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# SWOT Analysis of Selected Carbon Dioxide Removal Technologies

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supervised by
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# Affidavit

I, **ÁDÁM FÜZI, MA**, hereby declare

1. that I am the sole author of the present Master's Thesis, "SWOT ANALYSIS OF SELECTED CARBON DIOXIDE REMOVAL TECHNOLOGIES", 84 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
2. that I have not prior to this date submitted the topic of this Master's Thesis or parts of it in any form for assessment as an examination paper, either in Austria or abroad.

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## Abstract

In order to mitigate climate change, mankind must discover the appropriate method to restrain the increase in the Earth's mean temperature. In order to meet the goal set by the Paris Agreement of limiting global warming to below 2ºC, it is necessary to not only focus on discovering the appropriate technologies but also on managing the available time effectively. This thesis compares a several selected Carbon Dioxide removal technologies through analysis of literature reviews and secondary literature reviews, and subsequently compares the technologies using a SWOT analysis. The objective of this thesis is to identify the currently operational Carbon Dioxide Removal (CDR) technologies that are most likely to have a significant impact on reducing atmospheric $CO_2$ concentrations, in order to fulfill the target of limiting global warming to below 2ºC. The selected CDR technologies are: Direct Air Capture with Carbon Storage (DACCS), Bioenergy with Carbon Capture and Storage (BECCS), Biochar, Enhanced Rock Weathering, Ocean Alkalinization, Ocean Fertilisation, Afforestation and Reforestation, Soil Carbon Sequestration technologies. Through the SWOT analysis this thesis used different kinds of datas such as: TRL (Technology Readiness Level), storage type, durable storage, cost at scale, mitigation potential, MRV, risks, energy requirements, number of publications and patents through the last twenty years, social acceptance through public media and others.

Through the SWOT analysis, two technologies have emerged as having more potential than the others: DACCS and forestation and reforestation technologies.

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# 1. Introduction

Climate change is real and it has a critical importance to stop global warming somehow. The probability of human factors contributing to global climate change is 95% (IPCC, 2013).

Climate change is a worldwide issue that presents shared difficulties and necessitates synchronised efforts among nations. Individually, human activities create a range of harmful impacts that spread worldwide through various intricate routes, resulting in significant environmental, economic, and societal repercussions. GHG emissions specifically cause long-lasting and essential alterations in the Earth's overall climate and in the strength and occurrence of severe weather phenomena. In addition, the environmental aspects of the issue are tightly intertwined with economic and social factors such as fairness, inclusivity, sustainable development, and justice. This offers an extra difficulty that necessitates comprehensive efforts.

The Paris Agreement on climate change was developed and adopted in 2015 as an international framework to reduce greenhouse gas (GHG) emissions and enhance the ability to cope with the effects of the global climate catastrophe. The signing countries pledge to take specific actions at various time intervals to ensure that the global temperature rise remains below 2°C compared to pre-industrial levels (Samaniego et al., 2023). Additionally, they will strive to restrict this increase to 1.5°C (UNFCCC, 2015).

Based on climate projections by the Intergovernmental Panel on Climate Change (IPCC), the commitments outlined in the Paris Agreement, assuming a future scenario of significant reductions in emissions RCP 2.6, are expected to align with the proposed targets for global average temperature by the end of the century (Samaniego et al., 2023). Nevertheless, the present rate of emissions, as projected in the RCP 8.5 scenario, will result in a global average temperature increase that surpasses these objectives. The temperature rise is estimated to be at least 4°C, which would have catastrophic effects on ecosystems, the economy, and society as a whole (IPCC, 2013). The successful execution of the Paris Agreement necessitates an approach that acknowledges the local obligations and supplementary aims of the signatory nations, which are intertwined with the global goals.

Climate engineering, or geoengineering, refers to a collection of technologies that modify the Earth's climate system to attain a certain degree of control over climate. These technologies hold the potential to mitigate global and local climate change as well as identify and address global risks brought on by the climate crisis.

We distinguish between two main forms of Climate Engineering: Carbon Dioxide Removal (CDR), which removes atmospheric $CO_2$ and store it in geological, terrestrial, or oceanic reservoirs, and Solar Radiation Management (SRM), which aims to reflect some sunlight and heat back into space.

This thesis will investigate the potential of selected Carbon Dioxide Removal methods.

### 1.1. Motivation

In order to mitigate climate change, mankind must discover the appropriate method to restrain the increase in the Earth's mean temperature. In order to meet the goal set by the Paris Agreement of limiting global warming to below 2°C, it is necessary to not only focus on discovering the appropriate technologies, but also on managing the available time effectively. Here Carbon Dioxide removal technologies will be compared. In order to accomplish this, an analysis will be conducted of literature reviews and secondary literature reviews, and subsequently compare the technologies using a SWOT analysis in the thesis. In conclusion of this, the objective is to identify technologies that satisfy both of these crucial requirements and has the capacity to mitigate global warming in the long run.

### 1.2. Research question

The objective this thesis is to identify the currently operational Carbon Dioxide Removal (CDR) technologies that are most likely to have a significant impact on reducing atmospheric $CO_2$ concentrations, in order to fulfil the target of limiting global warming to below 2°C as set by the Paris Agreement. My research question is: *Is there a currently available carbon dioxide removal (CDR) technology that can effectively and consistently decrease atmospheric $CO_2$ levels in the near future, making a meaningful contribution to achieving the Paris Agreement's aim of keeping global warming below 2°C?*

## 2. What is the current relevance of debating CDR?

Five years after the implementation of the Paris Agreement on climate change it is increasingly acknowledged that unless there is a significant increase in efforts, it will not be feasible to restrict the increase in world average temperature to 1.5–2ºC. (UNFCCC, 2015). The World Metrological Organisation has determined that there is a 40% probability of the average world temperature exceeding 1.5ºC over preindustrial levels in at least one of the next five years (Samaniego et al., 2023; WMO, 2021). This poses a substantial threat to both natural and human systems, as well as our capacity to achieve sustainable development. (Masson-Delmotte et al., 2018).

Advancement towards attaining the objectives of the Paris Agreement has been sluggish. Despite the full implementation of all the current Nationally Determined Contributions (NDCs) under the Paris Agreement, it is anticipated that the Earth would still see a temperature increase of 3°C by the end of the century, with a 66% likelihood range of 3.0-3.5 Co (Samaniego et al. 2023; UNFCCC, 2020).

The IPCC Special Report on Global Warming of 1.5°C demonstrates the collective failure to effectively address global warming, as evidenced by the emission pathways it presents. (Masson-Delmotte et al., 2018). In order to restrict global warming to 1.5°C, it is necessary to employ Carbon Dioxide Removal (CDR) methods to extract $CO_2$ from the atmosphere. These possibilities suggest that it is necessary to eliminate between 100 billion and 1,000 billion tons (Gt) of $CO_2$ by the year 2100, highlighting the urgency of swift and unparalleled global measures. (Samaniego et al., 2023; Masson-Delmotte et al., 2018).

According to the latest IPCC assessment, out of the five scenarios examined, only two suggest that it is possible to restrict the average world temperature increase to 1.5–2°C. Both of these scenarios rely on significant reductions in emissions and the use of carbon dioxide removal (CDR) techniques to achieve a state of zero net emissions and eventually negative net emissions. (Masson-Delmotte et al., 2021). In this context, the proposal for CDR options is gaining traction. However, it is important to note that the concept of removing and storing $CO_2$ is not a recent one. It has been an integral part of global climate agreements since 1992, when the United Nations Framework Convention on Climate Change (UNFCCC) recognised that mitigation efforts encompassed both reducing emissions and removing $CO_2$ from the atmosphere (Masson-Delmotte et al., 2021; Mace et al., 2021).

Implementing CDR on a large scale, amounting to many Gigatons, is anticipated to result in global cooling impacts. However, these effects would only become noticeable over a period of several decades. The IPCC pathways incorporate and simulate such consequences. (IPCC, 2021; Masson-Delmotte et al., 2018). Attaining and maintaining a state of worldwide net negative $CO_2$ emissions would result in a slow reversal of global surface temperature increase. However, other climate changes consequences, such as sea-level rise, would persist on their current trajectory for several decades to thousands of years. (Masson-Delmotte et al., 2021).

Unless cost-effective and environmentally and socially acceptable carbon dioxide removal (CDR) becomes practical and widely accessible before 2050, achieving routes commensurate with limiting global warming to 1.5°C will be challenging. (Masson-Delmotte et al., 2018).

There are still significant uncertainties surrounding a number of the techniques, including their long-term carbon removal potential, potential impacts on a global scale, and the probable environmental, social, and economic costs associated with their implementation. Divergent decisions made by researchers concerning a multitude of complex factors, such as climate change scenario selection, probable future adaptation strategies, innovation timelines, opportunity costs, and future innovation cost discounting, exacerbate these uncertainties. They are all likely to have an impact on the results of their evaluations. Further controversies surround the suitability of existing governance frameworks for CDR as a whole and for each specific technique, in addition to the uncertainties surrounding CDR techniques themselves. Florin, et al. (2020) have authored comprehensive examinations of governance and international law that are pertinent to the CDR.

## 3. An introduction to Carbon Dioxide Removal

Carbon Dioxide Removal (CDR) is the process of human activities that extract carbon dioxide ($CO_2$) from the atmosphere and securely store it in geological, terrestrial, or oceanic reservoirs, or in products, according to the definition provided by the Intergovernmental Panel on Climate Change (Samaniego et al., 2023; Masson-Delmotte et al., 2018). It is alternatively referred to as carbon removal, carbon drawdown, or anthropogenic $CO_2$ removal (Samaniego et al. 2023). Negative Emissions Technologies (NETs) and Greenhouse Gas Removal (GGR) are broad concepts that encompass Carbon Dioxide Removal (CDR), but they also encompass other greenhouse gases like methane (Samaniego et al., 2023). Currently, there are no established techniques for effectively eliminating non-$CO_2$ greenhouse gases (GHGs) (Samaniego et al., 2023).

CDR and Carbon Capture and Storage (CCS) are frequently misunderstood and mixed together. CCS involves the capture of carbon dioxide ($CO_2$) emissions at their origin, such as a fossil fuel power plant, followed by the long-term storage of the captured $CO_2$ (Samaniego et al., 2023). When connected to a fossil fuel power station, this can be seen as a measure to reduce emissions by preventing the discharge of additional pollutants into the atmosphere. Consequently, CCS prevents the increase in the amount of $CO_2$ in the atmosphere, whereas CDR eliminates previously emitted CO2, thereby decreasing the overall volume of $CO_2$ in the atmosphere (Samaniego et al., 2023).

Carbon dioxide removal (CDR) strategies employ several methodologies to eliminate and sequester carbon. There are various approaches to removing carbon from the atmosphere. Some involve using engineering techniques to directly extract carbon from the air. Others combine natural systems with engineering methods. Nature-based approaches, such as tree growth or changes in land use management, can also be used to enhance carbon absorption._(Samaniego et al., 2023).

# 4. Selected CDR techniques

## 4.1. Afforestation and Reforestation

Afforestation and Reforestation, which involves deliberately planting trees in areas where they have not historically grown, and reforestation, which involves replanting trees in areas where they have been cut down, died, or removed, are crucial actions in addressing climate change. These actions result in a net absorption of $CO_2$ as the trees grow, making them significant in current climate change response efforts (Doelman et al., 2020). Once a tree's life cycle reaches its conclusion, it undergoes decomposition, which leads to the release of $CO_2$ back into the atmosphere (Samaniego et al., 2023).

Forest management can prevent the emission of $CO_2$ by selectively harvesting older trees and storing their biomass in durable wood products, such as those used in construction.

For instance, it has been proposed that approximately 0.5 to 1 gigatons of carbon dioxide per year may be captured and stored in buildings for extended periods of time (McLaren, 2012).

Productive forest management can also utilise byproducts for the production of bioenergy or biochar (RS/RAE, 2018). The net ability of forestation to remove carbon dioxide from the atmosphere is currently undetermined.

There are several unresolved concerns related to its efficiency, location, and impacts. These include effects on biodiversity and soil health, changes to watersheds, and implications for water resource management (Samaniego et al., 2023). There is a need for a more comprehensive knowledge of the trade-off between the carbon sequestration and warming consequences of tree planting (Samaniego et al., 2023). For instance, the presence of trees with predominantly dark leaves, such as conifers, can result in a net increase in temperature (Lundquist et al., 2013). More research on climate models is therefore required to better understand the full effects of changes to forestry cover (Samaniego et al., 2023; Winckler et al., 2019).

According to Griscom et al. (2017) recommodation, the potential of reforestation to remove carbon dioxide ($CO_2$) from the atmosphere ranges from 3 to 10 gigatons of $CO_2$ per year. This range depends on the assumptions made about the amount of land available for planting, which might vary from 350 to 1780 million hectares (Griscom et al., 2017). Previous research used to generate the estimate of the Intergovernmental Panel on Climate Change (IPCC) suggests that the world would have the ability to emit between 1 and 7 gigatons of carbon dioxide ($GtCO_2$) year by the year 2050 (Masson-Delmotte et al., 2018). However, there are other estimations such as Smith et al. (2015) predicts that the highest amount of carbon dioxide that may be captured and stored through the process of forestation will be only 12 gigatons per year by the year 2100 (Samaniego et al., 2023). For the swot analysis (see chapter 6), the latest available estimates based on Smith et al. (2023) (Table 4.) will be used. The establishment of forests will give rise to trade-off tensions about land use alteration and future land use possibilities, such as food production and other methods of $CO_2$ removal. Therefore, policy trade-offs may emerge as a significant future focus of forestation governance (Hammad, 2020). There is a need for a more comprehensive understanding of how to effectively manage trade-offs between different land use options, such as biomass and bio-fuel production, cropping and grazing, and forestation (Samaniego et al., 2023). This must be done while also ensuring the protection of the culture and rights of indigenous peoples in a fair, economically sustainable, and socially acceptable manner (Florin et al., 2020).

It is crucial to carefully evaluate local conditions before making any judgements about Afforestation and Reforestation, as there is no universally applicable strategy (RS/RA, 2018). Crucially, the act of planting may weaken the ability of landowners to make money in the near future, leading them to desire assurance regarding any payments that can cover the time between planting and harvest (Samaniego et al., 2023).

