Negative Emissions Technologies: An Overview of Direct Air Capture

Chayut Kovitchindachai

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Abstract

This paper will focus on Direct Air Capture (DAC), a type of Negative Emissions Technology (NET). Unlike other NETs, DAC allows for high storage permanence without the use of arable land or water sources, which minimizes impacts on agriculture and other land uses (Lebling et al., 2022). Additionally, the captured carbon can be used to create synthetic fuels, further reducing emissions (SFC Energy, n.d.). However, the main challenge of modern DAC is that it still requires additional funding to be deployed on a large scale. In addition, governments may be hesitant to provide the necessary funding because it is still not clear which NET would be the most prominent and profitable form of CO2 emission mitigation (Erans et al., 2022).Thus, to expand the deployment and bring DAC projects to fruition, more funding is required.

This literary review focuses on the comparison between DAC and other negative emission technologies based on the process, benefits, risk, economics and efficiency in carbon capture. The goal of this project is to investigate direct air capture and illustrate its role and advantages in reducing the impact on climate change.

Introduction

Climate change is one of the biggest challenges that humanity needs to overcome (United Nations, n.d.). From centuries of deforestation (Ritchie & Roser, 2021) and use of fossil fuels, we find ourselves in a situation where millions of people have lost their homes (CoreLogic, 2022), around 2.4 billion people are exposed to dangerous levels of air pollution and around 7 million people die every year due to the polluted air exposure (World Health Organization, 2022).

With only about 20% of the world's energy being renewable and most transportation and industries still relying on fossil fuels, we must start relying on Negative Emissions Technology (NET) to lower the concentration of CO2 in the atmosphere. Negative Emissions Technology are methods that remove greenhouse gasses from the atmosphere, and they are used to prevent or slow down the worsening of climate change. One of these NETs that has recently gained more attention is Direct Air Capture (DAC). The method uses chemical and physical processes to capture and store CO2 for future use. The idea for DAC was first suggested as a viable means of mitigating climate change in 1999 by Klaus Lackner (Ozin, 2022). Today, DAC is an effective means of removing CO2 from the atmosphere; although, as will be discussed, it can be costly.

Direct Air Capture

Development

When the idea of DAC emerged in 1999 (Ozin, 2022), the main research was on the sorption processes of capturing CO2 from the atmosphere. Most research was done on possible chemical solutions that had strong binding properties to efficiently capture concentrations of

CO_2 in the air that go as low as 0.6%. Additional research focused on improving the energy demands and cost reduction of industrial scale DAC plants (Erans et al., 2022).

It was only in May 2017 that the first industrial scale DAC plant started operating. The plant was built in Zurich, Switzerland (Climeworks, 2017). Today, there are a total of 27 operational and commissioned plants in Europe, North America, Japan and the Middle East–with 18 being operational in America, Canada and Europe (International Energy Agency, 2022).

Company	Country	CO2 use	Operational since
Global Thermostat	United States	R&D	2010
Global Thermostat	United States	R&D	2013
Climeworks	Germany	Customer R&D	2015
Carbon Engineering	Canada	Power to X	2015
Climeworks	Switzerland	Power to X	2016
Climeworks	Switzerland	Greenhouse Fertilization	2017
Climeworks	Iceland	CO2 Removal	2017
Climeworks	Switzerland	Beverage Carbonation	2018
Climeworks	Switzerland	Power to X	2018
Climeworks	Italy	Power to X	2018
Climeworks	Germany	Power to X	2019
Climeworks	Netherlands	Power to X	2019
Climeworks	Germany	Power to X	2019
Climeworks	Germany	Power to X	2019
Climeworks	Germany	Power to X	2020
Climeworks	Germany	Power to X	2020

Climeworks	Germany	Power to X	2020
Climeworks	Switzerland	CO2 Removal	2021

Table 1: List of location, use and operations start year of current operational Direct Air Capture plants

The table shows a list of Direct Air Capture plants, which company owns them, the country they are located in, and when the plants became operational. The CO2 use column shows for what the captured CO2 is being used. R&D stands for research and development, Power to X means that the electricity being generated is being used to make carbon neutral synthetic fuels (International Energy Agenecy, 2022).

Technologies

There are two types of sorbents that can be used in DAC: liquid and solid. Solid sorbents that are used in DAC are filters that bind with CO2. Solid sorbent DAC or S-DAC, uses a unit(s) with a fan to draw in air. The air then passes through the sorbent filters that absorb the carbon dioxide from the air.

Once the air passes through the filters, clean air is released, leaving only CO2 behind. Once the filters are filled with CO2, the unit(s) that houses the fans is closed and heated. After heating, the filters release the concentrated CO2–which is either stored for use or sequestered underground (International Energy Agency, 2022).

Liquid sorbents use chemical solutions to draw in the CO2. Liquid sorbent DAC or L-DAC, operates in two different loops. The first loop happens in the air contractor where the contractor brings the air in contact with the solution. The second loop occurs when CO2 is released from the solution by using pressure and heat. The released CO2 is stored or sequestered, and the sorbent is regenerated by heat at around 800 degrees Celsius. The largest operational S-DAC captures around 4000 tonnes of CO2 every year, and a liquid sorbent plant can capture around a megaton of CO2 a year (International Energy Agency, 2022).

