically interacts with the alkaline minerals formed via the weathering process. The resulting reaction yields newly formed rocks containing CO_2, most commonly in the form of carbonates. The CO_2 is then dissolved and stored naturally in water bodies such as oceans and rivers.[6]

Chart 5: How ERW captures and stores CO_2



Technology level

The TRL of ERW methods is **between 4 to 6**. This means that the technology is still being tested in laboratories or in demonstration stages today. Developing robust MRV frameworks remains a major challenge, as most methodologies are similar to soil carbon sequestration. ERW needs to tackle additional complexities as it relies on the hydrological cycle and the oceanographic cycle. This can make it difficult to detect mineralization and net CO_2 flux during the process.[6]

Costs

The cost of ERW is **moderate**. A large proportion of the cost comes from transporting rock and dust and the energy required for crushing and grinding rocks. The energy required also depends on the type of rock being used for application and the distance for transport. Overall, it is estimated that 77% to 94% of the energy required is for crushing and transporting the rock used for ERW, with a total energy consumption ranging from 650 to

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[33] **Jiang, K., Xing, R., Luo, Z., Huang, W., Yi, F., Men, Y., Zou, N., Chang, Z., Zhao, J., Pan, B. and Shen, G. (2024). Pollutant emissions from biomass burning: A review on emission characteristics, environmental impacts, and research perspectives. *Particuology*, 85, pp.296–309. DOI: https://doi.org/10.1016/j.partic.2023.07.012.**

3500 kWh per tonne of CO_2 removed.[34] In terms of costs, it can range from USD 60 per tonne of CO_2 removed for dunite rocks to around USD 200 per tonne of CO_2 removed for basalt.[35]

Co-Benefits

- Spreading certain rocks, such as basalt rock, on farmland can lead to higher crop yields, most notably in a temperate climate.[36]
- Increasing the soil pH by adding alkaline rocks may lead to lower emissions of other GHGs, such as methane and nitrous oxides, from the soil.[34]

Risks

- How much ERW deployed on a large scale could change the chemistry and possibly the water quality in streams is unknown. Such variations might impact marine and aquatic life.[34]
- Finely ground mineral-containing dust can contribute negatively to surrounding air quality and adversely affect the health of the population. Silicate rock dust, for example, can lead to silicosis, which is a long-term lung disease.[34]
- Transporting finely ground rocks from grinding sites potentially located far from the project site, can spread fine particles and disrupt the function of machinery.[34]

3.2.4. Biochar

Biomass decays naturally over time, releasing stored CO_2 back into the atmosphere. To delay that process, biomass can be converted into biochar, which is produced via thermal conversion of biomass in an environment without oxygen (to avoid combustion), optimized to produce solid char in open or controlled environments. The full process of producing biochar is outlined in Chart 5. During the production process, biochar, bio-oil, and syngas are co-produced in varying ratios depending on the pyrolysis time and temperature. Typically, a lower heating rate with moderate temperatures favors higher biochar yields.[37] The biochar is collected directly after the pyrolysis process through cyclone separation.[38] Bio-oil and syngas co-products are separated subsequently through a condensation column.[39] The resulting biochar remains stable for decades and even centuries and does not release CO_2 back into the atmosphere. The biochar can either be deposited into soil or used as a constituent of building materials such as concrete (Chart 6).[6]

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[34] Wentworth, J. and Forrest, N. (2024). *Enhanced rock weathering: Potential UK greenhouse gas removal*. [online] POST. Available at: https://post.parliament.uk/research-briefings/post-pn-0726/.

[35] Strefler, J., Amann, T., Bauer, N., Kriegler, E. and Hartmann, J. (2018). Potential and costs of carbon dioxide removal by enhanced weathering of rocks. *Environmental Research Letters*, 13(3), p.034010. DOI: https://doi.org/10.1088/1748-9326/aaa9c4.

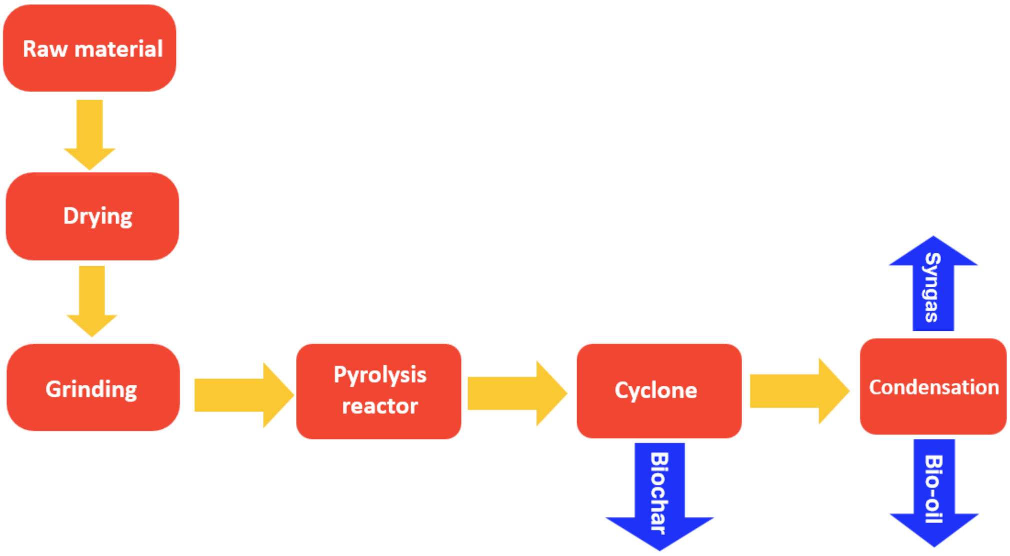
[36] Skov, K., Wardman, J., Healey, M., McBride, A., Tzara Bierowiec, Cooper, J., Ifeoma Edeh, George, D., Kelland, M.E., Mann, J., Manning, D., Murphy, M.J., Pape, R., Teh, Y.A., Turner, W., Wade, P. and Liu, X. (2024). Initial agronomic benefits of enhanced weathering using basalt: A study of spring oat in a temperate climate. *PloS one*, [online] 19(3), pp.e0295031–e0295031. DOI: https://doi.org/10.1371/journal.pone.0295031.

[37] Tisserant, A. and Cherubini, F. (2019). Potentials, Limitations, Co-Benefits, and Trade-Offs of Biochar Applications to Soils for Climate Change Mitigation. *Land*, 8(12), p.179. DOI: https://doi.org/10.3390/land8120179.