Currently, on a worldwide scale, the intention is to use forestation to fulfil 25% of all committed Nationally Determined Contributions (NDCs) for mitigating climate change by the year 2030 (UNFCCC, 2015). Furthermore, the Bonn Challenge, (IUCN, 2011) which aims to restore 350 million hectares of forest by 2030, has received official support and an extension through the New York Declaration on Forests during the 2014 UN Climate Summit (Samaniego et al., 2023; UN, 2014). So far, the Declaration has received support from 40 national governments, 56 enterprises, and over 70 civil society and indigenous peoples' organisations (Samaniego et al., 2023).

There is a need for enhanced monitoring of Afforestation and Reforestation rates, as well as the establishment of a globally agreed-upon accounting system (Samaniego et al., 2023). This task is demanding and will necessitate allocation of resources in order to achieve desired results. Monitoring challenges encompass accounting for the fluctuating species uptake capability over time in various environments, considering intricate soil and irrigation variations (Samaniego et al., 2023). Additionally, there are complexities in reporting and verifying gas fluxes across a sector that acts as both a sink and source of $CO_2$ and other greenhouse gases from natural and human origins (Samaniego et al., 2023; Welch, 2019).

## 4.2. Biochar

Biochar, a robust and durable carbon derivative, represents a widely recognised and established process. Biochar is produced via pyrolysis when biomass is heated to temperatures above 250°C in a confined container with little or no available air (Samaniego et al., 2023). It is possible to achieve carbon negativity when sustainable biomass production is integrated. Biochar is anticipated to not only store carbon but also enhance soil quality, crop yields, water quality, and nutrient levels when stored in soil for extended periods (Lehmann, 2015; Smith, 2016).

Research suggests that one metric ton of biochar has the potential to remove between 2.1 to 4.8 metric ton of carbon dioxide ($tCO_2$), although there is still some uncertainty. For instance, the Intergovernmental Panel on Climate Change (IPCC) estimates a global potential removal of carbon dioxide between 0.3 and 35 gigatons ($GtCO_2$) per year by 2050, while other studies propose a cumulative removal potential ranging from 78 to 477 $GtCO_2$ over the course of this century (Masson-Delmotte et al., 2018; ICRLP, 2018). According to Smith et al. (2023) the mitigation potential of Biochar is rather lower than it was estimated before. For the swot analysis (see chapter 6), the latest available estimates based on Smith et al. (2023) (Table 4.) will be used.

There is now a diverse array of ongoing biochar research aimed at gaining a deeper understanding of the characteristics that define "high-quality" biochar in its use for agricultural and environmental purposes (Woolf et al., 2010; Fuss 2018).

The deployment and build up of biochar are not anticipated to give rise to significant societal concerns, however there might be some social hesitancy and worries regarding potential impacts on forests or food supplies (Smith et al., 2010).

Developers of infrastructure should ensure clear communication with the local community regarding the combustion processes and their resulting by-products. Monitoring, reporting, and verifying the adoption and utilisation of biochar can pose challenges, both domestically and globally. (RS/RAE, 2018). Enhanced accounting will be crucial in the future, and there is a possibility that biochar will eventually be regulated by international governance systems like the CBD and UNFCCC (Samaniego et al., 2023).

## 4.3. Soil Carbon Sequestration

Carbon can be captured and stored in soil, depending on the characteristics of the soil, its usage, and the availability of resources. There are no major technical obstacles to the process of Soil Carbon Sequestration (Samaniego et al., 2023). The practices involved are well understood and, in certain cases, already implemented in farming (Samaniego et al., 2023). Furthermore, there are ongoing efforts to promote this method as a means of achieving the climate change goals outlined in the Paris Agreement, including the "4 per 1000 initiative" (RS/RAE, 2018; Soussana et al., 2019).

Evaluating the worldwide ability to store carbon in this manner is intricate, and estimates obtained from modelling are consequently diverse, spanning from 1 to 11 $GtCO_2$ each year (Lal, 2011; Lal, 2013; Minasny, 2017). In order to precisely assess the amount of carbon stored and the release of non-carbon greenhouse gases using this method, it is necessary to have fast and dependable techniques for measuring soil carbon and gas fluxes (Lal, 2011; RS/RAE, 2018).

According to Smith (2016), implementing the necessary techniques has the potential to generate a profit of up to $3 per ton of $CO_2$ by enhancing productivity. Under different conditions, contingent upon soil and environmental factors, Smith proposes that the deployment might potentially incur a cost of up to $12 per ton (Smith, 2016).

However, it is crucial to note that the ability to store more carbon each year will decrease over time as soils reach their saturation point. The process of sequestration can only be sustained for about 20 years, after which it becomes impossible to further store carbon through these interventions (Zomer et al., 2017).

Some members of the farming/land management community lack information about the benefits of the strategy. To expand its use, education and training will be necessary to overcome this obstacle (Minasny, 2017).

For the cost at scale values (see chapter 6), the latest available estimates based on Smith et al. (2023) and Möllersten & Naqvi (2022) (Table 4.) will be used during the swot analysis.

## 4.4. Direct Air Carbon Capture & Storage (DACCS)

DACCS encompasses a range of technologies that employ chemical engineering principles to extract carbon dioxide ($CO_2$) from the surrounding atmosphere. The carbon is subsequently sequestered in methods that do not contribute to the phenomenon of global warming. The literature mentions various potential ways for sequestration (Samaniego et al., 2023; GESAMP, 2019; IPCC, 2005).

Such as: include: injecting liquid $CO_2$ into the oceans; injecting into the seabed, seabed depressions, sediments or trenches; and, mineralisation of injected $CO_2$ within geologic structures (Samaniego et al., 2023).

DACCS units can be located independently of GHG generating industrial infrastructure. DACCS facilities can be strategically situated in close proximity to renewable or low emissions energy sources, ideally over geologically adequate formations for $CO_2$ storage, and in places that are neither environmentally sensitive nor densely populated (RA/RAE, 2018; Goeppert, 2012).

The literature mostly focuses on two DACCS techniques for extracting $CO_2$. Adsorption refers to the process in which a chemical collects molecules onto its surface from another substance. On the other hand, absorption involves the uptake of $CO_2$ into the volume of another material, essentially being absorbed. Additional new methodologies encompass electro-swing, humidity-swing, carbonate looping, and membrane separation (Voskian & Hatton, 2019; Fasihi, 2019; Samari et al., 2019; Fujikawa et al., 2021).

DACCS technologies are currently at the intermediate stage between pilot plant development and small-scale or prototype field demonstration. According to conservative estimates, as proposed by Viebahan et al. (2019), it seems improbable that Direct Air Capture and Carbon Storage (DACCS) would be widely accessible until the year 2030 (Hanna et al. 2021). Propose that allocating 1.2 to 1.9% of the global Gross Domestic Product (GDP) to DACCS would result in the annual removal of around 2 $GtCO_2$ (Samaniego et al., 2023).

Prior to the expansion of technology, several unresolved matters such as energy demands, the durability of $CO_2$ storage, and the requirements for natural resources must be addressed (RS/RAE, 2018).

By 2050, DACCS is projected to have a global sequestration potential ranging from 0.5 to 5 Gigatons of $CO_2$ per year in the long term (Fuss, 2018). According to Smith et al. (2023) the mitigation potential of DACCS can reach the 40 Gigatons of $CO_2$ per year. For the the swot analysis (see chapter 6), the latest available estimates based on Smith et al. (2023) (Table 4.) will be used.

Both adsorption and absorption methods need significant amounts of heat or energy to provide air to the plant and to regenerate the agents and release the $CO_2$. According to Daggash et al.

(2019), the process of absorption-based Direct Air Carbon Capture and Storage (DACCS) will necessitate an energy input ranging from 1500 to 2500 kWh for heat, in addition to an extra 220-500 kWh of power every metric ton of $CO_2$ removed. The energy needs for adsorbents range from 200 to 1000 kWh of power and 640 to 1700 kWh of heat per metric ton of $CO_2$ (Climeworks, 2020). Once $CO_2$ is removed, the process of sequestration, regardless of the chosen method, will require additional energy resources. For instance, in the context of transportation and the process of transferring fluids into reservoirs (Samaniego et al., 2023).
In order to optimise the capacity of Direct Air Carbon Capture and Storage (DACCS) to remove carbon from the atmosphere, it is most effective to obtain the necessary energy from environmentally friendly sources with minimal carbon emissions, such as solar, wind, and nuclear power (Samaniego et al., 2023).
Another option is to locate DACCS plants near industrial facilities that produce waste heat, such as gas power plants. Nevertheless, for widespread deployment of DACCS to depend on renewable energy sources, it is imperative to achieve higher efficiency and a significant increase in global renewable energy capacity (Samaniego et al., 2023). Aside from the energy and heat demands, there are additional expenses that necessitate careful consideration, such as: Water resources required for capturing and storing one ton of $CO_2$ range from 1 to 30 cubic metres (Climeworks, 2019; Smith, 2016). Although DACCS does not necessitate the use of biomass and does not pose a threat to ecosystems, it is necessary to conduct a life cycle assessment of DACCS technologies, as stated in the RS/RAE report of 2018 (RS/RAE, 2018). Sorbent replacement costs and other maintenance (Fuss, 2018). $CO_2$ sequestration costs–including preparation for deposition, transport and, depending on Location and type of storage, storage costs, capital investment and opportunity costs (Samaniego et al., 2023).
The financial expenses of scaled up DACCS vary significantly in estimates. For instance, (Sanz-Pérez et al. 2016). provide an estimated cost range of $30 to $1,000 per ton of $CO_2$ captured, as stated in their study. On the other hand, it is estimated a cost range of $100 to $300 per ton, according to their study (Fuss et al., 2018). The current cost of small-scale pilot plants is below $600 per ton (Climeworks, 2019; Samaniego et al., 2023). For the cost at scale value (see chapter 6), the latest available estimates based on Smith et al. (2023) and Möllersten & Naqvi (2022) (Table 4.) will be used during the swot analysis.

An analysis of research needs assessments conducted by indicates that the following areas are crucial for future DACCS research, without any specific order of importance: Enhancing energy, thermal, and water efficiency (Sandalow, 2018; Gambhir, 2019; NAS, 2019).

Enhancing comprehension of the sustainability effects of Direct Air Capture and Carbon Storage (DACCS) (Sandalow, 2018; Gambhir, 2019; NAS, 2019). Addressing lingering uncertainty in the carbon cycle (Sandalow, 2018; Gambhir, 2019; NAS, 2019). Enhancing the efficiency of producing synthetic renewable fuels by utilising collected carbon. (Sandalow, 2018; Gambhir, 2019; NAS, 2019). Acquiring a more comprehensive comprehension of the methods to effectively achieve ecologically neutral, long-lasting carbon removal and storage (Sandalow, 2018; Gambhir, 2019). The study of the economic and policy aspects of a carbon market that is compatible with DACCS. The societal approval of DACCS (Sandalow, 2018; Gambhir, 2019) exploring the relationship between DACCS (Direct Air Capture and Carbon Storage) and mitigation policy (Sandalow, 2018; Gambhir, 2019). International measurement and management of carbon emissions and the systems and structures that oversee it (Sandalow, 2018; Gambhir, 2019).

DACCS plants are expected to occupy a relatively modest area, in contrast to medium-sized industrial facilities, and they will not pose any risks in terms of land availability, including impacts on ecosystem services or food security (RS/RAE, 2018). In addition, DACCS plants are not limited by geographical constraints, meaning that they do not need to be located in sensitive locations or close to communities, as long as they have access to energy and water supplies. The placement of DACCS facilities is not anticipated to generate substantial concerns regarding social acceptability, except for those that may come from the plans for any medium-sized industrial complex (RS/RAE, 2018).

## 4.5. Bioenergy with Carbon Capture and Storage (BECCS)

Bioenergy with carbon capture and storage (BECCS) involves the combustion of biomass to produce power, heat, or liquid fuel. The carbon dioxide ($CO_2$) released during the process of burning is subsequently trapped and stored in underground reservoirs for an extended period of time, so effectively eliminating its presence in the carbon cycle (RS/RAE, 2018). Although BECCS is included in several integrated assessment models evaluated by the IPCC, it is still considered a nascent technology. While each component of the technology has been successfully shown and implemented at both demonstration and commercial scales, there are relatively few actual commercial-scale plants in existence globally (Brack & King 2021).

In order for BECCS to be successful, it is crucial to have a consistent and reliable source of biomass. This biomass can either be cultivated specifically for this purpose or obtained from waste materials (Samaniego et al., 2023). It is important to source the biomass locally to limit emissions caused by transportation. When farming, it is crucial that the crop chosen is fast-growing and can be quickly replenished (Samaniego et al., 2023). Additionally, it is necessary to ensure that the BECCS crop does not compromise the availability of crops for food security or other essential purposes. (RS/RA, 2018).

Implementing BECCS (Bioenergy with Carbon Capture and Storage) on a large scale will need altering land use, which could result in competition for resources with food production. (Samaniego et al., 2023).

This may lead to higher food costs or have implications for food security (Bui et al., 2017). Furthermore, the growth of biomass crops will necessitate the availability of both water and nutrients, which might potentially lead to additional conflicts, particularly in regards to the achievement of the Sustainable Development Goals (SDGs) (Samaniego et al., 2023).

The issue of land use change may lead to conflicts, and policy makers will have to find ways to strike a balance between the need for land to support BECCS (Bioenergy with Carbon Capture and Storage) and the requirements for settlements, energy production, carbon removal, and food production. It is crucial to promptly address the national policy commitments, bioenergy, BECCS deployment methods, and their environmental implications in nations that have already made these commitments (RS/RAE, 2019).

BECCS governance typically encompasses two components: biomass production and utilisation, as well as carbon capture and storage (CCS) features (Torvanger, 2019). The latter primarily pertains to the monitoring, reporting, and validation (MRV) of collection and storage, as well as the safety and permanence of long-term storage. The Biomass agenda focuses on the measurement of sustainability and resource utilisation in relation to the production, processing, and use of biomass energy, as well as its impact on the global carbon cycle. The need to balance the production of BECCS biomass with other land and water uses necessitates governance focus, typically at the local level (Torvanger, 2019).