Globally the average person produces around 4 tons of CO2 per year, which means the current S-DAC can capture 1000 people's worth of CO2 per year and a L-DAC can capture 250,000 people's worth of CO2 per year. Although solid sorbent DAC captures less than a liquid sorbent DAC, solid sorbent DAC comes in a modular design, can house as many units as needed, and is less capital intensive. Solid and liquid sorbents both have similar functions and goals but have their own benefits and disadvantages.

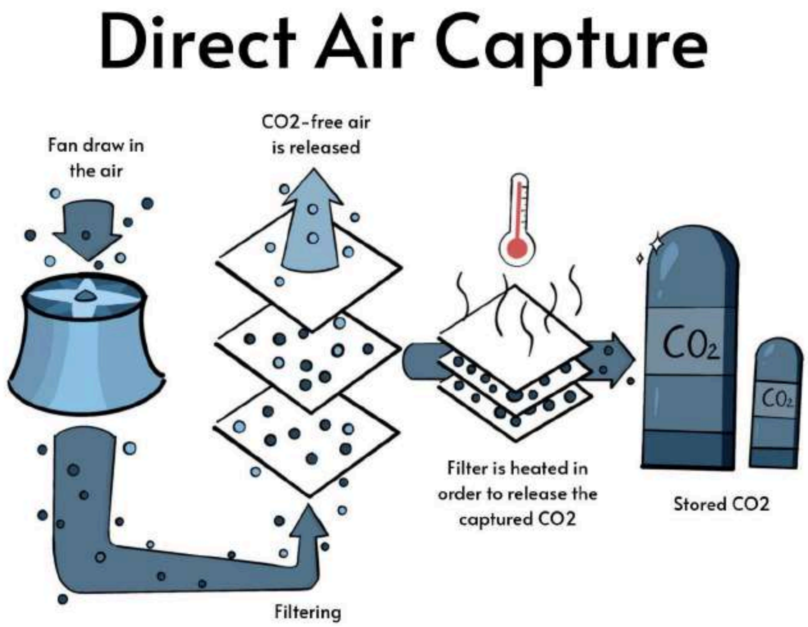

Figure 1: How S-DAC captures CO2

S-DAC first uses a fan to draw in air which is then filtered through solid adsorbents inside the unit. CO2 sticks to the adsorbent while clean air passes through and is released. The fan keeps drawing in air until the filters are full which then the unit housing the fan is closed to be heated up. The units are heated up to as low as 80°C or as high as 480°C in order to release the CO2. The released CO2 is then captured and transported to be purified. Graphic created by the Author (Kovitchindachai, 2023).

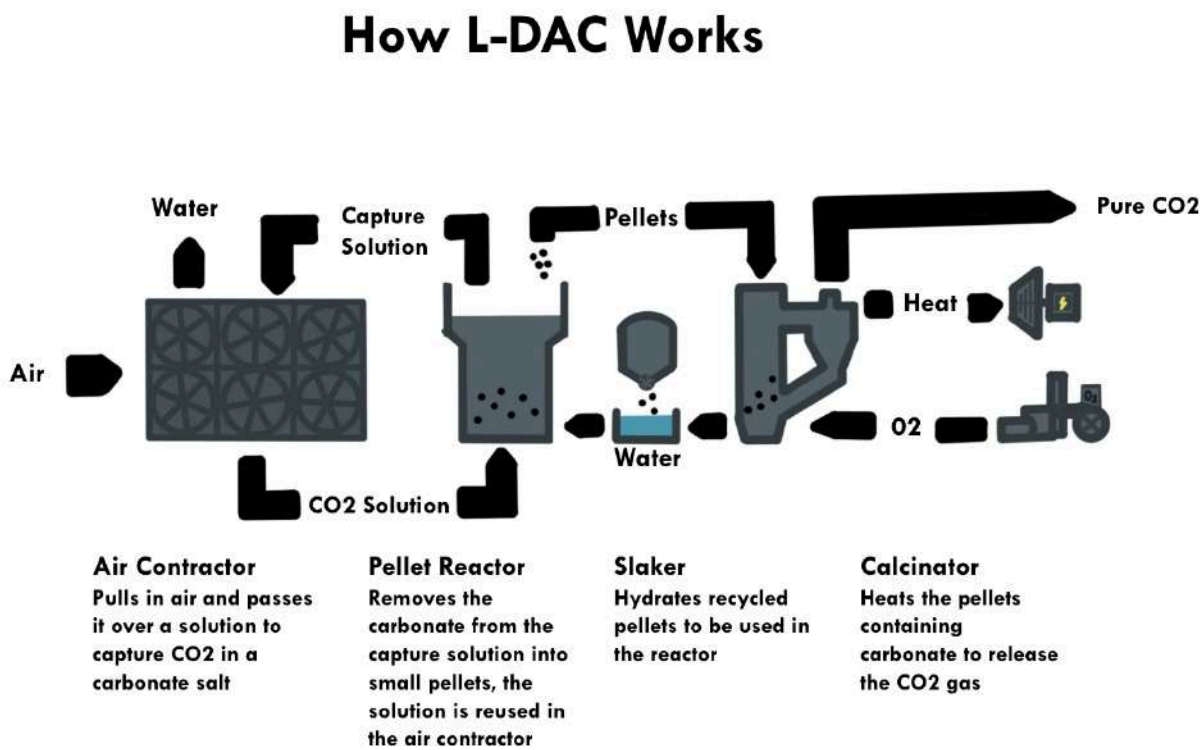

Figure 2: How L-DAC captures CO2

L-DAC uses an Air Contractor to pull in air that reacts to a solution to create carbonate salt. The salt is put in the pellet reactor where the carbonate is removed into the pellets. The pellets are then heated to release the CO2 gas. The capture solution and the pellets are reused in this process. Graphic created by the Author (Kovitchindachai, 2023).