[38] Cyclone separators are devices used to remove solid particulate matter from gas streams

[39] Khitab, A., Ahmad, S., Khan, R.A., Arshad, M.T., Anwar, W., Tariq, J., Khan, A.S.R., Khan, R.B.N., Jalil, A. and Tariq, Z. (2021). Production of Biochar and Its Potential Application in Cementitious Composites. *Crystals*, 11(5), p.527. DOI: https://doi.org/10.3390/cryst11050527.

Chart 6: Schematic diagram of producing biochar and other by-products via pyrolysis process



Technology level

The TRL level for traditional production and use of biochar is **between 8 and 9**. This means that the technology is well understood and can be deployed commercially.[6]

Costs

The cost of biochar is **moderate**. It can be broken down into cost of feedstock, production facility, and operating costs. Of these, the feedstock cost is the largest component, representing up to 40% to 75% of total expenditure. The cost of production can vary based on production scale. For the largest production facilities with optimized design, the production cost can be about USD 100 per tonne of CO_2 equivalent removed. At smaller facilities the costs can rise to USD 365 per tonne of CO_2 equivalent removed. [40]

Co-benefits

- Biochar, depending on the type of feedstock used, can increase soil organic carbon when added to soils and can thereby improve soil health.[37]
- Biochar can be made from organic waste products (e.g., manure, sewage sludge, food wastes) that minimize competition for crop biomass and that have high nutrient content (e.g., nitrogen, phosphorus, potassium), all of which are useful in agronomic processes.[37]
- Syngas and bio-oil are produced as co-products during biochar production can be used as intermediates for sustainable aviation fuel (SAF) production.[37]
- Biochar in soil increases the efficiency of nitrogen fertilizer use, as it is shown to increase nitrogen uptake of plants, therefore reducing the amount of fertilizer required and curtailing nitrogen emissions from soil.[37]

Risks

- Particulate emissions such as soot during the production process can degrade air quality.[37]
- Potential biodiversity and carbon stock losses from land use due to unsustainable biomass collection.[37]

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[40] **Biomass to Biochar Maximizing the Carbon Value ACKNOWLEDGMENTS. (2022). Available at:** https://wpcdn.web.wsu.edu/cahnrs/uploads/sites/44/Biomass2Biochar-Maximizing-the-Carbon-Value1.1.pdf **[Accessed 4 Feb. 2025].**

- Biomass used to make biochar can also compete for other end-uses such as bioelectricity or biofuel production.[37]
- The stability and variability of the biochar are highly dependent on factors affecting production such as pyrolysis time, pyrolysis temperature, and carbon content of the feedstock. Conditions of soil when biochar is stored also affect biochar stability, including pH, moisture, temperature, carbon/nitrogen ratio, and mineral content.[37]
- Biochar integration in the soil can reduce its albedo, or the proportion of solar radiation reflected from the soil. This increases the absorption of radiation of short wavelengths, making more solar energy available at the soil surface. This can cause further warming effects in the atmosphere.[37]
- When feedstock is not processed properly, toxic compounds and other impurities (e.g., heavy metals in sewage sludge) can contaminate the soil.[37] Moreover, biochar can require 3-5 years from field trial before it can be used for carbon crediting and other applications, increasing lead times.

Box 2: Lack of standardization in biochar credit certification

Many risks associated with biochar, as mentioned above, come from differences in feedstocks used and operating conditions to produce the biochar. There are many voluntary standards and protocols that have been developed, such as the Verified Carbon Standard (VCS) Methodology for Biochar Utilization in Soil and Non-Soil Applications[41], to ensure that biochar CDR credits sold in the market meet quality and durability standards. However, there is still a long way to go in terms of harmonization of standards for biochar production globally.

Harmonizing standards will involve including all types of feedstocks, adopting a common methodology to establish baseline emissions, and developing robust MRV frameworks to account for CO_2 being sequestered, including establishing CO_2 permanence criteria. This will help establish strong guidelines for producers of biochar to ensure their production is standardized and that biochar of relatively equal qualities is reaching the market.

4. Other CDR technologies

The CDR technologies presented in this section do not currently have a large presence in market transactions of CDR credits. This section covers notably novel ocean-based CDR technologies that have high CO_2 sequestration potential but low technological readiness and high costs today. These technologies are expected to have a greater impact on the market in the coming years.

Table 2: Summary of other CDR technologies

Technology	TRL	Cost	Type of storage	Durability in years[1]	Co-benefits	Risks
CBC	9	Low to Moderate	Soil and vegetation	10s to 100s	High	High
Ocean fertilization	4	High	Marine sediment	100s to 1000s	Moderate	High

[41] https://verra.org/methodologies/vm0044-methodology-for-biochar-utilization-in-soil-and-non-soil-applications/

AU/AD	4	High	Marine sediment	100s to 1000s	Low	High
OAE	6	High	Dissolved minerals in water bodies	10,000 +	Moderate	High
DOCCS	6	High	Geological storage	10,000 +	Moderate	Moderate

Note: CBC = Coastal Blue Carbon, AU/AD = Artificial Upwelling/Artificial Downwelling, OAE = Ocean Alkalinity Enhancement, DOCCS = Direct Ocean Capture and Storage

4.1. Coastal Blue Carbon

Coastal blue carbon (CBC) is the practice of restoring marine and coastal ecosystems, such as sea grasses, mangroves and, salt marshes, to capture and store CO_2 via photosynthesis, similar to AR. Compared to land-based ecosystems, such as forests, coastal ecosystems are shown to absorb and store CO_2 at faster rates.[42] In oxygen-free environments and if left undisturbed, these coastal ecosystems may store the CO_2 for long periods of time.[6]

Technology level

CBC methods are well-established and widely practiced today, and the **TRL is 9.**[6] It is well-known among policymakers and the scientific community that restoring and managing marine ecosystems sustainably will yield significant environmental and social benefits.[43]