## 4.6. Ocean Alkalinization

Since the absorption of $CO_2$ in oceans leads to acidity, increasing the alkalinity on the ocean's surface will cause the ocean to take in more $CO_2$ from the atmosphere. Increasing alkalinity would also mitigate the impacts of ocean acidification on the marine ecology (GESAMP, 2019; Samaniego et al., 2023). Although no field trials have been conducted, increasing alkalinity does not necessitate any innovative or new technology. The necessary raw materials are already accessible from cement and other industries or naturally occurring minerals (Samaniego et al., 2023). Alternatively, the distribution of carbonate and silicate mineral weathering could be enhanced through electrochemical methods using ships (RS/RAE, 2018; Samaniego et al., 2023). However, there is a very large carbon and energy footprint in the current manufacturing processes of some of the materials (RS/RAE, 2018). These approaches can also be implemented on land (see to Enhanced Rock Weathering below), thus eliminating the expenses associated with transportation over oceans (Samaniego et al., 2023).

The potential effects of introducing particles from these materials into the maritime ecosystem are uncertain, indicating that additional investigation would be necessary before adoption (GESAMP, 2019).

The IPCC does not provide an estimate for the potential capacity of chemically boosting alkalinity to remove $CO_2$ (Masson-Delmotte, et al., 2018). Presently, there is a scarcity of ongoing research on the technique (Bach et al., 2019), and additional research is necessary to enhance our understanding of which minerals or other substances would yield the most favourable net $CO_2$ reduction, the potential effects on marine ecosystems, the duration of sequestration, the economic and resource efficiency of the methods, and the monitoring of both implementation and its consequences (GESAMP, 2019; Samaniego et al., 2023).

Corner et al. (2014) indicate that the public may not be supportive of ocean-based interventions of this nature, suggesting acceptability research about the technique may also be warranted (Samaniego et al., 2023).

The approach can be classified as falling within Annex 4 of the London Convention and London Protocol, as well as UNCLOS (Hubert, 2020). Additional stakeholders may encompass intergovernmental or civil society organisations as well as commercial entities associated with chemical engineering (Samaniego et al., 2023).

## 4.7. Enhanced Rock Weathering

The principal mechanism by which carbon dioxide ($CO_2$) is removed from the atmosphere over long periods of time is through the weathering of carbonate and silicate rocks. During this process, the rocks react with $CO_2$ to generate carbonates, effectively reducing the amount of carbon in the atmosphere (RS/REA, 2018). Enhanced Rock Weathering aims to intentionally simulate and expedite this process by dispersing minerals onto the surface or incorporating them into agricultural soil. The existing mining, grinding, and farm machinery technology is anticipated to have the ability to extract, process, and distribute the material. Nevertheless, a significant expansion of the existing machinery and infrastructure on a worldwide scale would be necessary (Florin et al., 2020).

The fundamental comprehension of the chemical processes involved in enhancing weathering of carbonate or silicate minerals to reduce $CO_2$ is highly developed. This implies that the main obstacles to implementing this approach are related to scaling up, cost considerations, potential environmental impacts, and various governance issues, rather than technical uncertainties regarding the method itself (Samaniego et al., 2023). The potential of increased weathering to mitigate $CO_2$ emissions is almost unlimited, provided that a significant amount of minerals can be efficiently processed, distributed, and implemented on a broad scale (IPCC, 2013).

According to (Smith et al., 2016) applying 10 to 30 tons of material per hectare per year to two-thirds of all croplands might result in the removal of between 0.4 and 4 gigatons (Gt) per year of material through improved weathering by the year 2100.

The IPCC proposes a theoretical carbon removal range of 0.72 to 95 GtCO2 per year, but acknowledges the need for further evidence before reaching a consensus on these figures. A new experiment on accelerated weathering has indicated that the technique may be up to three times less efficient than previously believed (Masson-Delmotte et al., 2018; Amann, 2020).

For the mitigation potential value (see chapter 6), the latest available estimates based on Smith et al. (2023) (Table 4.) will be used during the swot analysis.

An important concern related to improved weathering is the necessity to extract, pulverise, transport, and distribute substantial amounts of material. According to the Royal Society and Royal Academy of Engineering (2018), if we had a technique that was 100% efficient, we would need to remove at least 7 $km^3$ of material per year to offset the same amount of $CO_2$ that we are now generating. This amount is twice the volume of all the coal that was mined in 2018 (Samaniego et al., 2023).

Additionally, it is proposed that the process of accelerated weathering on the Earth's surface could potentially have advantageous effects on crop development by altering the availability of nutrients (De Oliveira, 2020).

The technique can potentially result in adverse effects, such as the emission of fine particulate pollution and the accumulation and release of nickel and chromium into aquatic and marine systems (Edwards et al., 2017). Therefore, further research on the environmental impact is necessary, in addition to the existing proof of concept and small-scale field trials (McQueen et al., 2020; Kelemen, 2020; GGREW, 2020; Samaniego et al., 2023).

If improved weathering on land is carried out, it would be subject to the laws and governance norms of the countries where it takes place. If increased weathering were to be implemented on a large scale, it would necessitate the establishment of new international systems to monitor, verify, and report its effects. These processes should also take into consideration the potential impacts of the strategy across borders. (Samaniego et al., 2023).

### 4.8. Ocean Fertilisation

Plankton in the ocean perform the remarkable task of photosynthesis, which results in the removal of approximately 40 Gt $CO_2$ per year from the ocean surface. This carbon dioxide is then transported downwards to the deep ocean, contributing to the intricate carbon cycle (RS/RA, 2018). Iron ocean fertilisation aims to enhance this process by introducing extra micronutrients to stimulate greater plankton growth. It is technically feasible to distribute iron or nitrogen and/or phosphorus into the oceans, and the industrial infrastructure needed for this task is well understood (GESAMP, 2019).
According to some experts, taking into account all the associated costs such as production, transportation, and distribution, nitrogen fertilisation could be a more effective method of sequestration compared to iron fertilisation (Harrison, 2017; Matear & Elliot, 2004). According to Harrison, the technique has the potential to reduce annual global $CO_2$ emissions by up to 15% based on theoretical calculations (Harrison, 2017).
Further research is necessary to fully comprehend the feasibility of this approach and the necessary supply chain infrastructure and market mechanisms that would support its implementation. Given the decline in phosphorus stocks, there is growing concern about the future ability to fertilise crops. The limited supply and price volatility of phosphorus may also have significant implications for the geo-politics of its use (GESAMP, 2019).
This technique is covered by Annex 4 of the London Protocol, which imposes restrictions on dumping (Hubert, 2020). Various organisations, including intergovernmental and civil society groups, as well as commercial entities involved in food production and mining, may have a vested interest in the governance of this technique (Samaniego et al., 2023).

## 5. SWOT analysis

### 5.1. What is SWOT analysis

The SWOT (strengths, weaknesses, opportunities, threats) analysis, which examines an organization's internal and external environments and is commonly employed when a decision is uncertain, has emerged as an essential instrument for organisations to assess their market position (Rozmi et al., 2018; Wu, 2020). It entails a comprehensive and detailed examination of both internal and external factors pertaining to the business or process, with the intention of comprehending its viability and achievement (Sharath Kumar & Praveena, 2023). Strengths are intrinsic qualities of an organisation that aid in the achievement of its objectives, whereas weaknesses are internal qualities that impede the success of the organization (Benzaghta et al., 2021). Opportunities—extraneous factors that facilitate the achievement of an organization's objectives—include not only favourable environmental conditions but also prospects to fill in deficiencies and commence novel undertakings (Benzaghta et al., 2021). Conversely, threats refer to elements of the external environment that impede or have the potential to impede the

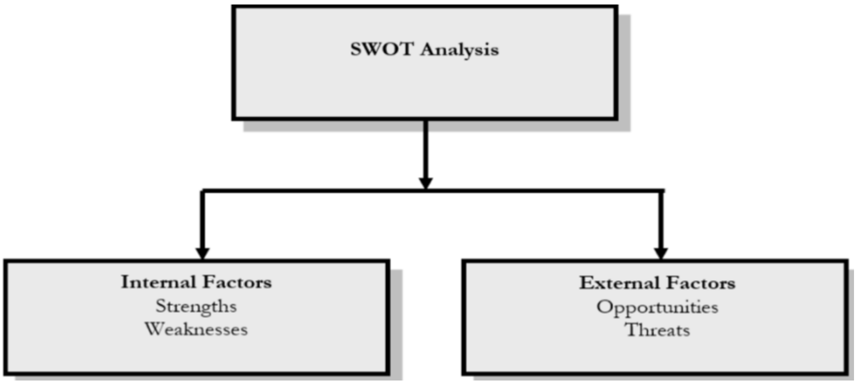


***Figure 1***: SWOT Analysis (Emet & Merba, 2017)

achievement of the organization's objectives (Aldehayyat & Anchor, 2008; Fleisher & Bensoussan, 2003; Lee & Lin, 2008; Shrestha et al., 2004).

## 5.2. The SWOT Matrix

The utilisation of a SWOT analysis enables the evaluation of business elements by considering their respective strengths, vulnerabilities, opportunities, and threats (Jackson et al., 2003; Kim, 2005). SWOT analysis identifies potential internal and external threats to the achievement of a company's objectives. The internal aspects pertain to characteristics that are under the jurisdiction of the organisation (Bull et al., 2016; David et al., 2017). In contrast, the external aspects are elements that are beyond the control of the organisation. The SWOT analysis, which combines evaluations of a company's opportunities, threats, vulnerabilities, strengths, and weaknesses, can be utilised to generate viable alternatives for the organisation (Lee & Ko, 2000; Valentin, 2001). These techniques can effectively elucidate the process of aligning opportunities and threats with strengths and vulnerabilities. Managers have the ability to formulate four distinct strategies, namely SO (strengths-opportunities), ST (threats-strengths), WO (weaknesses-opportunities), and WT (weakness-threats), in response to internal and external factors (David et al., 2019; Thomas et al., 2014) states that the SWOT matrix can also be constructed using instruments such as the internal factors evaluation (IFE) matrix, the external factors evaluation (EFE) matrix, or the competitive profile matrix (CPM).

According to (Benzaghta et al., 2021) the SWOT matrix is as follows:

• SO strategies: capitalising on favourable circumstances.

• ST strategies involve threat avoidance.

• WO strategies involve the mitigation of vulnerabilities in order to create new opportunities.

• WT strategies consist of minimising weaknesses to avert threats.


***Figure 2***: SWOT matrix (Benzaghta et al. 2021.)

SWOT analysis is a useful instrument during the evaluation phase for gaining a preliminary understanding of potential future repercussions. The SWOT analysis is a straightforward method of analysis that can offer an objective assessment of an organization's strengths and weaknesses. Furthermore, it conducts an analysis of the current competitive landscape and provides an overview of discrepancies between the current and future plans (Armstrong, 1982; Robinson & Pearce, 1988). Furthermore, SWOT analysis is a tried and true method that does not necessitate the use of specialised software or computer systems (Beeho & Prentice, 1997).

### 5.3. Approaches Employed in SWOT Studies

The underlying rationale for conducting a SWOT analysis seems to be valid. Ghazinoory et al. (2011) found that the majority of SWOT analyses are case studies implemented across various industries, whereas only a limited number of papers fall under the methodological or applied-methodological category. SWOT analyses also make extensive use of survey questionnaires (Dawes, 2002). According to (Dawes, 2002), the utilisation of five-point scale items has the potential to enhance the reliability of SWOT analyses. Subsequent to this methodology, the items were classified into categories based on a five-point scale and assigned weights commensurate with their significance (Dawes, 2002) and (Coman, & Ronen, 2009) assert that specific criteria ought to be adhered to when assessing the SWOT analysis: succinctness, actionability, significance, and reliability.

In addition, other methodologies have been employed by researchers in conjunction with the SWOT approach. As an illustration, the pottery industry in Bangladesh was examined by Muzahidul et al. (2020) through the implementation of an AHP method and a combination of SWOT analysis and suitable strategies. In a similar vein, (Wu, 2020) utilised a SWOT analysis in conjunction with the PESTEL framework and five forces model to assess IKEA's international and cost leadership strategies. By integrating such assessments, one can obtain a holistic understanding of the business environment. This is because a SWOT analysis primarily focuses on internal activities and decisions, while a PESTLE analysis acknowledges external factors that are predominantly beyond the control of the business (Sigcha et al., 2021). Furthermore, the competitive environment of a business can be assessed using a five forces model, which considers the following five critical elements: the impact of substitute products, the competitive rivals of the business, suppliers, consumers, and potential new entrants to the market (Wellner & Lakotta, 2020).

Adem et al. (2018) evaluated the occupational safety hazards throughout a wind turbine’s life cycle by uitilising a SWOT analysis and hesitant fuzzy linguistic sets. The integration of a SWOT analysis alongside alternative methodologies has yielded precise outcomes across a broad spectrum of circumstances.

By integrating qualitative and quantitative methodologies with the SWOT model, effective strategic decisions have been generated, as exemplified by the application of the analytic hierarchy process (AHP) within a SWOT model (Shrestha et al., 2004). The method by which the AHP is integrated into the SWOT model is known as A'WOT (Ahlat, 2015). In their study, (Zaerpour et al., 2008) combined the fuzzy AHP (FAHP) with the SWOT model. In a strategic decision-making framework, they implemented this method to ascertain whether a specific product be manufactured using a make-to-order (MTO) or make-to-stock (MTS) approach. The integration of FAHP and SWOT results in an innovative hybrid approach to the division of MTO/MTS products. (Ho, 2008) examined a SWOT analysis of an evaluation of the integrated analytic hierarchy process (AHP) and its applications. In their study, (Sevkli et al., 2012) examined and assessed the Turkish airline industry by integrating the analytic network process (ANP) and SWOT. The findings of their research demonstrated that the SWOT ANP is a practical and exceptionally proficient approach that offers significant insights for strategic management deliberations within the Turkish airline sector. Moreover, it can serve as an efficacious instrument for decision-making processes in other markets.