Benefits and Challenges

The main benefit of using DAC is that both solid and liquid options don't need a large amount of land to operate, they aren't limited by climate, and that they are fit for large scale operations, as well as small scale (Lebling et al., 2022). To further elaborate, this means that DAC can be deployed anywhere in the world regardless of the environment unlike other NETs that may require arable land or a body of water. On top of that, it also means that DAC is a more space efficient method to remove CO2 from the atmosphere compared to other methods.

In addition to the actual CO2 captured by DAC, the output can be used in oil recovery, manufacture of fuels, chemicals, and building materials. These secondary products help drive down the costs of producing DAC and reuse the captured CO2 that would otherwise be stored underground (Erans et al., 2022,).

However, the major problem of DAC lies in its high energy need and cost compared to other NETs. DAC requires 1200 Kilowatt hours to capture a tonne of CO2, consuming $250-$600 every hour. However, depending on the rate of deployment and development, the cost of DAC technology is expected to drop as low as $150-$200 per hour by the end of this decade (Lebling et al., 2022).

	Energy Cost	Water Usage	Possible Sorbents	Benefits	Challenges
S-DAC	7.2-9.5 GJ/ton of CO2 [1]	-2-0 tonnes of H2O/ton of CO2 [2]	Silica Activated Carbon Graphite Polymers Zeolite [3]	Possible water production Less capital intensive Modular Likely to see cost reduction [5]	More energy intensive Requires manual maintenance for adsorbent replacement [6]
L-DAC	5.5-8.8 GJ/ton of CO2 [1]	0-50 tonnes of H2O/ton of CO2 [2]	Aqueous Alkaline Solutions Aqueous Amines Amino Acids Peptides [4]	Less energy intensive Uses commercial solvents Large scale carbon capture [5]	More capital intensive Relies on natural gas combustion for solvent regeneration [6]
Sources	[1](International Energy Agency, 2022)	[2](International Energy Agency, 2022)	[3](Zachary, 2022) [4](Custelcean, 2022)	[5](International Energy Agency, 2022)	[6](International Energy Agency, 2022)

Table 2: Comparison of S-DAC and L-DAC

This table compares the energy cost, water usage, as well as the benefits and challenges of each. The statistics of the energy cost and water usage show the ranges into which the costs could fall. They are information that has been taken from all of the current operational DAC plants. A Gigajoule is equivalent to a billion joules or enough to power an average American home for a week (U.S. Energy Information Administration, 2022).

Other NETs

In addition to DAC, there are other NETs that are viable options for removing CO2 from the atmosphere. These include Bioenergy with Carbon Capture and Sequestration (BECCS), Coastal Blue Carbon, and Carbon Mineralization.

Bioenergy with Carbon Capture and Sequestration

Within BECCS, biomass, wood, crops, and manure are burned to create bioenergy, which in turn is used for electricity, liquid fuels, gas, or heat. The byproduct of the burning is then captured and stored underground for later use. The biomass that is used for burning would be sustainable and constantly take in atmospheric CO2 with the constant cycle of harvest and regrow. This means that in theory, energy would be produced while taking atmospheric CO_2 and not allowing the CO_2 byproduct to get in the atmosphere (Karlsson et al., 2021). However, the main problems of BECCS are, but not limited to, land usage, efficiency and costs.

Another concern with BECCS is that if the CO_2 is improperly stored underground it can harm the nearby soil reducing growth in vegetation and plant life (Babin et al., 2021). The biggest operating BECCS project is the Illinois Industrial CCS Project, which has been storing captured CO_2 underground since 2018, with the Red Trail Energy Bioethanol Project being operational in 2022 (International Energy Agency, 2023).