Cost

The cost of CBC can be **highly variable, from low to high**, depending on the type of coastal blue ecosystem being restored. For example, the cost of saltmarsh restoration is estimated to be around USD 470,000 per tonne of CO_2 removed costs, which is significantly more than mangrove restoration, which can cost around USD 560 per tonne of CO_2 removed, according to one study.[44] The study suggests that the large disparity can be attributed to important historical land-use changes for saltmarshes, for example, when these ecosystems were used to build ports, which require much more human engineering for restoration than other ecosystems, greatly adding to costs. On the other hand, mangrove restoration projects in developing regions such as Southeast Asia, benefit from lower labor costs and capital needs for restoration.[44] A further study suggests that CO_2 sequestration via seagrass plating can cost as little as USD 20 per tonne of CO_2 removed.[45] Thus, some of the factors that influence the cost of CBC are historical land-use change of the associated marine and/or coastal

[42] https://oceanservice.noaa.gov/facts/bluecarbon.html
[43] Williamson, P. and Gattuso, J.-P. (2022). Carbon Removal Using Coastal Blue Carbon Ecosystems Is Uncertain and Unreliable, With Questionable Climatic Cost-Effectiveness. *Frontiers in Climate*, 4. DOI: https://doi.org/10.3389/fclim.2022.853666.
[44] Taillardat, P., Thompson, B.S., Garneau, M., Trottier, K. and Friess, D.A. (2020). Climate Change Mitigation Potential of Wetlands and the Cost-Effectiveness of Their Restoration. *Interface Focus*, 10(5). DOI: https://doi.org/10.1098/rsfs.2019.0129.
[45] Meyer, A. and Spalding, M. (2021). *A Critical Analysis of the Ocean Effects of Carbon Dioxide Removal via Direct Air and Ocean Capture -Is it a Safe and Sustainable Solution?* [online] Available at: https://oceanfdn.org/wp-content/uploads/2021/04/Direct-Carbon-Removal-Strategies-TOF-1Apr21-.pdf [Accessed 4 Feb. 2025].

ecosystem, the geographical area in which the restoration activity is taking place, and the costs associated with MRV.[43]

Co-benefits

- Establishment of mangrove protected areas is associated with long-term gains in fisheries production.[46]
- Provides coastal protection against sea level rise.[46]
- Calcium carbonate dissolution can occur in coastal blue carbon ecosystems, which can further help capture and store CO_2 in water bodies such as rivers and oceans.[43]
- Coastal blue carbon ecosystems such as mangroves attract birds and other marine life, making it popular for recreational activities including birdwatching and fishing, and providing economic opportunities through tourism.[46]

Risks

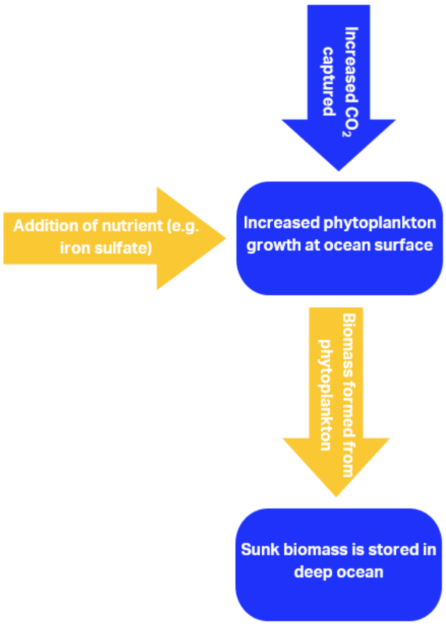
- Quantifying blue carbon losses is still challenging due to a lack of understanding of the historical and spatial extent of these ecosystems, making it difficult to establish historical coastal blue carbon stock baselines.[46]
- Factors driving degradation of coastal blue ecosystems can vary greatly by region, physical modification, pollution, and climate change. Degradation can also be driven indirectly by socio-economic factors such as coastal development, energy, food, infrastructure development and tourism.[46]
- Anaerobic conditions of coastal blue ecosystems favor the production of non-CO_2 greenhouse gases such as methane and nitrous oxide.[43]
- It may take a long time after the start of restoration projects before the coastal blue ecosystem mature to achieve a high CO_2 uptake.[43]
- Both calcium carbonate precipitation, which releases $CO_{2,}$ and dissolution, which stores CO_2, can occur in coastal blue carbon ecosystems. This raises uncertainty regarding the net benefit of the mechanism.[43]

4.2. Ocean Fertilization

Ocean fertilization applies the addition of micronutrients such as iron, and micronutrients including phosphorus, nitrogen or silica, to the ocean surface water (0 to 200 meters depth). Adding these nutrients stimulates CO_2 uptake by marine phytoplankton at the surface via photosynthesis. This eventually creates algae blooms which naturally sink to the bottom of the ocean for storage in marine sediment.[6]

[46] **Macreadie, P.I., Costa, M.D.P., Atwood, T.B., Friess, D.A., Kelleway, J.J., Kennedy, H., Lovelock, C.E., Serrano, O. and Duarte, C.M. (2021). Blue carbon as a natural climate solution. *Nature Reviews Earth & Environment*, 2(2). DOI: https://doi.org/10.1038/s43017-021-00224-1.**

Chart 7: Schematic diagram of ocean fertilization process



Technology level

Ocean fertilization is at **TRL 4**. Currently, there are no companies developing solutions for commercialization, and the main focus has been on academic research and laboratory-scale experiments.[6]

Cost

The cost of implementing ocean fertilization is expected to be **high**, mainly due to the technology costs given its early development stage. Projected costs are highly variable, based on the materials used for the nutrient and overall efficiency of CO_2 exported to the deep ocean. Other cost considerations include transport of nutrients to the sea, typically either aerially or by ship, and costs associated with environmental monitoring and verification, which are still underdeveloped. Data availability regarding current costs is limited as the method is in the research and development phase with prototype testing. Best-case estimates, based on one study conducting iron fertilization, claim a cost of USD 7 per tonne of CO_2 captured versus the worst-case scenario expecting a cost of USD 1,500 per tonne of CO_2, neither accounting for the cost of verification.[47] Given its low technological readiness level, significant investment in research and development is required regarding delivery and availability of nutrients, MRV of CO_2 removals via ocean fertilization, monitoring ecological impacts in the ocean, and demonstration facilities and pilot plants.[54]

Co-benefits

- Ocean fertilization can reduce ocean acidification of ocean surface water thanks to reductions in atmospheric CO_2.[48]

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[47] Emerson, D., Sofen, L.E., Michaud, A.B., Archer, S.D. and Twining, B.S. (2024). A Cost Model for Ocean Iron Fertilization as a Means of Carbon Dioxide Removal That Compares Ship- and Aerial-Based Delivery, and Estimates Verification Costs. *Earth's future*, 12(4). DOI: https://doi.org/10.1029/2023ef003732.