Furthermore, (Arshadi-Khamseh & Fazayeli 2013) proposed a SWOT fuzzy ANP method that addresses the challenges posed by ambiguity and criteria effects for the distribution company. The model was implemented within a drug distribution organisation to determine the most appropriate strategy for a case study in the drug distribution market. Subsequently, a comparison was made between this approach and alternative fuzzy and non-fuzzy multi-criteria decision making (MCDM) methods. They indicated that problem-solving at any level of management would be feasible with the aid of their proposed method and solution. Numerous scholars have implemented the AHP and ANP methodologies in their research (Shrestha et al., 2004).

By employing AHP and ANP techniques, a SWOT analysis can be concluded in a manner that yields accurate and perceptive outcomes. The AHP and ANP methods incorporate both tangible and ethereal factors into the decision-making process, thereby offering a streamlined approach that can be advantageous for organisations conducting a SWOT analysis. Additionally, they have the capacity to serve various objectives, including planning, efficacy, and risk and benefit assessment (Oguztimur, 2011). Moreover, similar to how a SWOT analysis assesses the market position of a company in terms of its strengths, weaknesses, opportunities, and threats, AHP and ANP methodologies can supplement SWOT by providing assessments from specialists and experts from various fields, thereby generating alternative viewpoints regarding the company's decision (Oguztimur, 2011).

## 5.4. Advantages of SWOT analysis

***Table 1*: Advantages of SWOT analysis (*Sharath & Praveena 2023)***

| ***ADVANTAGES OF SWOT ANALYSIS*** |
|---|
| The SWOT Analysis is a method of analysis characterised by its broad scope and provision of general solutions. Specific details and concerns are not the focal point of the SWOT Analysis; rather, those are addressed in the subsequent analyses. The SWOT Analysis functions as a strategic guide, providing direction from the overall to the particular. |
| SWOT Analysis is a technique for interactional analysis that enables macro assessments. As an analytical instrument, SWOT enables one to concentrate on the positive and negative aspects of the organization's internal and external environments, or, alternatively, the components of this environment that contribute positive and negative value collectively from a connected standpoint. Furthermore, one could characterise SWOT Analysis as a "Two-by-Two Matrix" in this context. |
| SWOT Analysis is a valuable tool that can assist organisational management in identifying advantageous opportunities. Weaknesses can be utilised to the advantage of threat management and elimination. By conducting a SWOT Analysis on an organisation and its competitors, it is possible to develop strategies that differentiate a business from its rivals. |
| As both a methodology and a paradigm of thought, SWOT Analysis serves as an organisational management evaluation technique. This model enables one to restrict the agenda during the information gathering and interpretation phases and identifies the criteria upon which decisions are made. Put simply, SWOT Analysis establishes the foundation for strategic decision-making. |
| It is compatible with various theories and instruments utilised in strategic decision-making. As an illustration, the SWOT framework comprises various forms of analysis, including but not limited to Porter's Five Forces Model, Delphi Panel, Norton Balanced Score Card, and others. |
| SWOT Analysis encourages group discourse regarding strategic concerns and the formulation of strategies. By employing innovative participatory methods like brainstorming and group discussions, it is possible to aggregate knowledge. |
| The SWOT Analysis is applicable across various analytical levels, including the organisational, national, and international levels. It is applicable to educational institutions, non-profit organisations, governments, countries, multiculturalism initiatives, and more. |
| SWOT Analysis facilitates a dialogue between organisational management and the organization's future and objectives by transcending day-to-day challenges and the present circumstances. |

## 5.5. Disadvantages of SWOT analysis

***Table 2*:** Disadvantages of SWOT analysis (*Gürel, 2017)*

| ***DISADVANTAGES OF SWOT ANALYSIS*** |
| --- |
| As an approach, SWOT Analysis adopts a broad perspective and proposes general solutions. The SWOT Analysis was formulated during a time when environmental conditions were relatively stable. As a consequence, this technique is deemed invalid in the contemporary world characterised by constant change and intense competition. Changes in structure and dynamics at the system, subsystem, and supersystem levels have an impact on the validity of entries in a SWOT matrix. |
| The SWOT Analysis methodology is beset by issues pertaining to both quantity and quality. By utilising SWOT Analysis, one can discern a multitude of factors. Nevertheless, quantity does not equate to quality. Determining the priorities of the factors identified in a SWOT Analysis, devoting complete attention to them, resolving conflicts and developments across multiple dimensions, and incorporating perspectives and recommendations derived from diverse data and analyses are all unattainable objectives. |
| The current strengths, vulnerabilities, opportunities, and threats constitute the SWOT Analysis's foundation. In order to formulate appropriate strategies for a specific timeframe, SWOT analysis must modify its inventory to produce one that precisely reflects the expected strengths, vulnerabilities, opportunities, and threats of the organisation during that time period. If not, strategies will be generated using information from the present or the past, rather than the future. |
| There is no comparison to competitors in the SWOT analysis. In a highly interdependent environment, the absence of a quantitative index that serves as an operational criterion for benchmarking impedes competitive analysis. In order to assess the magnitude of competitive gaps, an organisation must be aware of the pertinent performance levels exhibited by all its immediate competitors. |
| The information contained in a SWOT Analysis may be unreliable if it is influenced by corporate culture; it is entirely tied to the hopes, ambitions, and biases of those involved in organisation management. |
| The SWOT Analysis is overly limited in scope, as it concentrates on the environment. When strategies depend on conventional interpretations of their industry and competitive landscape, they frequently restrict their attention excessively to contemporary customers, technologies, and rivals. |
| A SWOT Analysis provides a static perspective of an evolving subject. An inherent limitation of the SWOT analysis is its predominantly static nature. It directs an excessive amount of an organization's focus towards a single moment in time. This is essentially equivalent to examining a single frame of a photograph. |
| One aspect of strategy is overemphasised in the SWOT Analysis. Occasionally, businesses become fixated on a solitary asset or a pivotal characteristic of the product or service they provide, neglecting other essential elements required to achieve a competitive edge. |

# 6. Factors for the SWOT analysis

## 6.1. Durable storage

Fossil $CO_2$ emissions have a long-lasting impact on increasing temperatures that can persist for thousands of years. This is a crucial factor to take into account when striving to achieve a balance between emissions and removals. Storage durations lower than this extended timescale will only partially offset fossil $CO_2$ emissions (Lyngfelt et al., 2019). In order to achieve net-zero emissions and prevent further global temperature rise, it is necessary to offset any remaining emissions of fossil carbon by storing it for a period of one thousand years (Fankhauser et al., 2022).

At present, there is a lack of scientific evidence to establish a certain level of durability that can be used to define Carbon Dioxide Removal (CDR). Additionally, policymakers do not agree on this matter. Although long-term storage has been considered the best option for millennia, there are practical obstacles to guaranteeing the success of such operations. In addition, it is generally acknowledged that shorter-term storage can still contribute to achieving climate objectives. However, it is important to note that products that release carbon back into the atmosphere within a year, such as Direct Air Capture to fuels or biomass to food, are not considered carbon dioxide removal (CDR) methods. Current governmental and voluntary standard-setting policies establish different minimum time periods for storage, which can range from 25 years to 100 years. In some cases, shorter time periods may be eligible for discounted credits. (Australian Government Clean Energy Regulator 2018; California Air Resources Board 2018).

***Table 3***. displays the distinct storage timescales of different carbon reservoirs. The duration of storage is determined by both the inherent timescale of a pool and human activities. Storage in soils can be terminated by a change in land use, but it can also be prolonged via diligent maintenance. Geological formations, such as saline aquifers, depleted oil and gas fields, and minerals, have the longest periods of time and are the least likely to release $CO_2$ into the atmosphere due to human and natural disruptions. Consequently, they are very capable of achieving a comparable equilibrium in offsetting fossil $CO_2$ emissions.

*Table 3. Durable storage of CDR technologies (Source: Smith et al., 2023; Klimate.co)*

| Storage type | Durable storage *(years)* | CDR technology |
|---|---|---|
| Vegetation, soil, sediment | 10 - 1.000 | Afforestation and Reforestation, Soil Carbon Sequestion, Ocean Fertilisation |
| Biochar | 10 - 1.000 | Biochar production |
| Marine sediment | 100 - 10.000 | Ocean Alkalinization |
| Geological formations | 10.000 - 100.000 | DACCS, BECCS |
| Minerals | 10.000 - 100.000 | DACCS, Enhanced Rock Wheathering |

***Table 4.*** Table of CDR methods (Source: Smith, et al., 2023; Möllersten & Naqvi 2022)

| Method | TRL | Cost at scale *($/tCO₂)* | Mitigation potential *(GtCO₂/yr)* | MRV | Risks |
|---|---|---|---|---|---|
| DACCS | 5-9 | 600 - 700 | 5-40 | Capture: v high, no<br>Storage: high, yes | High energy consumption – GHG emission<br>competition for renewable energy<br>$CO_2$ leakage |
| BECCS | 5-8 | 15 - 400 | 0.5-11 | Capture: high, yes<br>Storage:high, yes | Competition for land and water resources. Loss of biodiversity, Use of potentially contaminated biomass residues |
| Biochar | 5-9 | 20 - 165 | 0.3-6.6 | Capture: high, yes<br>Storage: med, yes | Particulate and greenhouse gas emissions from biochar production; biodiversity and carbon stock loss<br>Lowers efficiency of pesticides<br>Limit activity of worms in soil |
| Enhanced rock weathering | 3-4 | 50 - 200 | 2-4 | Capture: low, no<br>Storage: low, no | Mining impacts;<br>air quality impacts of rock dust.<br>Heavy metal contamination: Ni, Cr |
| Peatland and wetland restoration | 8-9 | 10 - 100 | 0.5-2.1 | Capture: low, yes<br>Storage: low, yes | Increased methane emissions. |
| Ocean alkalinisation | 1-2 | 40 - 260 | 1-100 | Capture: low, no<br>Storage: low, no | Increased seawater pH and saturation states may have local adverse impacts on marine biota. Possible release of nutritive or toxic elements and compounds may perturb marine ecosystems. Mining impacts. |
| Ocean fertilisation | 1-2 | 50 - 500 | 1-3 | Capture: low, no<br>Storage:low, no | Nutrient redistribution, enhanced oxygen consumption and acidification in deeper waters. Could encourage toxic algae. The fraction of removed CO2 reaching durable storage is uncertain, due to re-metabolisation. |
| Afforestation and Reforestation | 8-9 | 0 - 240 | 0.5-10 | Capture: high, yes<br>Storage: high, yes | Reversal of CDR through wildfire, disease, pests. Reduced catchment water yield and lower groundwater level if species and biome are inappropriate.<br>Finite carbon carrying capacity of land; capacity may be reduced under climate change. |
| Soil carbon sequestration | 8-9 | -45 - 100 | 0.6-9.3 | Capture: med, yes<br>Storage: low, yes | Increased nitrous oxide emissions due to higher levels of organic nitrogen in soil.<br>Finite capacity of soil to protect organic matter; capacity may be reduced under climate change. |

## 6.2. TRL (Technology Readiness Level)

According to (NASA) Technology Readiness Levels (TRL) are a measurement system that evaluates the maturity level of a specific technology. Every technology project undergoes a thorough evaluation based on its specific parameters and is subsequently assigned a TRL rating that reflects its progress. There are nine levels of technology readiness. TRL 1 represents the lowest level of technology readiness, while TRL 9 signifies the highest level of readiness.

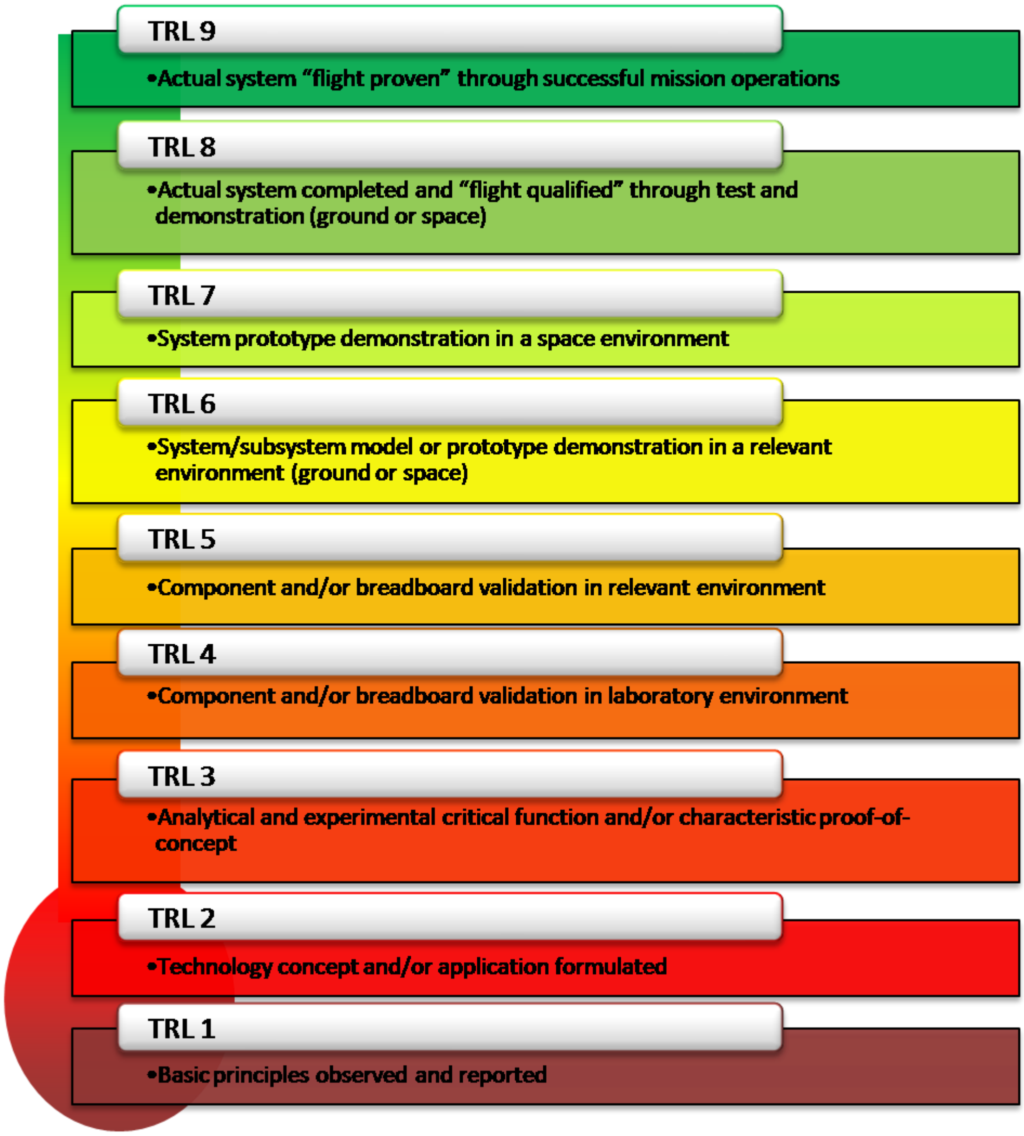


**Figure 3.**TRL table (Source: NASA[1] )

At TRL 1, scientific research is just starting and its findings are being applied to future research and development.