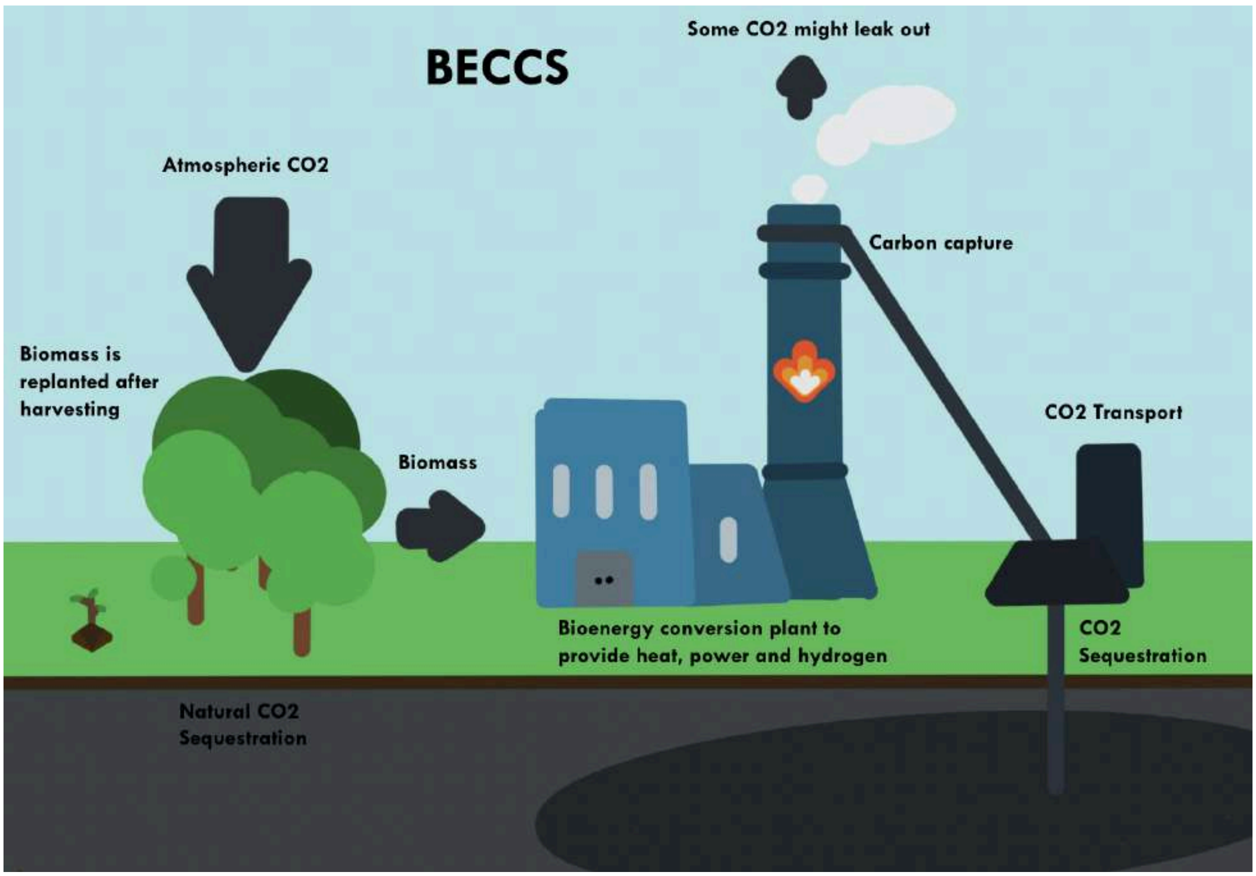

Figure 3: BECCS

Bioenergy with Carbon Capture and Sequestration works by using biomass. This includes but is not limited to wood, crops and manure. It starts when Biomass is harvested and put in a conversion plant to create heat, power or hydrogen. The carbon produced would be ideally captured and transported to where they will be sequestrated. In this diagram, the biomass used is trees which absorb atmospheric CO2 and naturally sequesters CO2. It is natural that some CO2 might leak out but is usually counter acted by the amount of CO2 absorbed by the biomass. Graphic created by the Author (Kovitchindachai, 2023).

Coastal Blue Carbon

Coastal Blue Carbon refers to the carbon that the plant life in coastal or wetland ecosystems capture and stored in the vegetation and soil. These living organisms act as a natural carbon sink that accumulates and stores carbon for an indefinite amount of time. Coastal Blue Carbon relies on the marine plants around the coasts like microplankton, algae and seaweed. Marine plants around the coast take in and sequester carbon much faster than forests, making them an effective carbon sink.

Currently the only way that we can use Coastal Blue Carbon is by preserving, protecting, or restoring these marine ecosystems, which have shown positive effects and benefits for the wildlife (National Ocean Service, 2022). Although Coastal Blue Carbon looks good on paper, there are concerns with the method. Some of the main problems with Coastal Blue Carbon is that it has a lack of permanence due to the fact that although you can restore an ecosystem, it will degrade and release the stored carbon if it is not maintained. In addition, it lacks a standardized methodology that can regulate the stored carbon, and Coastal Blue Carbon often lacks funding to implement them on a large scale despite having a large global warming reduction potential (Smoot, 2023) (Williamson & Gattuso, 2022).