[48] Williamson, P., Wallace, D.W.R., Law, C.S., Boyd, P.W., Collos, Y., Croot, P., Denman, K., Riebesell, U., Takeda, S. and Vivian, C. (2012). Ocean fertilization for geoengineering: A review of effectiveness, environmental impacts and emerging governance. *Process Safety and Environmental Protection*, 90(6), pp.475–488. DOI: https://doi.org/10.1016/j.psep.2012.10.007.

- Biomass from phytoplankton that absorbs CO_2 is likely to decompose by the time it reaches the ocean floor, releasing CO_2 in the deep ocean. The release of CO_2 near the seafloor can stimulate the growth of seafloor biomass.[48]

Risks

- Uncertainties regarding biological mechanisms by which generated biomass will sink to the ocean (e.g., predators can consume biomass before it reaches the ocean floor).[6]
- Uncertainties regarding the timeframe within which biomass will stay on the ocean floor before rising to the ocean surface and potentially re-emitting the stored CO_2.[6]
- Oxygen levels below the ocean surface may decrease due to increased CO_2 uptake from fertilization-enhanced biomass.[6]
- There are potential negative far-field impacts on nutrient availability in the ocean beyond the location where ocean fertilization is taking place.[6]

Box 3: Machine learning and marine CDR

One of the biggest risks of ocean fertilization and many marine CDR (mCDR) methods is CO_2 not being securely stored by marine sediments reaching the seafloor. Another related uncertainty is how long the marine sediments will remain on the seafloor before re-emitting the CO_2 back to the atmosphere. While it is challenging and costly to develop MRV protocols to ensure that CO_2 storage is secured over many years, recent advances in machine learning and engineering have sought to solve some of these issues.

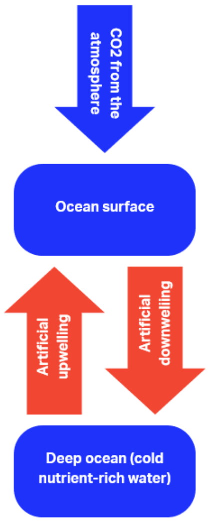
Engineering nutrient particles with a gravity controlling core ensures that the particles are able to reach the seafloor effectively, ensuring that CO_2 is durably stored. With the help of machine learning, models are able to predict the best locations and conditions to deposit the particles, maximizing resources and time.[49]

4.3. Artificial Upwelling and Artificial Downwelling (AU/AD)

Artificial downwelling refers to the downward transfer of carbon-rich surface water and carbon to the deep ocean. This can be done via human-made pumps which push surface ocean water into the deep ocean, cooling surface waters so that it becomes denser and sinks to the deep ocean or increasing salinity through thickening of sea ice. Artificial upwelling brings nutrient-rich seawater from the deep ocean to the surface, to stimulate phytoplankton activity. Phytoplankton absorbs CO_2 from the atmosphere on the ocean surface via photosynthesis, which then undergoes natural biomass sinking to reach the deep ocean, where the CO_2 is stored (Chart 8).[6]

[49] https://www.csaocean.com/news/blog/harnessing-nature-driven-carbon-capture-and-removal

Chart 8: Schematic diagram of AU/AD



Technology level

AU/AD methods are at **TRL 4,** meaning that the technology is not mature and not ready for commercial deployment.[6] It is currently a method in the theoretical stage, and feasibility studies have only been conducted in small-scale experiments.[50] Any co-benefits and potential risks have not been extensively studied yet.

Costs

The cost of artificial upwelling and artificial downwelling is **high**. Since the TRL is low, there is a large gap between the technological readiness and the projected sequestration potential of AU/AD at maturity. It is expected that there would need to be large capital investments in technology and in developing and building new pipe systems that are able to withstand the harsh ocean conditions.[51] Due to limited deployment, limited data is available on the costs of CO2 removal via AU/AD, but it is expected that costs will also relate to the development and application of a robust MRV system for carbon sequestration. One study indicates that costs will be in the USD 100-150 per tonne of CO_2 removed range or higher.[54]

Co-benefits

- Local reduction of sea surface temperature from AU can support fisheries and aquaculture as well as support cloud-formation.[55]

Risks

- Phytoplankton is a primary food source of certain marine life and hence only a fraction of the sequestered carbon in phytoplankton reaches the deep ocean.[52]
- Much uncertainty pertaining to the determination of how much CO_2 is being captured and stored via phytoplankton and from the surface ocean prevails, and the related MRV protocols are still in the development phase.[52]

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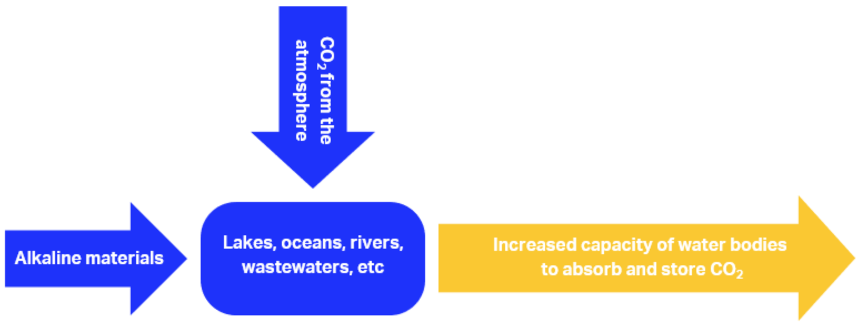
[50] https://www.geoengineeringmonitor.org/technologies/artificial-upwelling
[51] Webb, R.M., Silverman-Roati, K. and Gerrard, M.B. (2022). ***Removing Carbon Dioxide Through Artificial Upwelling and Downwelling: Legal Challenges and Opportunities***. [online] Scholarship Archive. Available at: https://scholarship.law.columbia.edu/faculty_scholarship/3337 [Accessed 4 Feb. 2025].
[52] https://medium.com/@ankump2/gigablue-phytoplankton-based-carbon-sequestraio-9c58247012d7

- AU/AD requires infrastructure such as floating platforms and large pumps that reach the ocean floor to be built, and its impact on marine life, shipping, and fishery is expected to be negative, through it remains to be studied and better understood.[50]
- Upwelling of carbon-rich deep ocean water to the surface may increase the risk of additional CO_2 being released back into the atmosphere.[55]
- Increased biological activity at the ocean surface would also mean a depletion of oxygen levels below the ocean surface, which may cause harm to other marine life in those regions.[55]