[1] NASA, Available at: https://www.nasa.gov/directorates/somd/space-communications-navigation-program/technology-readiness-levels/

At TRL 2, researchers have gained a solid understanding of the fundamental principles and are now able to put those initial findings into practical use. TRL 2 technology is highly speculative, with minimal experimental evidence to support its concept.

Once active research and design commence, a technology reaches TRL 3. Typically, a combination of analytical and laboratory studies is necessary at this stage to determine the feasibility and readiness of a technology to advance in the development process. Typically, at TRL 3, a proof-of-concept model is built. After the proof-of-concept technology is developed, it progresses to TRL 4. During TRL 4, various component pieces undergo testing together.

At TRL 5, the technology moves beyond TRL 4 and enters the realm of breadboard technology. This stage requires more rigorous testing compared to TRL 4. Simulations should be conducted in environments that closely resemble reality.

After the completion of TRL 5 testing, a technology has the potential to progress to TRL 6. A TRL 6 technology has a prototype or model that is fully functional.

For TRL 7 technology, it is necessary to showcase the working model or prototype in a space environment.

TRL 8 technology has undergone rigorous testing and has been deemed "flight qualified," making it ready for seamless integration into an existing technology or technology system.

Once a technology has been thoroughly tested and proven successful during a mission, it can be classified as TRL 9.

### 6.3. Cost at scale

The cost of operating the technology in *($\$/tCO_2$)*. For those technologies where it is possible to utilise $CO_2$ in addition to storage, the resulting cost reduction is automatically included.

### 6.4. Mitigation potential

Mitigation potential refers to the potential for future scale expansion and capacity growth in *($GtCO_2/yr$)*.

### 6.5. MRV

Assessing MRV involves evaluating the ease and accuracy of measuring the amount of carbon removed, which is categorised as low, medium, high, or very high based on opinions (Smith et al., 2023). Additionally, it considers whether there is an MRV methodology outlined in the

IPCC Guidelines for National Greenhouse Gas Inventories, indicating a yes or no answer (Smith et al. 2023).

### 6.6. Risks

Context specific risks of the CDR technologies **(Table 4.)** (Smith, et al., 2023; Möllersten & Naqvi 2022).

### 6.7. Energy requirments

There is no precise data to characterise the energy needs of most technologies. This thesis is going to work with estimated values.

***Table 5.*** *Source: (SmartStones; Temmerman & Rochette, 2023)*

| **Technology** | **Energy requirements** |
|---|---|
| DACCS | High |
| BECCS | Low |
| Biochar | Low |
| Enhanced Rock Weathering | Medium |
| Peatland and Wetland Restoration | Low |
| Ocean Alkalinization | Medium |
| Ocean Fertilisation | Low |
| Afforestation and Reforestation | Low |
| Soil Carbon Sequestration | Low |

### 6.8. Number of publications

One way to gauge the status of CDR is by assessing the amount of scientific research being conducted. Research on Carbon Dioxide Removal has experienced significant growth since the early 1990s, surpassing the overall rate of research on climate change. By the end of 2021, there were approximately 28,000 scientific studies in the English language focused on CDR in the Web of Science and Scopus, which are the two largest commercial bibliographic databases (Minx et al., 2017; Bibliography: Greenhouse Gas Removal). This represents a significant number of publications, surpassing previous indications in scientific discussions and ongoing community efforts to track CDR research. According to estimates, the Web of Science encompasses approximately 43% of the entire scientific (Khabsa & Giles 2014). If we assume that this percentage also applies to the literature on CDR, it suggests that there might be around 50,000 English-language studies on CDR in total **(**Smith et al., 2023).

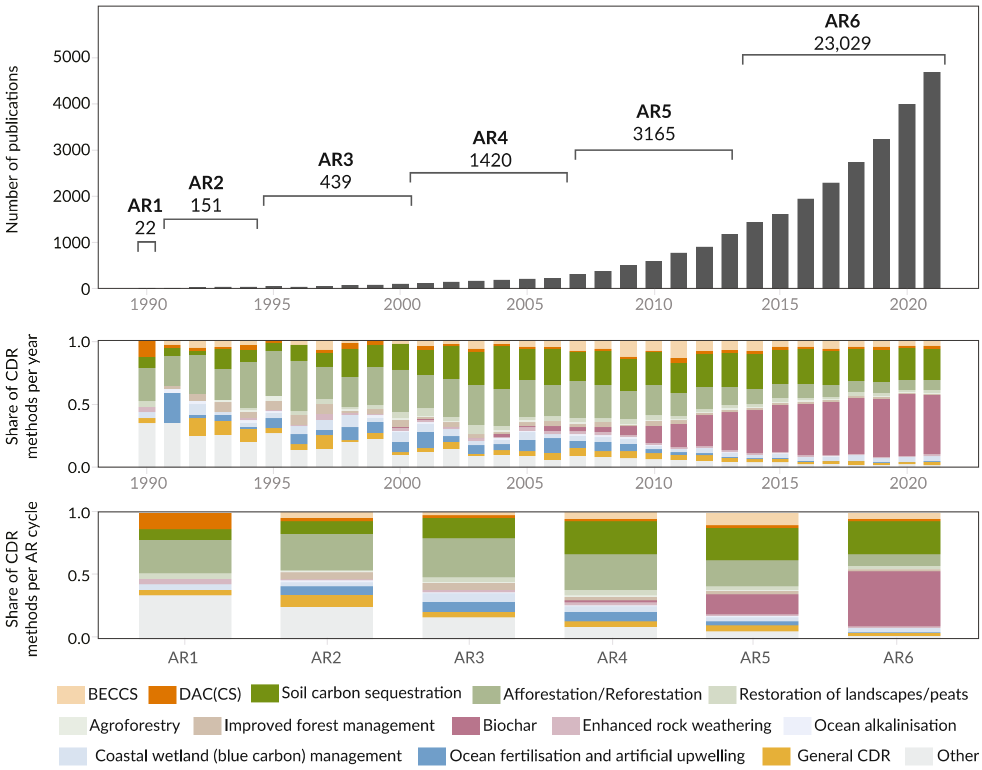


**Figure 4.** Number of publications (Source: Smith et al., 2023.)

The scientific literature on Carbon Dioxide Removal (CDR) has experienced significant growth over time. On ***Figure*** *7*. the top panel displays the total number of scientific publications on CDR per year from 1990 to 2021 in the Web of Science and Scopus (*Smith, S. M. et al., 2023)*. Percentage of carbon dioxide removal (CDR) methods discussed in these scientific publications each year (middle panel). The bottom panel displays the percentage of CDR methods discussed in scientific publications released during each Assessment Report (AR) cycle of the Intergovernmental Panel on Climate Change (Smith et al., 2023).

## 6.9. Patenting activity

Patenting activity is a valuable indicator of innovation as it reflects the rate of invention. Supply-side research, development, and demonstration, along with scale-up efforts, drive inventive activity (Smith et al., 2023). Additionally, niche markets and demand pull can also provide support. Based on our analysis of CDR patenting activity worldwide, it is evident that there has been a significant rise in the past 15 years (Smith et al., 2023). Notably, a substantial portion of this patenting surge is happening in China, indicating its growing importance in this field (Smith et al., 2023). DAC is the most significant factor driving patent growth (Smith et al., 2023). China is a major hub for scientific research on CDR, with a particular focus on biological methods (Smith et al., 2023). Patenting activity is just one way to gauge innovation, and fortunately, there is readily available data on this. However, it's important to note that innovation can also take place beyond what companies decide to patent (Smith et al., 2023). Retaining invention, experimentation, and learning as tacit knowledge and trade secrets is possible (Smith et al., 2023).

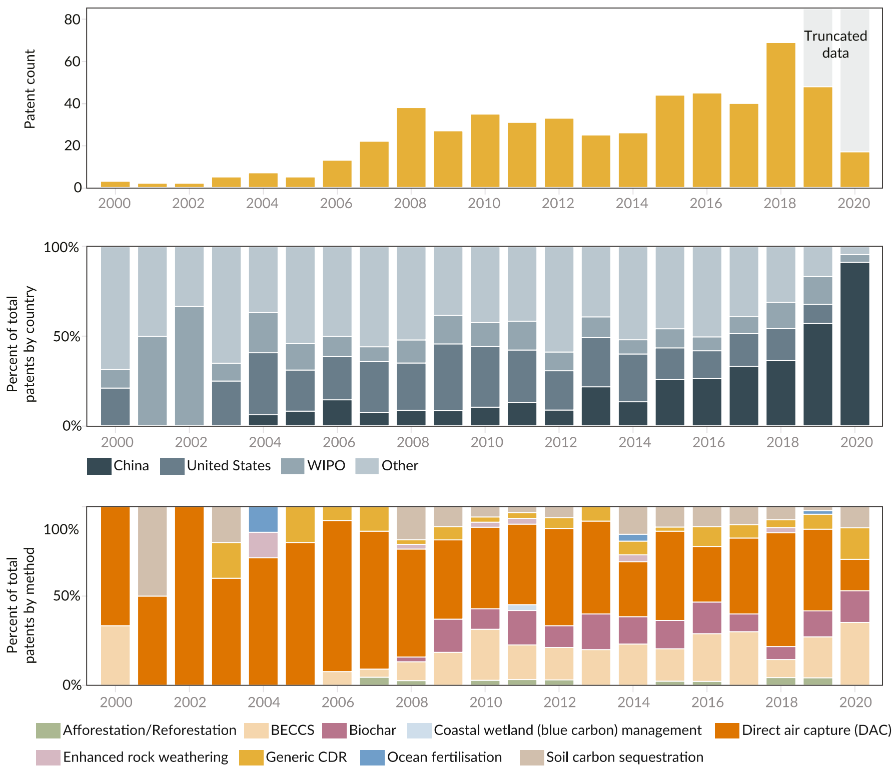


**Figure 5.** Patent numbers and ratios (Source: Smith et al., 2023).

The global patenting activity for Carbon Dioxide Removal (CDR) has increased. The total number of patents issued annually from 2000 to 2020, organised by patent families (top). The same invention files are referenced by families in multiple nations (Smith et al., 2023).

The data is truncated in 2019 and 2020 due to the processing time required to publish the application (Smith et al., 2023). The percentage of individual patent applications filed annually by the country in which the patent was lodged (middle) (Smith et al., 2023). The World Intellectual Property Organisation (WIPO) is a centralised patent office (Smith et al., 2023). The percentage of total patent families per year by method/component is presented at the bottom (Smith et al., 2023).

## 6.10. CDR on Twitter

Finding a representative measure of social acceptance of CDR technologies is not an easy task. The growing number of reactions from people on social media could help find a reference point. As an indicator, I looked at the quantitative change Twitter posts related to CDR technologies in recent years (Smith et al., 2023).

Twitter attention to CDR has increased dramatically in recent years, outpacing the growth of attention to climate change overall. Afforestation and Reforestation are two techniques that are discussed more highly than others (Smith et al., 2023).

Twitter is a social media site that is well-known for promoting political discussions online. Twitter data demonstrates the public discourse surrounding communicators who are aware of CDR (Smith et al., 2023). The results are not reflective of the broader public because users are committed communicators such as experts, legislators, media professionals, and company representatives (Cody et al. 2015; Mellon & Prosser 2016.; Klašnja et al., 2018; Barberá, & Rivero, 2014.). However, by studying this data, we can follow the evolution of CDR communication over time. ***Figure 9.*** represents the tweets written in the English language for 2010–2021 (Smith et al., 2023).