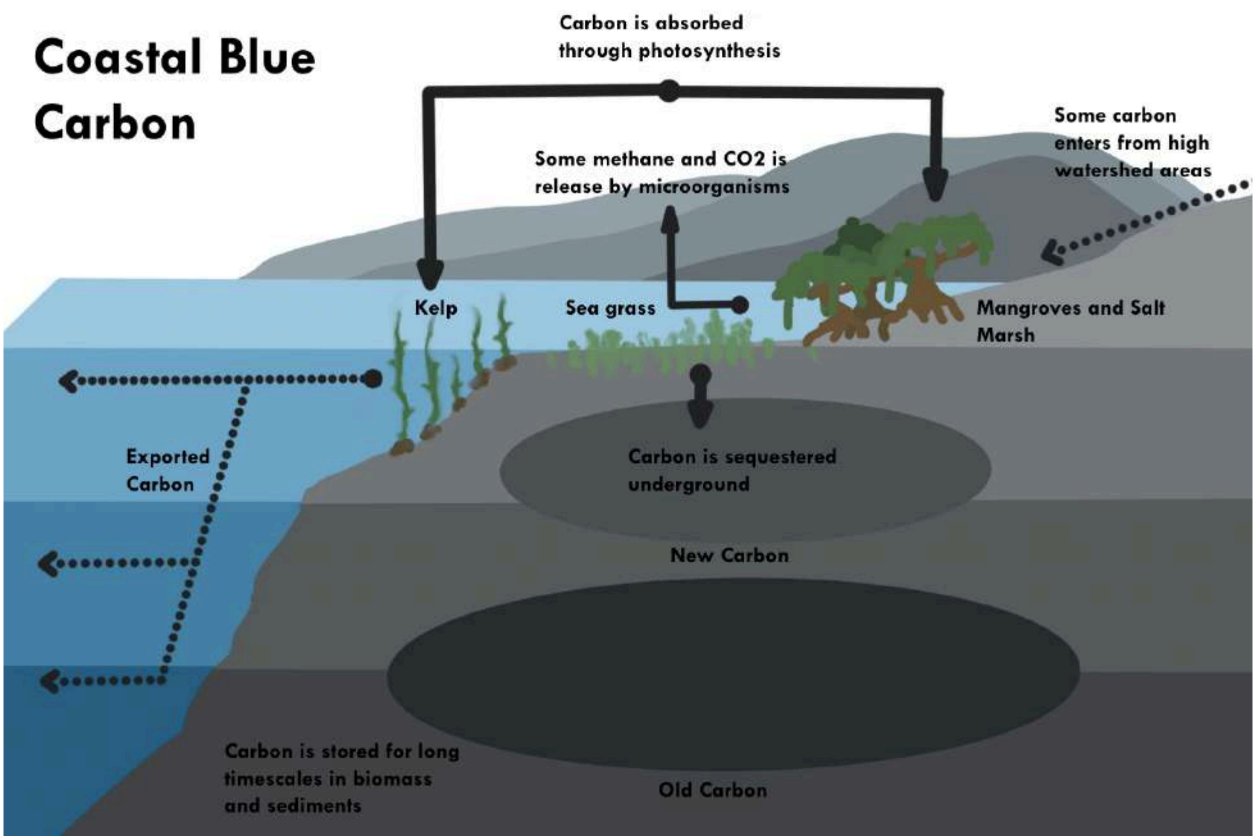

Figure 4: Coastal Carbon Blue

Coastal Blue Carbon works with many ecosystems, including mangroves, seagrass and kelp. It all starts when carbon is absorbed through photosynthesis. Carbon that is absorbed from mangroves and seagrasses are sequestered in sediments or biomass. While carbon absorbed from Kelp is exported throughout the ocean. During this process some methane and carbon is *released by microorganisms, however in theory, the rate at which carbon is absorbed from the atmosphere would counteract it.* Graphic created by the Author (Kovitchindachai, 2023).

Carbon Mineralization

Carbon Mineralization occurs when CO2 becomes a solid through chemical reactions as it is exposed to certain rocks. In the specific case of carbon capture, CO2 is injected into these underground rocks, using heavy machinery. The rocks with the best potential of mineralizing carbon are basalt and ultramafic (Gadikota, 2021) rocks. Ultramafic refers to the type of rock that has high amounts of magnesium and iron and Basalt refers to a rock that is formed by the rapid cooling of magma.

The biggest advantage of using carbon mineralization is that once the carbon has been mineralized it cannot escape back to the atmosphere. (United States Geological Survey, 2019) Although Carbon Mineralization is a good method of storing carbon, it does not come without risks. The biggest concern is the potential of triggering earthquakes with the injection. Other hazards would include negatively impacting underground and surface ecosystems, as well as the large use of water during the process (Smoot, 2023).