4.4. Ocean Alkalinity Enhancement (OAE)

OAE involves the addition of alkaline material to a water body to increase its pH. This can include a direct addition of alkali (sodium, potassium) or alkaline (magnesium or calcium) silicates, carbonates, and hydroxides, either as solids or in an aqueous form. The OAE process can also occur as a result of terrestrial ERW or coastal ERW, whereby alkaline materials spread on the land surface eventually reach the water bodies. Decreasing the pH of the water body enhances its ability to capture CO_2 from the atmosphere since CO_2 exhibits acidic properties when dissolved in water (Chart 9).[6]

Chart 9: Schematic diagram of OAE



Technology level

OAE is at **TRL 6**. Hence, it is still not well-established and requires further research and development, as well as pilot testing before it can be commercialized.[6]

Costs

The cost of OAE is **high**. Similar to ERW, a large cost component is the energy required to mine, grind, and process the alkaline materials required for OAE. In order to maximize the effectiveness of the alkaline materials deposited, they must be grinded into finely ground particulates which increase the surface area of the material, further adding to energy costs.[53] Due to its low technological readiness, significant investment is required in research and to scale-up the solution. Based on a study from the National Academies of Science, Engineering, and Medicine, significant investment is required in research and development of pilot-scale facilities, understanding the impacts on the ocean ecosystem, and in MRV systems covering potential of CO_2 removal via OAE, in addition to analyzing the potential side effects of using OAE as a CDR solution.[54] Moreover, transporting materials across the water bodies implies further uncertainty regarding the CO_2 removal cost, which could range

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[53] Eisaman, M.D., Geilert, S., Renforth, P., Bastianini, L., Campbell, J., Dale, A.W., Spyros Foteinis, Grasse, P., Hawrot, O., Löscher, C.R., Rau, G.H. and Jakob Rønning (2023). Assessing technical aspects of ocean alkalinity enhancement approaches. DOI: https://doi.org/10.5194/sp-2023-1.
[54] National Academies of Sciences, E. (2021). *A Research Strategy for Ocean-based Carbon Dioxide Removal and Sequestration.* [online] *nap.nationalacademies.org*. Available at: https://nap.nationalacademies.org/catalog/26278/a-research-strategy-for-ocean-based-carbon-dioxide-removal-and-sequestration.

from USD 14 to more than USD 500 per tonne of CO_2 removed based on one study.[31] Raw material costs are likely to be similar to those for ERW.

Co-benefits

- Potential local neutralization of ocean acidification caused by anthropogenic CO_2 concentrations in the atmosphere, promoting increasing fish stocks as a result.[55]
- Non-calcifying macroalgae is observed to decline under alkalinization, which could reduce harmful algae blooms in coastal waters.[56]

Risks

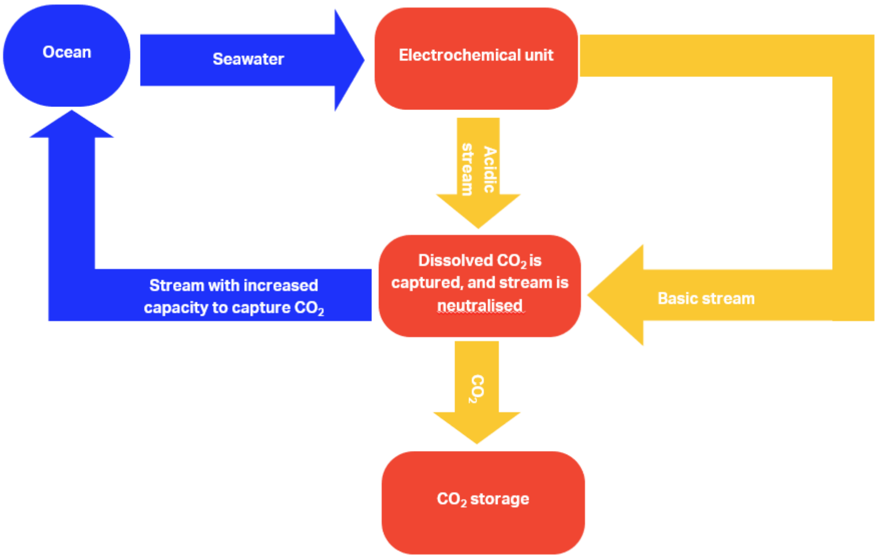
- When silicate rocks are used, they need to be grinded into fine particles, and these can degrade the surrounding air quality.[53]
- Seawater density must not increase when alkaline materials are deposited into water bodies, such that pH change only occurs at the water surface to ensure interaction with atmospheric CO_2.[53]
- Uncertainties regarding how much alkali can be added to water bodies without harming marine life.[53]
- There may be secondary precipitation when alkaline materials are added to seawater such that the effective number of alkaline materials deposited decreases.[53]
- Uncertainty in quantifying the residence time of CO_2 in the water body before some of the stored CO_2 contained in the water bodies is re-released to the atmosphere.[53]
- MRV tools that measure the carbon concentrations in the ocean over space and time need to be developed, as much remains unknown regarding how to quantify the air-sea CO_2 flux field and how to quantify the effects of OAE that can extend to large temporal and spatial scales.[57]

4.5. Direct Ocean Carbon Capture and Storage (DOCCS)

DOCCS harnesses electrochemistry to enhance the ocean's natural ability to capture and store CO_2 from the atmosphere (Chart 10). There are several variations of DOCCS technologies, involving different electrochemical cells. The most prominent DOCCS technologies today exploit electrochemical units to divide seawater into an acidic stream, which contains CO_2, and an alkaline stream. The acidic stream containing dissolved CO_2 is captured directly from the stream and stored in a geological formation or other suitable CO_2 storage medium. This decreases the acidity of the stream as CO_2 exhibiting these properties is removed. The alkaline stream is then added to the now CO_2-stripped stream, which neutralizes the rest of the acid in the seawater. The resulting stream of seawater is deposited back into the ocean, increasing its original capacity to capture and store CO_2.[6]

[55] Rosen, P., Neuberger, J., J, C.Z. and Wenzel, L. (2023). Guidance for the Potential Application of Marine Carbon Dioxide Removal (mCDR) in U.S. National Marine Sanctuaries. *Noaa.gov.* [online] DOI: https://doi.org/10.25923/chkd-fd21.
[56] Röschel, L. and Neumann, B. (2023). Ocean-based negative emissions technologies: a governance framework review. *Frontiers in Marine Science*, 10. DOI: https://doi.org/10.3389/fmars.2023.995130.
[57] Ho, D.T., Bopp, L., Palter, J.B., Long, M.C., Boyd, P.W., Griet Neukermans and Bach, L.T. (2023). Monitoring, Reporting, and Verification for Ocean Alkalinity Enhancement. DOI: https://doi.org/10.5194/sp-2023-2.