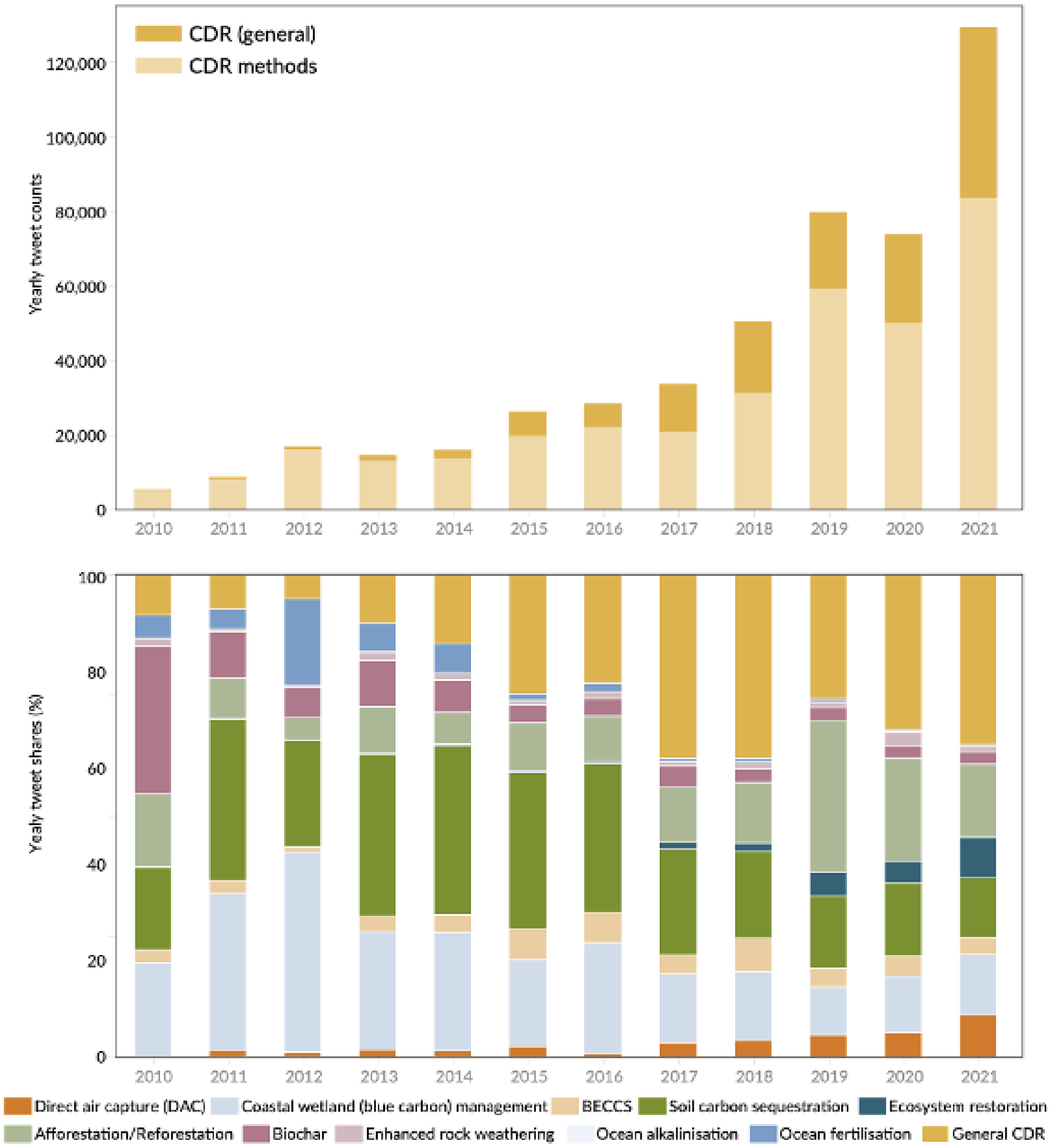


**Figure 6.** Number of tweets (Source: Smith et al., 2023.; Nguyen et al., 2024).

The first panel displays the annual count of tweets related to generic Carbon Dioxide Removal (CDR) and method-specific CDR (Smith et al., 2023). The second panel displays the proportionate distribution of CDR tweets according to the approach used. Discussions that do not focus on specific approaches for CDR are categorised as "CDR (general)" (Smith et al. 2023).

## 6.11. The positive and negative attitudes in tweet posts

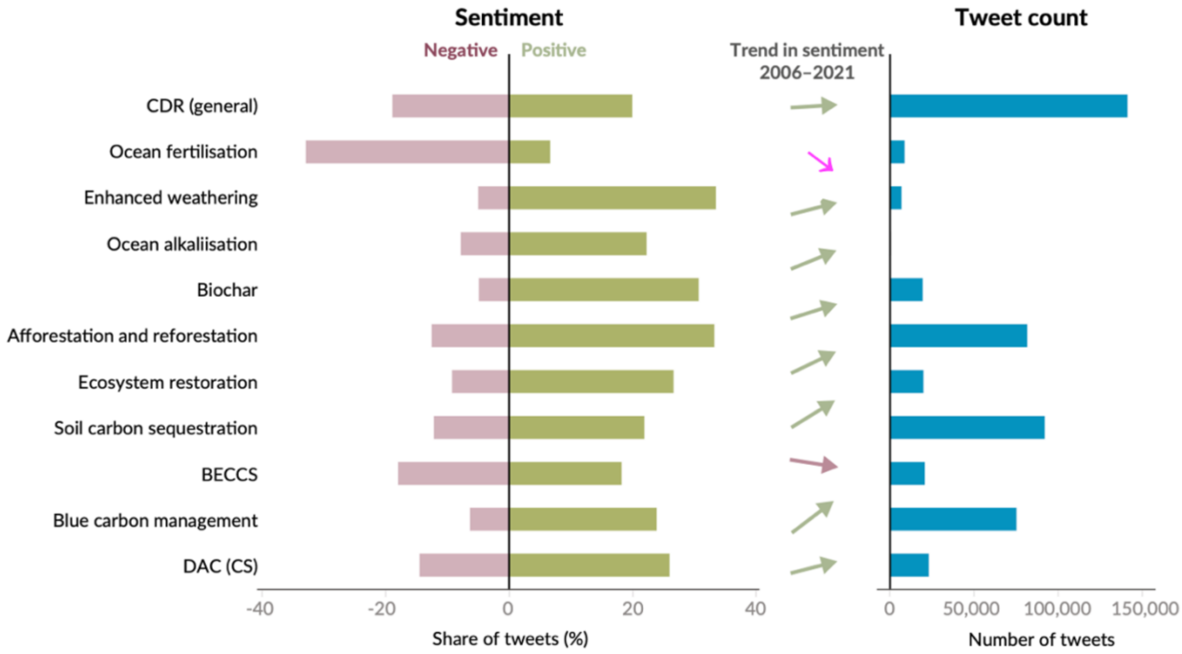


**Figure 7.** Positive-Negative ratio of tweets (Source: Smith et al., 2023)

On Figure 10. we can see the ratio of original tweets discussing carbon dioxide removal (CDR) that express positive or negative emotions (2010-2021); the trends of emotions (positive - green arrow; negative - red arrow) over time; the number of tweets related to different CDR methods (2010-2021) (Smith et al., 2023).

## 6.12. Policymaking

Dedicated Carbon Dioxide Removal governance examples are generally observed at the national level and within the European Union (Smith et al., 2023). The guidance and incentives provided by the United Nations Framework Convention on Climate Change and other global initiatives are rather restricted (Smith et al., 2023).

Over 120 national governments have set a goal of achieving net-zero emissions, which necessitates the implementation of Carbon Dioxide Removal (CDR) methods (Hans et al., 2022). The ratification of the latest Intergovernmental Panel on Climate Change (IPCC) Working Group III report by governments indicates their acknowledgement that, in addition to significant and immediate reductions in emissions, Carbon Dioxide Removal (CDR) can serve three complementary functions (IPCC. Summary for Policymakers. in Climate Change 2022).

To achieve a significant reduction in net emissions in the near future, it is necessary to offset difficult-to-reduce residual emissions from sectors such as agriculture, aviation, shipping, and industrial processes. This will enable us to reach a state of net-zero $CO_2$ or greenhouse gas (GHG) emisvsions within a moderate timeframe. Additionally, if the deployment of emission reduction measures exceeds the annual residual emissions, it may be possible to achieve or maintain net-negative emissions (Smith et al., 2023). The IPCC report evaluates global mitigation paths that demonstrate the continuous use of traditional land-based carbon dioxide removal (CDR) techniques throughout the century. Additionally, it highlights the gradual expansion of innovative CDR approaches over time (Smith et al., 2023).

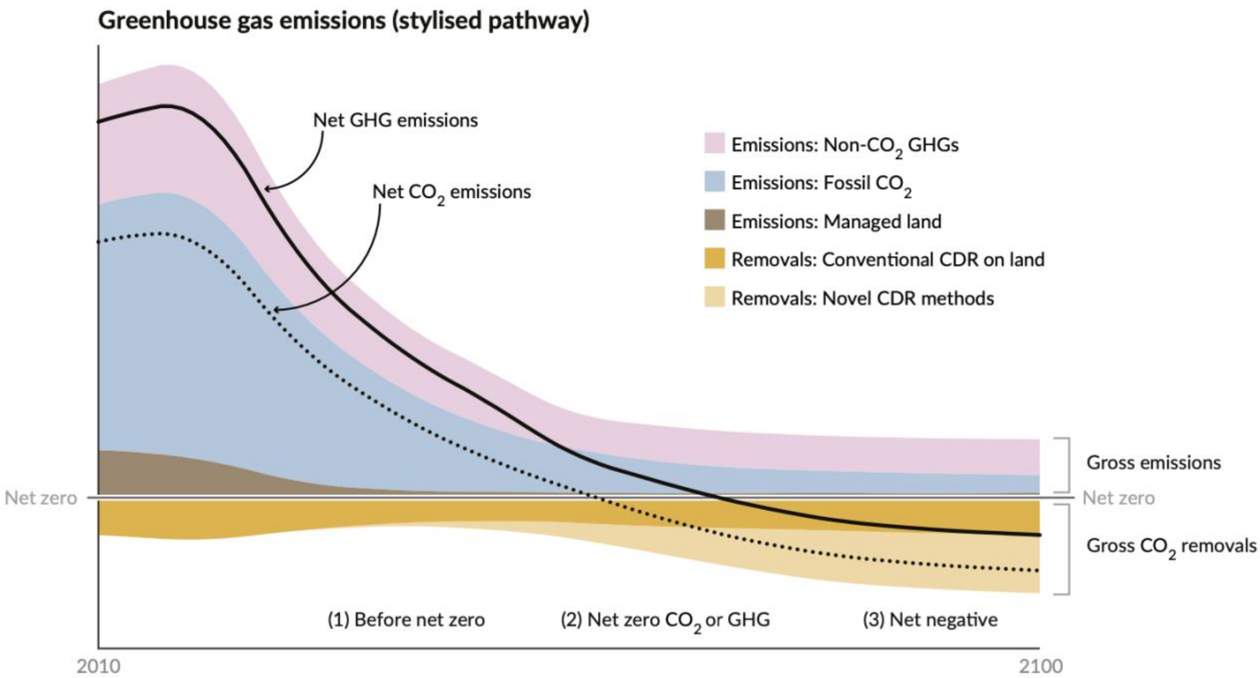


**Figure 8. $CO_2$** Emission pathways (Source: Smith et al. 2023)

The roles of Carbon Dioxide Removal (CDR) in ambitious mitigation programmes, which can be implemented at both national and global levels, are discussed. This document outlines the fundamental elements involved in mitigating emissions, including the processes of emission and removal. It also presents the projected paths for reducing both net carbon dioxide ($CO_2$) and greenhouse gas (GHG) emissions (Babiker et al., 2022).

Although only a small number of governments have concrete strategies for implementing Carbon Dioxide Removal (CDR), a few countries are starting to include CDR into their climate policies, albeit in various ways (Smith et al., 2023).

### 6.13. Policy making in the light of the aims of the Paris Agreement

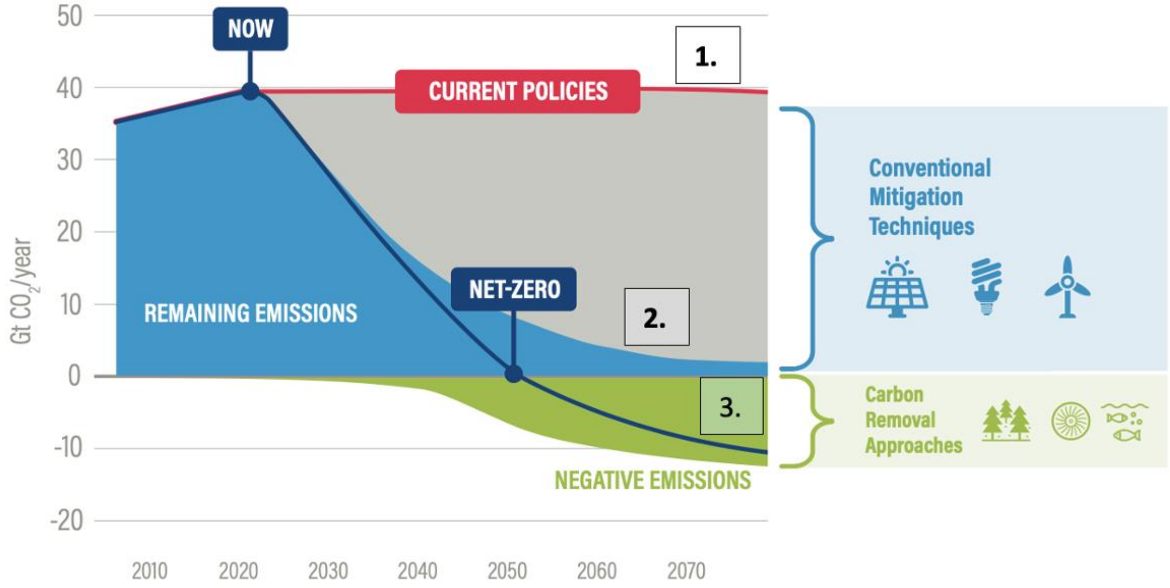


***Figure 9***.: Staying below 1.5°C of global temperature (Sources: based on: Lebling at al., 2022; V. Masson-Delmotte et al., 2018; CAT 2021).

The graph (Figure 11.) is derived from cumulative emission data obtained from the IMAGE integrated assessment model (Stehfest et al., 2014). The data displays the annual carbon dioxide emissions in gigatons. The first line (1.) represents the current path, which would be the carbon dioxide emission in the future, if there were no significant reduction in carbon dioxide emissions and no utilisation of carbon removal technologies. In the future, the second line (2.) showcases the potential reduction in $CO_2$ emissions if we were to replace all fossil fuel-based energy sources with renewable sources. Additionally, it assumes the successful attainment of energy efficiency targets, widespread adoption of electric vehicles, and the exclusive use of hydrogen in industries. If we were able to significantly decrease our reliance on fossil fuels, we could make a substantial reduction in emissions. However, achieving net zero emissions would still be a challenge. The third line (3.) illustrates the potential future $CO_2$ emissions if we were able to implement the discussed changes and utilise carbon removal techniques.

Based on the graph, it is evident that by implementing carbon removal techniques, we can not only achieve net zero carbon emissions but also surpass it with negative emissions targets. This is the only way we can achieve the below 2°C target, which is the aim of the Paris Agreement.

In Article 4.1 of the Paris Agreement, it is defined that a "balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases" must be reached "in the second half of this century" (UNFCCC, 2015). Additionally, the use of CDR is assumed in all IPCC mitigation scenarios that are expected to limit warming to 2°C or lower, and nearly all of those that limit warming to 1.5°C assume net-negative $CO_2$ emissions. (Smith, et al., 2023). However, this has not yet been reflected in the corresponding UNFCCC decisions regarding the global necessity of large-scale CDR (Fridahl, 2017.; Honegger at al., 2021.). Recent developments in the context of implementing the Paris Agreement's Article 6 on international cooperation suggest that the UNFCCC could play a more active role in the near term, despite the fact that the negotiations of CDR-specific issues are nascent (UNFCCC, 2015). To operationalize CDR as a component of mitigation strategies, it would be crucial to make further efforts to develop methodologies for monitoring, reporting, and verification (MRV) of carbon flows.