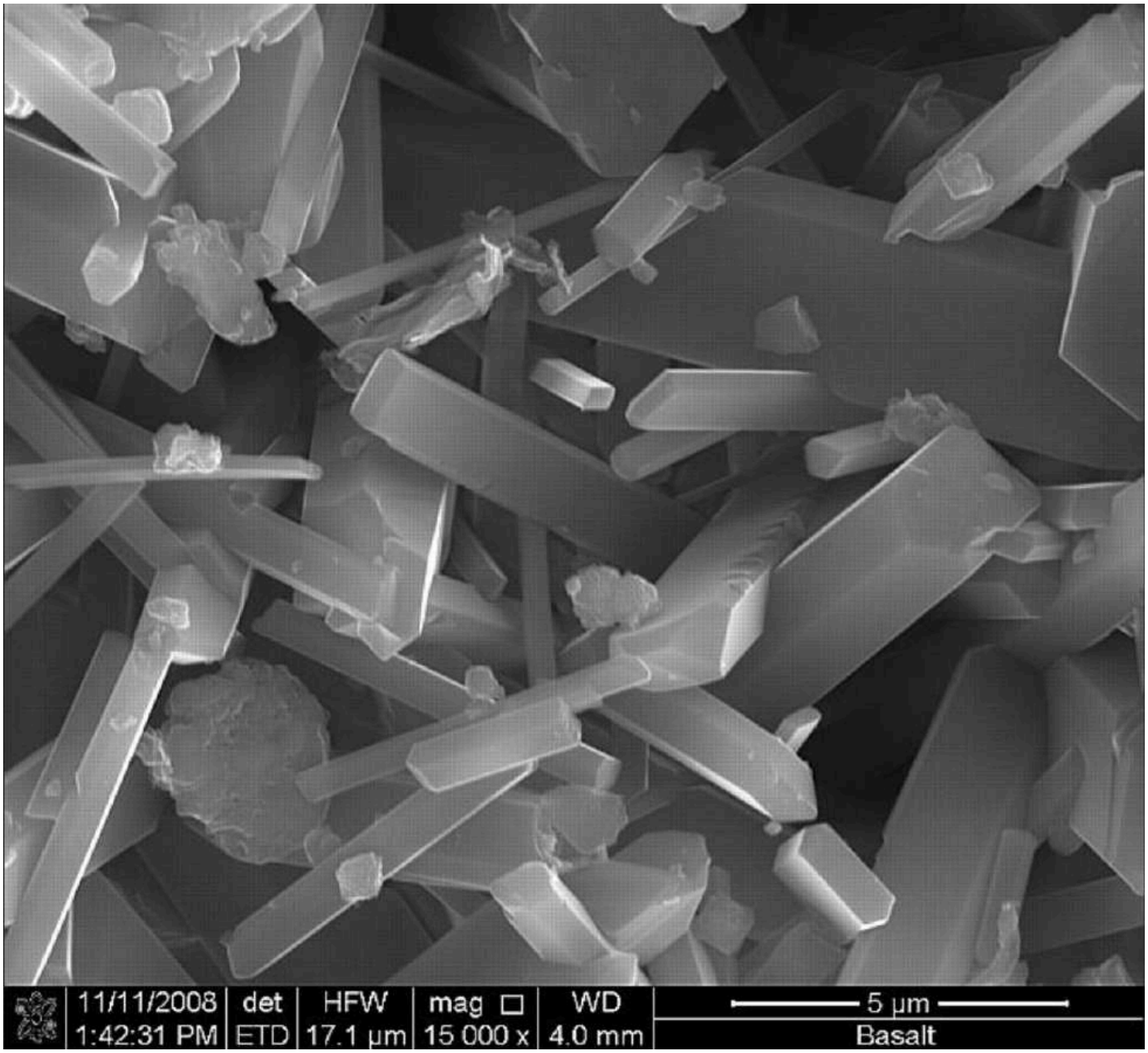

Figure 5: Carbon Mineralization

Carbon Mineralization is when ultramafic rocks are exposed to carbon which overtime creates a new mineral which stores carbon. This result can also be achieved by directly injecting carbon into veins of ultramafic rocks. While this process is relatively simple, it is expensive and carries risks: possible earthquakes due to the disruption of geological formations and negative effects to ecosystems nearby. "Carbon dioxide capture" by Oregon State University is licensed under CC BY-SA 2.0.
https://www.flickr.com/photos/pnnl/8678026507/in/gallery-153442368@N06-72157690173227850/

	DAC	BECCS	CBC	Mineralization
Main principle	Extracting CO2 directly from the atmosphere at any	Capturing and permanently storing CO2 from biomass	Sequestering CO2 by using and preserving coastal	Sequestering CO2 by exposing ultramafic rocks to

	location [1]	that is converted into fuels or directly burned to generate energy [6]	marine ecosystems [11]	CO2 or directly injecting CO2 into them [15]
Advantages	DAC plants come in a modular design which can reduce manufacturing and operating costs. [2] They are able to be scaled up or down in size to fit our needs. [2] They can contain as many units as needed. [2] DAC produces zero if not almost zero onsite emissions that will negatively impact human health or the environment [3]	Generates heat, electricity and hydrogen [7] Has potential for a greater efficiency with geothermal energy [8]	Advantageous for climate adaptation, food provision and biodiversity conservation [12] Protects coastal communities from rising sea and flooding [12] Highly effective at sequestering CO2 [13]	Plenty of possible reserves to store CO2[16]
challenges	Constraints with costs and energy requirement makes it hard to scale up or implement DAC worldwide [4] There are risks with sequestering CO2 into geological formations. Pipelines could leak polluting groundwater and disrupting geological formations may lead to earthquakes [5]	Rainwater carrying nitrogen fertilizer can causes eutrophication in aquatic systems [9] Changes in Soil Organic Carbon and air quality [9] BECCS uses a lot of arable land which can be used for agriculture [10] BECCS could potentially harm biodiversity by harvesting from	Coastal Blue Carbon solutions often lack permanence, a standardized methodology and financial support [14]	Biochar applications may cause negative effects in soil and the environment. [17] May suppress soil nutrient availability and crop productivity due to the reduction in plant nutrient uptake or reduction in soil carbon mineralization [17]

		existing forests and converting the forest into a monoculture plantation [10] Requires large amounts of water [10]		
Sources	[1] (International Energy Agency, 2023) [2](Beuttler et al., 2019) [3](Lebling et al., 2022) [4](Lebling et al., 2022) [5](Rhode, 2021)	[6](International Energy Agency, 2023) [7](Bui et al., 2021) [8](Titus et al., 2023) [9](Albanito et al., 2019) [10](Fern & d'Edimbourg, 2022)	[11](International Union for Conservation of Nature, n.d.) [12](Williamson & Gattuso, 2022) [13](Sustainable Travel International, 2021) [14](Smoot, 2023)	[15](National Energy Technology Laboratory, n.d.) [16](Kelemen et al., 2020,) [17](El-Naggar et al., 2019)

Table 3: A comparison of different NETs

The table compares the principles and possible advantages and challenges of each NET. Biomass refers to anything that is organic that can be used for Bioenergy production. Geothermal energy refers to energy that is produced from the internal heat of Earth. Eutrophication refers to when a body of water becomes over abundant of minerals, leading to algal blooms which eventually kills off fish and seagrass. Arable lands refers to any land that is capable of being plowed and used for growing crops. Ultramafic rocks refer to igneous rocks that have a low silica content. Biochar refers to charcoal that is made from plant matter.