Chart 10: Schematic diagram of a prominent DOCCS technology



Technology level

DOCCS is at **TRL 6.** Today, DOCCS systems have demonstrated high potential at the laboratory scale but remain unproven at a commercial-scale plant.[6]

Costs

The cost of DOCCS is **high**. Costs are mainly driven by the high energy requirements of using DOCCS and high investment needs to increase the technological maturity and costs of electrochemical cells. High energy is required for the electrochemical cell to perform water-splitting on seawater, which contains high salt concentrations. There is only limited data on costs and energy requirements for a commercial-scale plant given the early stage of development.

Large variations in costs and energy requirements are expected depending on the type of electrochemical separation method used. For example, DOCCS systems using Bipolar-Membrane Electrodialysis (BMPED) cells, one of the more established DOCCS technologies, have an estimated energy consumption of 1,400 kWh per tonne of CO_2 removed. Recently introduced technologies using chlorine-mediated electrodialysis cells may use only 700 kWh per tonne of CO_2 removed. The plant should also ideally be co-located near a desalination plant to remove the salt content of the seawater before electrochemical separation, which will reduce the energy required, but also reduce the removal potential of DOCCS.[22] Due to the low technological readiness of DOCCS, significant investment is also required in research and development in areas such as MRV protocols, assessment and development of novel and improved electrode and membrane materials, and assessment of potential environmental impacts on the ocean, among other priorities.[54]

Co-benefits

- Regulates the pH of seawater, (increasingly acidified due to higher CO_2 concentrations in the atmosphere), helping to protect coral and fish communities, which are sensitive to changes in pH.[55]
- Potential to build DOCCS plants offshore and above CO_2 reservoirs in the seafloor, reducing land-use impact onshore.[22]
- DOCCS plants can be built in smaller sizes than DAC plants, for example, since the amount of fluid processed using DOCCS technology is smaller.[22]

- Co-production of hydrogen gas during the separation process, would be of great value as hydrogen can be used during chemical processes and to produce energy.[58]

Box 4: Green hydrogen production from DOCCS

One of the most notable co-benefits of using DOCCS is that it can produce hydrogen gas as a by-product during the CO_2 capture process. Assuming the DOCCS system is powered by renewable energy, the hydrogen produced is carbon-neutral or so-called green hydrogen. Hydrogen is a key resource in the production of chemicals and energy, including the aviation sector, for its use in the production of sustainable aviation fuels (SAF) and for utilization in hydrogen aircraft. As hydrogen is a valuable resource for most economic sectors, its co-production can also help offset some of the cost of the CO_2 removal itself, as there are market actors that are willing to pay high prices for green hydrogen.

A pre-purchase of 62,000 tonnes of CO_2 removed via DOCCS and 2,100 tonnes of hydrogen co-product produced during the removal process was agreed in 2023.[59]

Risks

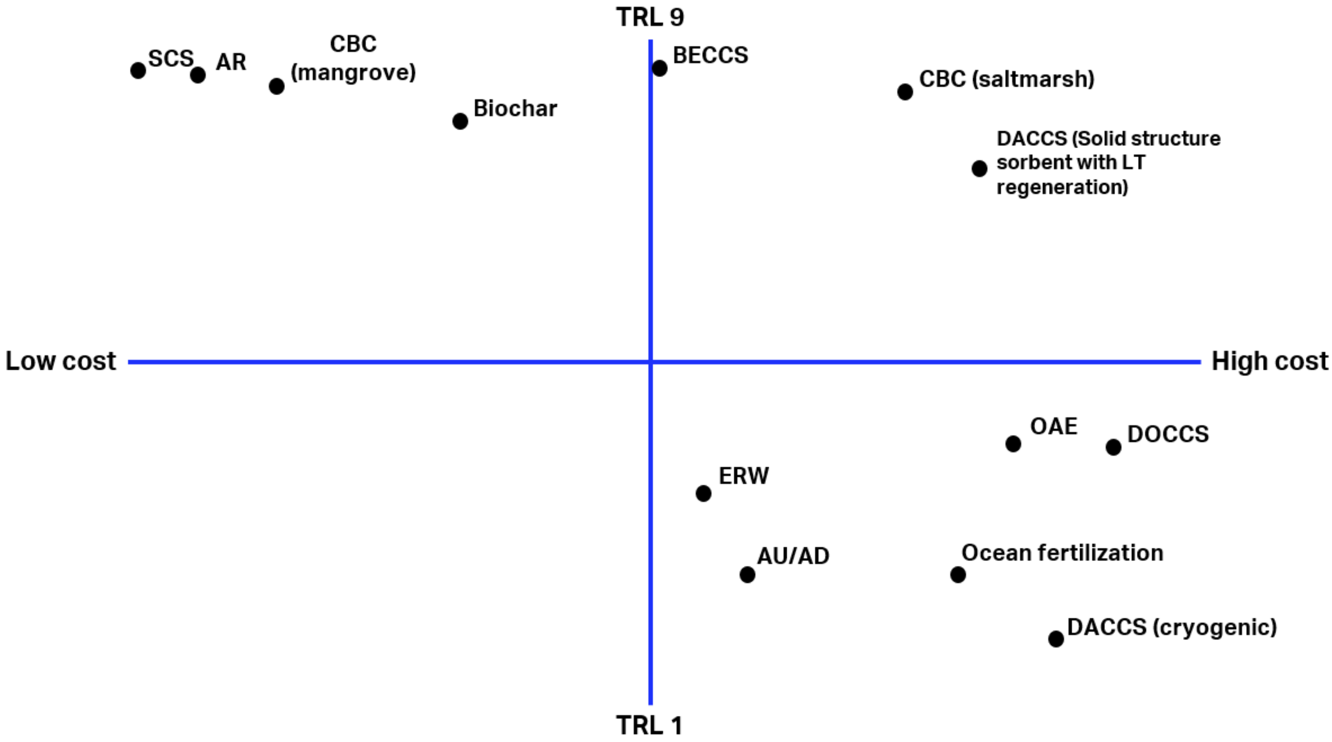
- Uncertainties regarding how much alkali can be added to water bodies without harming marine life.[57]
- Uncertainties over temporal and spatial impact of pH changes in the water bodies.[57]
- MRV of carbon flux of the ocean can be challenging given large uncertainties regarding carbon flux in the ocean and between the ocean and the atmosphere.[57]
- CO_2 stored via geological storage under the seafloor may be subject to leakage and can cause drops in pH of the coast and negatively impact the surrounding ecosystems. The increase in CO_2 concentrations due to leakage can also reduce the ocean's ability to absorb any additional CO_2 emissions.[60]