Although national governments are beginning to acknowledge the crucial role that carbon dioxide removal (CDR) will playin achieving climate targets, their actual implementation of CDR measures is inadequate (Smith et al., 2023). For instance, while establishing a net-zero emissions objective implies that governments are relying on some sort of carbon dioxide removal (CDR), there is a lack of comprehensive strategies for implementing CDR (Smith et al., 2023). Net zero announcements sometimes fail to specify the extent to which carbon dioxide removal (CDR) should contribute and which specific CDR methods should be employed (Rogelj et al., 2021). This lack of clarity is a common issue among countries. Instances of committed CDR policy and governance are primarily observed at the national and supranational levels, with only minimal representation in global multilateral initiatives including the United Nations Framework Convention on Climate Change (UNFCCC) (Smith et al., 2023).

### 6.14. Policy making in the context of investor incentives

Country-specific policy approaches to CDR are influenced by a variety of factors, including the relative importance of different economic sectors, the relevance of different actors, the relative importance of different economic sectors, political interests, and respective climate policy paradigms and institutional architectures (Smith et al., 2023).

The United States has expanded tax credits as one of the most prominent instruments to support CDR deployment in order to establish new funding and revenue streams (IRA 2022). In contrast, the United Kingdom and the European Union are investing in innovation funds (Smith et al., 2023). The Brazilian government has implemented substantial initiatives to advance CDR in the LULUCF sector, despite the absence of significant funding for CCS-based CDR methodologies (Smith et al., 2023). Although none of the four cases has yet established an explicit target for novel CDR, they are all striving to further integrate CDR into climate policy (Smith et al., 2023). This includes the advancement of MRV and standards for removal accounting to further operationalize CDR as a critical component of the mitigation toolbox (Smith et al., 2023).

Innovations in CDR governance and policymaking are anticipated to occur primarily at the national and supranational levels in the near future. It will be crucial to customise the approach to the unique circumstances of each country (Smith et al., 2023).

## 7. SWOT analysis of CDR technologies

Below are the components of the SWOT analysis that will be evaluate. The data from the prior figures and tables will be employed. By using a variety of colours to emphasise the distinctions between the technologies for each aspect. The most promising technologies are awarded green, the promising technologies are awarded yellow, and the least promising technologies are awarded red.

**The SWOT table**

***Table 6.*** SWOT table

| **Strenghts** | **Weaknesses** |
|---|---|
| Energy requirements | Risks |
| Proven technology | Measurability |
| Durable storage | Lack of investors |
| **Opportunities** | **Threats** |
| Scalability | Cost |
| Contribution to the below 2°C target | Social acceptance |
| R&D | Policy making |

### 7.1. The SWOT analysis of Direct Air Capture with Carbon Storage (DACCS)

**Proven technology**

According to the data presented in ***Table 4.***, most CDR technologies have reached a high level of development. Often, in certain instances like DACCS technology, the TRL value can be quite high, even reaching the maximum 9 value. It is indicated with a green colour in the SWOT table.

### Durable storage

The longest storage opportunities are offered by both mineral and geological storage options (***Table 3***). Consequently, the SWOT table emphasises the durable storage of DAACS in green.

### Energy requirements

***Table 5.*** demonstrates that DACCS systems now require a significant amount of energy. While there are numerous instances of renewable energy sources, it will be designated as red in the SWOT table, taking into account the existing data.

### Risks

When the technology is not powered by renewable energy sources, there are higher greenhouse gas (GHG) emissions due to the high energy demands (***Table 4***). Nevertheless, considering the remarkably significant capacity for reducing the impact (***Table 4***.) the slightly greater greenhouse gas emissions can be considered insignificant.

The assertion that utilising renewable energies to fulfil the goals of the Paris Agreement demonstrates competence is not a genuine cause for concern. In order to achieve the goal of limiting global warming to below 2°C, it is crucial to promptly and significantly decrease the amount of carbon dioxide in the atmosphere (***Figure 8***).

The likelihood of $CO_2$ leakage is minimal. Since the 1970s, there have been only a limited number of instances where seismic activity has caused little $CO_2$ leakage in geological $CO_2$ storage. In the SWOT table, it will be designated as a positive aspect by highlighting it in green, as it presents little threats and risks.

### Measurability

Although this thesis includes numerous aspects, there is currently insufficient evidence to accurately predict and plan for the future. An example is the MRV value (***Table 4.***) which quantifies the ease and precision of measuring the quantity of carbon eliminated. In the context of the DACCS, the quantification of $CO_2$ removal during capture and storage can be done with precision and ease. Therefore, this element will be indicated as favourable in the SWOT table by marking it in green.

### Lack of investors

CDR technologies are commonly misunderstood. From an investor's standpoint, the likelihood of recuperating costs is minimal. Additional incentives are required at both the national and international levels. Policy formulation can facilitate this procedure. For instance, in the United States, the implementation of tax credits, in the European Union and the United Kingdom, the endorsement of innovation funds, are progressively expanding the possibilities for potential investors (see chapter 6.14). The colour orange will be used to emphasise this characteristic across all technologies.

### Scalability

Based on the mitigation potential (***Table 4.***) it is possible to infer the future feasibility of the technique. DACCS exhibits significant scalability, with a potential absorption capacity of up to 40 million tons per year, and the possibility for further expansion in the future. Consequently, this issue will be emphasised by using the colour green in the SWOT table.

### Contribution to the below 2°C target

Due to its extremely high mitigation potential (***Table 4.***) DACCS has one of the highest potential contributions of all the technologies listed. It will be highlighted in green in the table.

### Research and Development

In order to calculate the R&D component, data on publication and patenting activities will be utilised, as shown in ***Figure 4.*** and ***Figure 5.*** The quantity of research articles on CDR technologies has experienced exponential growth in recent years (***Figure 4***). The proportion of papers pertaining to DACCS is rather low in comparison to other technologies. Nevertheless, the figures on patent activity (***Figure 5.***) clearly indicate that DACCS technologies have the highest number of patents. By doing a comparison of these two aspects, this aspect will be designated this aspect as orange in the SWOT table.

### Cost

The present cost of DACCS technology is significantly the highest, as indicated in ***Table 4.*** While it is anticipated that this will be reduced by 50% in the future, this aspect will be emphasised by marking it in red in the SWOT table.

### Social acceptance

The societal acceptance of DACCS, as observed by the fluctuation in the number of tweets on social media (***Figure 6.***) is now a relatively unknown technology. The public perception of DACCS, based on the ratio of positive to negative tweets, is distinctly positive (***Figure** 7*). After comparing the two data points, this factor will be highlighted with the colour orange in the SWOT table.

### Policy making

Although there are several encouraging attempts, such as the implementation of tax credits in the United States and the allocation of funds to stimulate innovation in the European Union and the United Kingdom, there is currently limited worldwide advancement in this field (see chapter 6.14). Consequently, this factor will be emphasised by marking it in red in the SWOT chart.

### The SWOT table of DACCS

***Table 7.*** *The SWOT table of DACCS*

| Strenghts | Weaknesses |
|---|---|
| Energy requirements | Risks |
| Proven technology | Measurability |
| Durable storage | Lack of investors |
| **Opportunities** | **Threats** |
| Scalability | Cost |
| Contribution to the below 2°C target | Social acceptance |
| R&D | Policy making |

## 7.2. The SWOT analysis of Bioenergy with Carbon Capture and Storage (BECCS)

### Proven technology

According to the data presented in ***Table 4.*** most CDR technologies have reached a high level of development. Often, in certain instances like BECCS technology, the TRL value can be quite high, even reaching the value 8. Therefore, it is indicated with a green colour in the SWOT table.

### Durable storage

The geological storage option enables the longest possible duration of storage (***Table 3***). Accordingly, durable storage of BECCS will be marked with the colour green in the SWOT table.

### Energy requirements

Based on ***Table 5.*** BECCS is not considered a very energy-intensive technology. The technology itself also generates energy. Accordingly, it will be marked it with a green colour in the SWOT table.

### Risks

Due to the threat to biodiversity and the potential release of air pollutants from burning contaminated biomass (***Table 4.***) this factor will be highlighted this in orange in the SWOT table.

### Measurability

Although this thesis includes numerous aspects, there is currently insufficient evidence to accurately predict and plan for the future. An example is the MRV value (***Table 4.***) which quantifies the ease and precision of measuring the quantity of carbon eliminated. In the context of BECCS technology, the quantification of $CO_2$ removal during capture and storage can be done with precision and ease. Therefore, this element will be indicated as favourable in the SWOT table by marking it in green.

### Lack of investors

CDR technologies are commonly misunderstood. From an investor's standpoint, the likelihood of recuperating costs is minimal. Additional incentives are required at both the national and international levels. Policy formulation can facilitate this procedure. For instance, in the United States, the implementation of tax credits, in the European Union and the United Kingdom, the endorsement of innovation funds, are progressively expanding the possibilities for potential investors (see chapter 6.14). The colour orange will be used to emphasise this characteristic across all technologies.

### Scalability

Through the mitigation potential (***Table 3.***) it is possible to assume the scalability of the technology in the fure. The estimate for the scalability of BECCS forecasts an expansion capability of approximately 11 million tons of absorption per year. Therefore, this particular element will be designated with the colour orange in the SWOT chart.

### Contribution to the below 2°C target

Due of its 'moderate' mitigation potential (***Table 4***). It will be marked in orange in the SWOT table.

### Research and Development

In order to calculate the R&D component, data on publication and patenting activities will be utilised, as shown in ***Figure 4.*** and ***Figure 5.*** The quantity of research articles on CDR technologies has experienced exponential growth in recent years (***Figure 4***). The proportion of publications related to BECCS is rather low compared to other technologies. Based on the patent activity data (***Figure 5.***) it is evident that the number of patents is significant compared to other technologies. Therefore, this aspect will be marked in the SWOT table by with the colour orange.

### Cost

The cost of BECCS technology is relatively expensive, as indicated in ***Table 4.*** While it is anticipated that this will diminish in the future, this aspect will be emphasised in red in the SWOT table.

**Social acceptance**

The current level of public awareness and acceptance of BECCS, as indicated by the fluctuation in the number of tweets on social media (***Figure 6.***) is rather low. Based on the positive/negative ratio of tweets, the general sentiment towards BECCS is predominantly unfavourable (***Figure*** *7*). Given these two pieces of evidence, this element will be designated as red in the SWOT table.

**Policy making**

Although there are several encouraging attempts, such as the implementation of tax credits in the United States and the allocation of funds to stimulate innovation in the European Union and the United Kingdom, there is currently limited worldwide advancement in this field (see chapter 6.14). Consequently, this factor will be emphasised by marking it in red in the SWOT chart.

**The SWOT table of BECCS**

***Table 8.*** The SWOT table of BECCS

| Strenghts | Weaknesses |
|---|---|
| Energy requirements | Risks |
| Proven technology | Measurability |
| Durable storage | Lack of investors |
| **Opportunities** | **Threats** |
| Scalability | Cost |
| Contribution to the below 2°C target | Social acceptance |
| R&D | Policy making |

### 7.3. The SWOT analysis of Biochar

**Proven technology**

According to the data presented in ***Table 4.***, most CDR technologies have reached a high level of development. Often, in certain instances like Biochar technology, the TRL value can be quite high, even reaching the maximum 9 value. Therefore, it is indicated with a green colour in the SWOT table.

## Durable storage

The durable storage capacity of $CO_2$ in the form of biochar is significantly lower compared to that contained in geological formations or mineral deposits (***Table 3***). However, a storage value that lasts for up to 1000 years is considered to be an entirely satisfactory duration for reducing long-term greenhouse gas emissions. Therefore, the long-lasting storage is shown with the colour orange in the SWOT table.

## Energy requirements

Biochar manufacturing is a distinct low-energy technology (***Table 5***). It will be given a green colour to emphasise it in the SWOT table.

## Risks

Biochar manufacturing can lead to the release of particulate greenhouse gases, as shown in ***Table 4.*** The utilisation of Biochar may result in a reduction in biodiversity and carbon storage, as well as a decrease in the effectiveness of pesticides and the activity of worms in the soil (***Table 4***). It will be given the colour yellow to emphasise it in the SWOT table.

## Measurability

Although this study presents numerous elements, the existing understanding of the future remains uncertain. An example is the MRV value (***Table 4.***) which quantifies the ease and precision of measuring the quantity of carbon eliminated. Regarding Biochar, the precise measurement of $CO_2$ removal during capture is possible, however the precision of determining the amount of $CO_2$ retained during storage is moderate. This feature will be designated with an orange colour in the SWOT table.

## Lack of investors

CDR technologies are commonly misunderstood. From an investor's standpoint, the likelihood of recuperating costs is minimal. Additional incentives are required at both the national and international levels. Policy formulation can facilitate this procedure. For instance, in the United States, the implementation of tax credits, in the European Union and the United Kingdom, the endorsement of innovation funds, are progressively expanding the possibilities for potential investors (see chapter 6.14). The colour orange will be used to emphasise this characteristic across all technologies.

### Scalability

Based on the mitigation potential (***Table 4.***), it is possible to infer the feasibility of the technology in the future. Biochar is somewhat scalable, with a maximum capacity to absorb 6 million tons per year. Consequently, this component will be emphasised by marking it in orange in the SWOT table.

### Contribution to the below 2°C target

The relatively high mitigation potential will be marked with the colour orange in the SWOT table (***Table 4***).

### Research and Development

In order to calculate the R&D component, data on publication and patenting activities will be utilised, as shown in ***Figure 4.*** and ***Figure 5.*** The quantity of research articles on CDR technologies has experienced exponential growth in recent years (***Figure 4***). The prevalence of publications on Biochar has been significantly higher in comparison to other technologies. Nevertheless, the patent activity data (***Figure 5.***) indicates that the quantity of patents associated with Biochar is quite limited. Upon analysing these two aspects, it will be designated as orange in the SWOT table.