Methods

Scoping Review

A scoping review is a literary review that is commonly used to summarize or show known information about a specific topic. The main reasons for using a scoping review are to identify the extent, range and nature of a topic. In addition scoping reviews are also used to disseminate research findings and make recommendations for future research. (Mak & Thomas, 2022) (Peters et al., 2021).

Terms Searched

(de Jonge et al., 2019, #) keywords "DAC" "Efficiency"

(Azarabadi & Lackner, 2019, #) keywords "DAC" and "Sorbent"

(Beuttler et al., 2019, #) keywords "Direct Air Capture" and "Benefits"

(Bui et al., 2021, #) keywords "BECCS" and "Electricity"

(Titus et al., 2023, #) keywords "BECCS" and "Efficiency"

(Yang et al., 2021, #) keywords "BECCS" and "Cost"

(Albanito et al., 2019, #) keywords "BECCS" and "Environmental Impact"

(Wang et al., 2023, #) keywords "Coastal Blue Carbon" and "Cost"

(Lovelock & Reef, 2020, #) keywords "Coastal Blue Carbon" and "Maintenance"

(Williamson & Gattuso, 2022, #) keywords "Coastal Blue Carbon" and "Benefits"

(Kelemen et al., 2020, #) keywords "Carbon Mineralization" and "Megaton"

(El-Naggar et al., 2019, #) keywords "Carbon Mineralization" and "Environmental Impact"

Supplementary sources

In addition to the articles that have been searched, This paper has also used data from government, and organization websites to help support the overall argument. Two that were specifically used a lot were the International Energy Agency and Climeworks which gives a full analytical report on the different operational Direct Air Capture plants.

Results

The research done provided the information regarding the current capacity, costs, benefits and impacts of these NETs. The results include data on the amount of CO2 captured by each method per year globally, the estimated costs, any resources they may rely on and any benefits or effects it may have.

An average person's carbon footprint is 4 tonnes

1 Megaton = 1,000,000 tons

1 Gigaton = 1,000,000,000 tons

	DAC	BECCS	CBC	Min.
Current capacity	Almost 0.01 Mt CO2 globally every year (International Energy Agency, 2023) Land usage 0.42 sq. meters/ton of CO2 (Climeworks, n.d.) 50-700kJ per mole CO2 captured	All BECCS plants currently removes 56 MtCO2 combined per year (Bui et al., 2021, #) Land usage 1000-4000 sq. meters/hypothetical ton of CO2 (Fern & d'Edimbourg, 2022)	Current blue carbon solutions remove 0.4-1.2 metric Gigatons (1000 Megatons) of CO2 every year Emerging solutions can add up to an extra 1.8 Gigaton of CO2 per year to about 3 Gigatons per year.	Total Global reserves of 100 million tonnes Total possible reserves estimated ten to hundred of trillions tonnes Total reserves refer to underground alkaline rocks that have been used. Possible reserves

	More effective once a renewable source of energy is used (de Jonge et al., 2019, #)		Mangroves 23.5-42.9 tonnes of CO2 every year/ha Seagrass 12.5-17.4 tonnes of CO2 every year/ha Kelp Forest 1.4 tonnes of CO2 every year/ha Restoring mangroves costs around $9,000 per hectare Around 600,00 hectares need to be restored meaning a cost of 5.4 billion dollars (McKinsey & Company et al., 2022)	refer to alkaline rocks underground (Kelemen et al., 2020)
Costs	Estimated costs ranging from $50-$600/ton of CO2 (Zeechan et al., 2023, #)	PC-CCS $37.76/ton of CO2 PBC-CCS $59.58/ton of CO2 (Yang et al., 2021)	Mangrove forests, salt marshes, and seagrasses Costs ranging from $15-250/ton of CO2 sequestered (McKinsey & Company et al., 2022)	Weathering and Calcining Costs ranges from $48-$193/ton of CO2 mineralized Dispersal in soil or seawater Costs ranging from $25-$52/ton of CO2 (Kelemen et al., 2020)
Reliance on rare metals and resources	DAC relies heavily on the special sorbents with high capture capacity, fast kinetics, long	BECCS uses resources that are easily obtainable and produced	Coastal Blue Carbon is easily reversible so it requires a lot of maintenance	Alkaline rocks, tailings and byproducts (Kelemen et al.,

	life time but affordable. (Azarabadi & Lackner, 2019) Examples Aqueous Calcium Hydroxide Aqueous Sodium Hydroxide Ionic Liquid Aqueous Amine Modified Solid Amine (Zeechan et al., 2023)	Crops, wood, waste (Bui et al., 2021)	(Lovelock & Reef, 2020)	2020)
Other environmental impacts	DAC produces zero if not almost zero onsite emissions that will negatively impact human health or the environment (Lebling et al., 2022)	Rainwater carrying nitrogen fertilizer can causes eutrophication in aquatic systems Changes in Soil Organic Carbon and air quality (Albanito et al., 2019)	Restoration of coastal blue carbon ecosystems, coastal protection, food provision and biodiversity conservation (Williamson & Gattuso, 2022)	Biochar applications may cause negative effects in soil and the environment. May suppress soil nutrient availability and crop productivity due to the reduction in plant nutrient uptake or reduction in soil carbon mineralization (El-Naggar et al., 2019)
Benefits	DAC plants come in a modular design which can reduce manufacturing and operating costs. They are able to be scaled up or down in size to fit our needs.	Generates heat, electricity and hydrogen (Bui et al., 2021, #) Has potential for a greater efficiency with geothermal energy (Titus et al., 2023)	Advantageous for climate adaptation, food provision and biodiversity conservation Protects coastal communities from rising sea and flooding (Williamson &	Plenty of possible reserves to store CO2 (Kelemen et al., 2020,)

	They can contain as many units as needed. (Beuttler et al., 2019,)		Gattuso, 2022) Added benefits of recreation and tourism. (American University, 2018)	

Table 4: Costs and efficiency of NETs

The table shows and compares the current capacity or efficiency, costs, reliance on any rare resources, environmental impacts and benefits of the four mentioned NETs: DAC, BECCS, CBC and Carbon Mineralization. The Current capacity compares the amount of CO2 sequestered or stored globally, as well as some land requirements. The costs compare the costs of running/maintaining the plant/ecosystem.