5. Summary

The relationship between TRL levels and the cost of the CDR technology is a key factor in developing this market (Chart 11). Technologies with low cost and high TRL levels (upper-left quadrant) are ideal for short-term investment with short-term returns in CO_2 removal. CDR technologies with high cost and low TRLs (bottom-right quadrant) are likely technologies that require further research and development and further support in pilot testing and deploying FOAK plants. These technologies are most suited for either short-term investments with the CO_2 removal expected to take place in the longer term, such as offtake agreements, or long-term investments allowing technologies to mature.

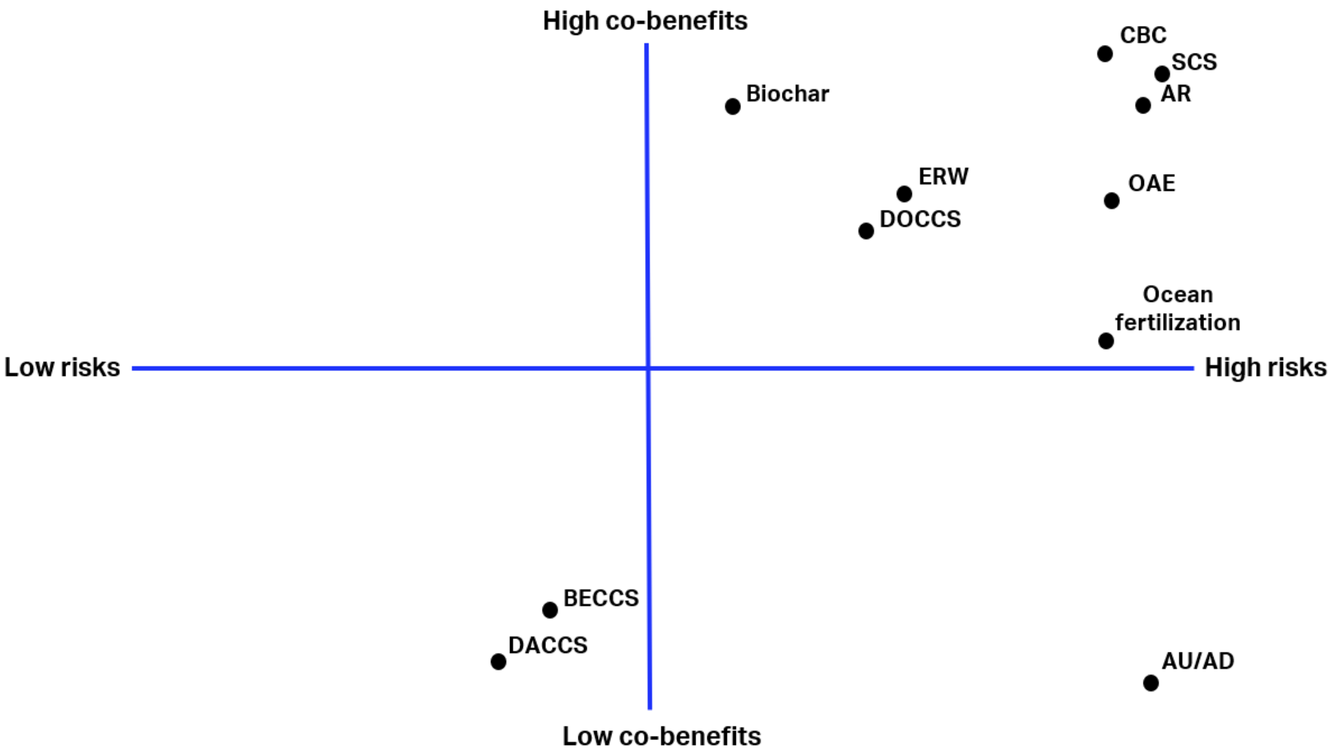
[58] https://www.weforum.org/stories/2024/10/direct-ocean-capture-carbon-removal-technology/
[59] https://green.simplifiying.com/p/equatics-ocean-tech-makes-waves-boeing

Chart 11: Techno-economic chart of different CDR technologies



Co-benefits and risks of different CDR technologies are plotted in Chart 12. Technologies with low risks and high co-benefits (upper-left quadrant) are of course ideal. However, given many intricate variables for each technology, this ideal is hard to meet. Technologies with low co-benefits and high risks are not preferable for investment in the short term, though this can evolve hopefully with some speed as research is ongoing.