Discussion

So which NET is the best for reducing our carbon footprint? There's no clear answer to this question. Every method has its benefits and constraints: DAC is efficient with space at the cost of high costs and energy usage; BECCS tends to be on the cheaper side however, it requires a lot of space; CBC sequesters the most CO2 per year but costs a lot to restore and maintain; Carbon mineralization's main advantage is the amount of reserves that are available to use for sequestering, but come with risks of possible earthquakes and negative impacts on the environment on top of high costs.

Although DAC can capture and store CO2 directly from the atmosphere at any location, the costs and energy usage makes it hard for its widespread deployment. Even though BECCS tends to be cheaper, it uses a tremendous amount of water, as well as land that could be used for agriculture. CBC helps biodiversity, provides protection to coastal communities and sequesters CO2 much faster than any other NET. That said, restoration and maintenance of CBC ecosystems is costly. Carbon mineralization, even though having the resources and technology to sequester a large amount of CO2, carries the risk of possible earthquakes and negative effects to the soil and environment.

Although it is difficult to pinpoint any one NET that substantially triumphs over the others, it appears that DAC has the most potential. This is because it is the most space efficient, able to be deployed anywhere in the world and also has a lot of room for growth and development. However, more resources are needed to develop DAC on a large enough scale to leverage it as a substantial climate change solution. In addition, we must concurrently dedicate resources and research to other NETs. As has been previously discussed, often where one NET fails, another prospers. NETs that would help preserve biodiversity while providing benefits to communities like CBC should be considered, since protecting biodiversity in ecosystems, I would argue, is just as important as solving the current climate crisis.

The growth and development of NETs promise large gains, DAC promises the reduction in costs, energy usage and the deployment of larger DAC plants that would capture much more CO2. BECCS promises a higher efficiency in using different fuels. And CBC promises an increase of 1.8 Gigatons of CO2 captured per year with the use of emerging solutions. Despite promising good results, the reality is that for these scenarios to be in reach they usually need a lot more funding. As things currently stand, there is no accurate data to which NET will triumph over the other.

To help NETs generate more funding or conduct research, some governments establish policies or create programmes. As for DAC in The United States, Canada, the European Commission, and the United Kingdom, they have all established policies and programmes. The United States established the 45Q tax credit, the California Low Carbon Fuels Standard credit, the Inflation Reduction Act, the Infrastructure Investment and Jobs act, the funding of four large scale DAC hubs, and the transport and storage of related infrastructure (International Energy Agency, 2023).

Moreover, Canada placed an investment tax credit at 60% for investment of DAC equipment from 2022-2030 (International Energy Agency, 2023). The European Commission supported DAC through research and innovation programmes, including Horizon Europe, the Innovation Fund and the ReFuelEU Aviation Proposal. The United Kingdom, announced the latest 2023 spring budget which aims to help fund all CCUS applications which includes DAC (International Energy Agency, 2023).

The combined efforts of these governments will without a doubt help DAC progress to its next stages of development to achieve the Net Zero Scenario. In fact, the funding of multiple large-scale DAC plants has helped DAC stay close on track with the Net Zero Scenario by 2050.

As of now, due to the large cost of DAC the future research regarding it should mainly focus on the reduction of manufacturing and energy costs. As the process of re-releasing the CO2 after capture is the most intensive part of the process, innovation is required to create different separation systems. One of these innovative systems currently being developed is the Electro Swing Adsorption. The Electro Swing Adsorption relies on electrochemical cells that use charges to capture and release carbon. A power source creates a voltage that causes electrons to travel to the quinone, a class of organic compounds, causing it to become negatively charged. When air containing CO2 comes in contact with these quinones, the CO2 molecules get captured by the quinone. The quinone will keep capturing CO2 until all of its surfaces are filled up. During the release, the voltage is reversed, which makes the quinone no longer negatively charged, and thus no longer has any chemical affinity with CO2. The CO2 is then released and sent out of the system to be stored or sequestered. Although there has not been a full performance test conducted yet, capital plus operating costs are estimated to be at $50-100 per ton of CO2 captured (Stauffer, 2020). This is a large reduction from the current operating costs of around $50-600 per ton of CO2 captured.

With new emerging systems for DAC, it is likely that there will be a large reduction in operating costs of DAC somewhere in the near future. This would practically negate the negatives of DAC and turn it into a viable option for the Net Zero Scenario.

Conclusion

This paper is meant to educate willing readers about current technologies and recent developments in Carbon Capture while mainly focusing on Direct Air Capture. As NETs become more important, it is crucial that people understand the urgency and the recent developments of such technologies. To scale up these technologies, public support is required as well as a need for a broad public education about the benefits and challenges of such technologies.

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