Chart 12: Chart on co-benefits and risks of CDR technologies



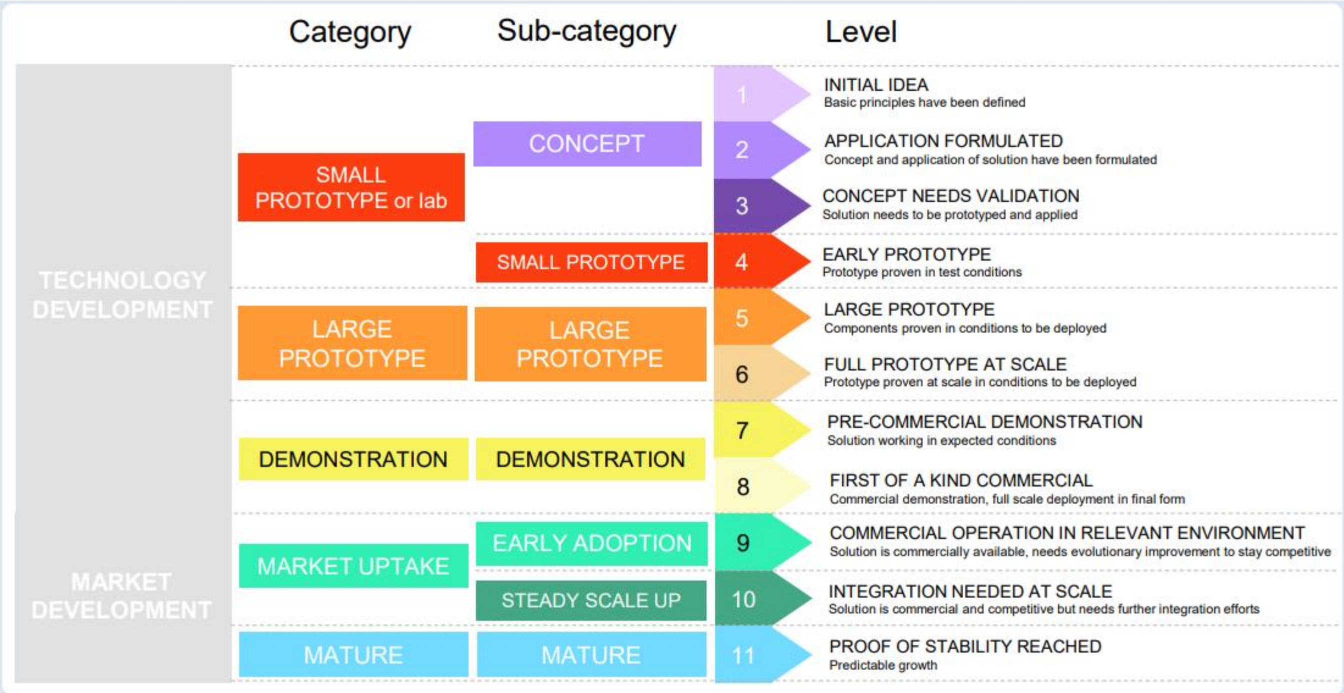
Overall, both techno-economic characteristics of CDR technologies and the associated co-benefits and risks of these technologies beyond their CO_2 removal potential, are important considerations that can be combined to assess the feasibility and effectiveness of the technology to meet decarbonization goals.

Appendix 1: Full methodology and criteria

Technology level

- Describes the **technological readiness levels (TRL)** of each technology on a scale of 1 to 9. This is used to assess empirically the technological maturity of the approach within a defined timescale. Typically, TRLs 1 to 6 indicate that the CDR technology is still at the pre-demo stages, requiring further reach and development, prototype, and pilot testing. TRL 7 to 8 means that the technology is established, proven and ready for demonstration. TRL 9 implies that the technology is ready to be commercially deployed.[61] The image below illustrates the characteristics of the technology at different TRLs:

Chart 13: Characteristics of a technology at different TRL levels[62]



Costs

- Describes the **relative cost** of each technology with respect to other technologies listed in this document. The cost reflects the cost of developing a commercial-scale plant today. The costs can be divided into relatively **low, moderate** and **high**. Table 2 shows relative costs of the CDR technologies discussed in this document.

[61] RMI (2023). *The Applied Innovation Roadmap for CDR*. [online] RMI. Available at: https://rmi.org/insight/the-applied-innovation-roadmap-for-cdr [Accessed 4 Feb. 2025]

[62] IEA (2022). *Direct Air Capture 2022 – Analysis*. [online] IEA. Available at: https://www.iea.org/reports/direct-air-capture-2022.

Co-benefits

- Describes potential co-benefits that can come with deploying a certain technology **in addition to its primary use** to remove CO_2 from the atmosphere. This can include but is not limited to **associated benefits to the environment, society, and economy** that result from the project activity.

Risks

- Describes potential **risk factors while deploying and using a CDR technology**. Similarly to co-benefits, these risks can include risks to the environment, society, and economy while deploying and using the technology. Risk also factors in the durability of the CDR technology, which is an important consideration for any CDR technology, i.e., to assess the timescale that CO_2 is stored, and the likelihood of CO_2 being re-released to the atmosphere.

Appendix 2: Summary of DACCS technologies

Table 3: Summary of different DACCS technologies

DACCS method	TRL[6]	Description6
Solid structured sorbent with LT regeneration	9	Refers to solid, structured chemical compounds with high porosity to capture CO_2 that require relatively low temperatures to regenerate. These are technologically mature systems and most commonly use solid amine sorbents. Other sorbents like metal organic frameworks (MOFs) and zeolites are still being developed for commercial use. The regeneration temperature for solid amines is approximately 120°C.
Liquid solvent with HT regeneration	7	Refers to capture of CO_2 using liquid solvents that require high temperatures to regenerate. The hydroxide-carbonate system is typically used, which is ready for commercial use. The regeneration temperature is approximately 900°C.
Liquid solvent with LT regeneration	5	Refers to liquid sorbents to enable CO_2 capture that requires low temperatures to regenerate the solvent. The solvent used is typically amino acid solution that requires temperatures less than 120°C to regenerate.
Liquid sorbent with electrochemical regeneration	6	Similarly to liquid solvents with HT regeneration, CO_2 is passed over alkaline solutions (like potassium hydroxide) and chemically bound. However, the solvent, in this case, is placed in an electrochemical cell and is regenerated through a change in voltage to release the concentrated CO_2 from the solvent after capture.
Solid unstructured sorbent with HT regeneration	6	CO_2 is typically captured using an unstructured mineral sorbent such as crushed calcium oxides to form limestone. The sorbent is regenerated at high temperatures of about 600-1200°C.
Solid sorbent with electrochemical regeneration	6	CO_2 is adsorbed onto the surface of a solid sorbent, unlike liquid sorbents where the CO_2 is chemically bound. The solid sorbent is similarly regenerated in an electrochemical cell by applying a voltage to separate the CO_2 from the sorbent.
Solid sorbent with humidity swing regeneration	6	CO_2 is captured by chemically binding it onto the surface of suitable capture material such as solid resin under dry conditions. The sorbent is then regenerated by releasing the CO2 in an aqueous form through increasing the humidity.

Membrane separation	2	Permeable membrane materials such as polymer membranes are used to separate CO_2 from other gases via differences in their permeability. This is often repeated in cycles to achieve the desired CO_2 concentration.
Cryogenic separation	4	Involves cooling ambient air to very low temperatures so that the CO_2 can be extracted through phase separation from other gases.

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