### Cost

The expenses of Biochar technology are moderately high (***Table 4.***) in comparison to other carbon dioxide removal (CDR) technologies. This factor will be designated with the colour orange in the SWOT table.

### Social acceptance

The level of public awareness and acceptance of Biochar technology is currently low, as indicated by the fluctuation in the number of tweets on social media (***Figure 6.***). Based on the positive/negative ratio of tweets, the general opinion of Boichar is highly positive (**Figure 7**). Comparing the two data, this element will be designated as orange in the SWOT chart.

### Policy making

Although there are several encouraging attempts, such as the implementation of tax credits in the United States and the allocation of funds to stimulate innovation in the European Union and the United Kingdom, there is currently limited worldwide advancement in this field (see chapter 6.14). Consequently, this factor will be emphasised by marking it in red in the SWOT table.

#### The SWOT Table of Biochar

***Table 9.*** The SWOT table of Biochar

| Strenghts | Weaknesses |
|---|---|
| Energy requirements | Risks |
| Proven technology | Measurability |
| Durable storage | Lack of investors |
| **Opportunities** | **Threats** |
| Scalability | Cost |
| Contribution to the below 2°C target | Social acceptance |
| R&D | Policy making |

### 7.4. The SWOT analysis of Enhanced Rock Weathering

#### Proven technology

According to the data presented in ***Table 4***. most carbon dioxide removal (CDR) methods are advanced. Regarding Enhanced Rock Weathering, it is important to note that the TRL value is exceptionally low, with a maximum of 4. Consequently, the SWOT table indicates the highlighted information in red.

#### Durable storage

The mineral storage facilities provide one of the greatest duration of storage (***Table 3***). Hence, the long-lasting storage is shown with the colour green in the SWOT table.

#### Energy requirements

Enhanced Rock Weathering is classified as a medium-high energy technology, as seen in ***Table 5.*** It will be emphasised be using the colour orange in the SWOT table.

#### Risks

The Enhanced Rock Weathering technique carries significant hazards, including the potential repercussions of mining and the effects on air quality due to the presence of rock dust, which may lead to heavy metal pollution, including Nickel (Ni) and Chromium (Cr) as shown in ***Table 4***. These hazards will be indicated by using the colour red in the table.

### Measurability

Although this study presents numerous elements, it is now difficult to make any certain statements regarding the future. An example is the MRV value (***Table 4.***) which quantifies the ease and precision of measuring the quantity of carbon eliminated. Regarding Enhanced Rock Weathering, the estimation of the quantity of $CO_2$ extracted during the capture process and the quantity of $CO_2$ stored during storage is characterised by a low level of precision. The aforementioned feature will be highlighted in the SWOT table using the colour red.

### Lack of investors

CDR technologies are commonly misunderstood. From an investor's standpoint, the likelihood of recuperating costs is minimal. Additional incentives are required at both the national and international levels. Policy formulation can facilitate this procedure. For instance, in the United States, the implementation of tax credits, in the European Union and the United Kingdom, the endorsement of innovation funds, are progressively expanding the possibilities for potential investors (see chapter 6.14). The colour orange will be used to emphasise this characteristic across all technologies in the SWOT table.

### Scalability

Based on the mitigation potential (***Table 4.***) we can infer the feasibility of the technology in the future. Biochar has a limited scalability, with a maximum absorption capacity of 4 million tons per year. Consequently, this particular feature will be emphasised by marking it in the SWOT table with the colour orange.

### Contribution to the below 2°C target

Due of its relatively low mitigation potential (***Table 4***). It will be marked in red in the SWOT table.

### Research and Development

In order to calculate the R&D component, data on publication and patenting activities will be utilised, as shown in ***Figure 4.*** and ***Figure 5.*** The quantity of research articles on CDR technologies has experienced exponential growth in recent years (***Figure 4***). The ratio of publications and patent activity associated with Enhanced Rock Weathering (***Figure 4; Figure 5.***) is rather low in comparison to other technologies. After the evaluation these two aspects, this aspect will be designated with red colour in the SWOT table.

### Cost

The expenses associated with the Enhanced Rock Weathering technology are deemed to be somewhat expensive in comparison to other technologies (***Table 4***). Therefore, this aspect will be denoted with an orange marker in the SWOT table.

### Social acceptance

The current level of familiarity with Enhanced Rock Weathering technology, as indicated by the shift in the number of tweets on social media (***Figure 6.***) is quite low. Based on the positive/negative ratio of tweets, the public opinion of improved weathering is highly favourable (***Figure 7***). After the comparison of the two data sets, this particular element will be designated as orange in the SWOT table.

### Policy making

Although there are several encouraging attempts, such as the implementation of tax credits in the United States and the allocation of funds to stimulate innovation in the European Union and the United Kingdom, there is currently limited worldwide advancement in this field (see chapter 6.14). Consequently, this factor will be emphasised by marking it in red in the SWOT chart.

### The SWOT Table of Enhanced Rock Wheathering

***Table 10.*** The SWOT table of Enhanced Rock Wheathering

| Strenghts | Weaknesses |
|---|---|
| Energy requirements | Risks |
| Proven technology | Measurability |
| Durable storage | Lack of investors |
| **Opportunities** | **Threats** |
| Scalability | Cost |
| Contribution to the below 2°C target | Social acceptance |
| R&D | Policy making |

## 7.5. The SWOT analysis of Soil carbon sequestion

### Proven technology

According to the data presented in ***Table 4.***, most CDR technologies have reached a high level of development. Often, in certain instances like Soil carbon sequestion technology, the TRL value can be quite high, even reaching the maximum 9 value. It is indicated with a green colour in the SWOT table.

### Durable storage

The durable storage capacity of $CO_2$ in the form of soil is significantly lower compared to that contained in geological formations or mineral deposits (***Table 3***). However, a storage value that lasts for up to 1000 years is considered to be an entirely satisfactory duration for reducing long-term greenhouse gas emissions. Therefore, the long-lasting storage is shown with the colour orange in the SWOT table.

### Energy requirements

The energy associated with Soil Carbon Sequestration technology are the lowest in comparison to other methods, as indicated in ***Table 5***. This factor will be marked using the colour green in the SWOT table.

### Risks

The process of soil carbon sequestration carries significant hazards that must not be ignored. The rise in nitrous oxide emissions can be attributed to elevated quantities of organic nitrogen in the soil. The soil has a limited capacity to protect organic matter, which may be diminished due to climate change (***Table 4***). Therefore, it will be marked with the colour orange in the SWOT table.

### Measurability

Although this study presents numerous elements, it is now difficult to make any certain statements regarding the future. An example is the MRV value (***Table 4.***) which quantifies the ease and precision of measuring the quantity of carbon eliminated. Regarding Soil Carbon Sequestration, the quantity of $CO_2$ that can be eliminated during the capture process can be estimated with moderate precision, but the amount of $CO_2$ stored during storage can only be established with limited precision. This feature will be designated with the colour orange in the SWOT table.

### Lack of investors

CDR technologies are commonly misunderstood. From an investor's standpoint, the likelihood of recuperating costs is minimal. Additional incentives are required at both the national and international levels. Policy formulation can facilitate this procedure. For instance, in the United States, the implementation of tax credits, in the European Union and the United Kingdom, the endorsement of innovation funds, are progressively expanding the possibilities for potential investors (see chapter 6.14.) The colour orange will be used to emphasise this characteristic across all technologies.

### Scalability

Based on the mitigation potential (Table 3.) we can infer the feasibility of the technology in the future. Soil Carbon Sequestration has a moderate scalability estimate, with a maximum of 9.3 million tons sequestered year. Consequently, this particular feature will be emphasised by marking it in the colour red in the SWOT table.

### Contribution to the below 2°C target

Because of the relatively medium mitigation potential, it will be designated with the colour orange in SWOT the table.

### Research and Development

In order to calculate the R&D component, data on publication and patenting activities will be utilised, as shown in ***Figure 4.*** and ***Figure 5.*** The quantity of research articles on CDR technologies has experienced exponential growth in recent years (***Figure 4***). The proportion of publications (***Figure 4.)*** pertaining to Soil Carbon Sequestration is rather substantial when compared to other technologies. However, the quantity of patents is exceedingly limited ***Figure 5***). After conducting a comparison of these two aspects, this feature will be designated with the colour orange in the SWOT table.

### Cost

The Soil Carbon Sequestration technology is regarded as having the most affordable costs in comparison to other technologies (Table 4). This factor will be designated with the colour green in the SWOT table.

### Social acceptance

The level of acknowledgement for Soil Carbon Sequestration, as indicated by the fluctuation in the quantity of tweets seen on social media (***Figure 6.***) is presently not a comprehensively known technology. Based on the positive/negative ratio of tweets, the general public's impression of Soil Carbon Sequestration is highly positive (***Figure** 7*). This element will be highlighted in green in the SWOT table.

### Policy making

Although there are several encouraging attempts, such as the implementation of tax credits in the United States and the allocation of funds to stimulate innovation in the European Union and the United Kingdom, there is currently limited worldwide advancement in this field (see chapter 6.14). Consequently, this factor will be emphasised by marking it in red in the SWOT chart.

### SWOT table of Soil Carbon Sequestion

**Table 11.** The SWOT table of Soil Carbon Sequestion

| Strenghts | Weaknesses |
|---|---|
| Energy requirements | Risks |
| Proven technology | Measurability |
| Durable storage | Lack of investors |
| **Opportunities** | **Threats** |
| Scalability | Cost |
| Contribution to the below 2°C target | Social acceptance |
| R&D | Policy making |

## 7.6. The SWOT analysis of Ocean Fertilization

### Proven technology

According to the data presented in Table 4. most carbon dioxide removal (CDR) methods are advanced. Nevertheless, the technological readiness level (TRL) of ocean fertilisation technology is exceedingly low. Consequently, it will be indicated in the colour red in the SWOT table.

### Durable storage

The capacity for long-term storage of $CO_2$ in vegetation is significantly reduced compared to that in geological formations or mineral beds (Table 3). Its maximum duration can only be quantified in terms of decades. Hence, durable storage is shown with the colour red in the SWOT table.

### Energy requirements

Ocean Fertilisation is classified as a low-energy technology, as seen in Table 5. It will be marked with green colour in the SWOT table.

### Risks

Ocean Fertilisation technology has considerable dangers, including the redistribution of nutrients, increased oxygen use, and acidification in deeper waters. May promote the growth of harmful algae. The proportion of $CO_2$ that is successfully stored in a long-lasting manner is unknown, mostly because of the process of re-metabolization (Table 3). It will be marked with the colour red in the SWOT table.

### Measurability

Although this study presents numerous elements, it is now difficult to make any certain statements regarding the future. An example is the MRV value (Table 4.) which quantifies the ease and precision of measuring the quantity of carbon eliminated. Regarding ocean Fertilisation, the estimation of the quantity of $CO_2$ that can be eliminated during the capture process and the quantity of $CO_2$ that can be held during storage are both subject to imprecise determination. This issue will be indicated using the colour red in the SWOT table.

### Lack of investors

CDR technologies are commonly misunderstood. From an investor's standpoint, the likelihood of recuperating costs is minimal. Additional incentives are required at both the national and international levels. Policy formulation can facilitate this procedure. For instance, in the United States, the implementation of tax credits, in the European Union and the United Kingdom, the endorsement of innovation funds, are progressively expanding the possibilities for potential investors (see chapter 6.14.) The colour orange will be used to emphasise this characteristic across all technologies.

### Scalability

Based on the mitigation potential (Table 4.), we can infer the feasibility of the technology in the future. Ocean Fertilisation exhibits limited scalability, with a maximum sequestration capacity of 3 million tons per year. Consequently, this particular feature will be emphasised by marking it in red in the SWOT chart.

### Contribution to the below 2°C target

Due to the very limited mitigation potential (Table 4.) this component will be included marked in red in the SWOT table.

### Research and Development

In order to calculate the R&D component, data on publication and patenting activities will be utilised, as shown in ***Figure 4.*** and ***Figure 5.*** The quantity of research articles on CDR technologies has experienced exponential growth in recent years (***Figure 4***). The proportion of publications and patent activity associated with ocean fertilisation (***Figure 4; Figure 5.***) is notably lower in comparison to other technologies. Through the comparison of these two aspects, this particular component will be emphasised by marking it in red in the SWOT table.

### Cost

Ocean Fertilisation technology is deemed to have a notably high cost in comparison to other methods (Table 4). Cost will be emphasised with the colour red in the SWOT table.

### Social acceptance

Based on the fluctuation in the number of tweets detected on social media (***Figure 6.***) the technology of Ocean Fertilisation is now not well recognised. The primary concern of ocean fertilisation is the bad public impression of this practice, as depicted in ***Figure** 7*. Upon comparing the two data, this aspect will be designated in the colour red in the SWOT table.

**Policy making**

Although there are several encouraging attempts, such as the implementation of tax credits in the United States and the allocation of funds to stimulate innovation in the European Union and the United Kingdom, there is currently limited worldwide advancement in this field (see chapter 6.14). Consequently, this factor will be emphasised by marking it in red in the SWOT chart.

**The SWOT table of Ocean Fertilisation**

**Table 12.** The SWOT table of Ocean Fertilisation

| Strenghts | Weaknesses |
|---|---|
| Energy requirements | Risks |
| Proven technology | Measurability |
| Durable storage | Lack of investors |
| **Opportunities** | **Threats** |
| Scalability | Cost |
| Contribution to the below 2°C target | Social acceptance |
| R&D | Policy making |

## 7.7. The SWOT analysis of Ocean Alkalinization

**Proven technology**

According to the data presented in Table 4. most carbon dioxide removal (CDR) methods are advanced. Nevertheless, the technological readiness level (TRL) of Ocen Alkalization technology (such as Ocean Fertilisation technology) is exceedingly low. Consequently, it will be indicated in the colour red in the SWOT table.

**Durable storage**

The long-term retention of $CO_2$ in marine sediments is comparable to that in geological formations or mineral beds (Table 3). At most, it can take up to ten thousand years. Therefore, long-lasting storage is indicated with the colour green in the SWOT table.

**Energy requirements**

Ocean Alkalinization is classified as a low-energy technology, as seen in Table 5. It will emphasised with the colour green it in the SWOT table.

### Risks

The technology of Ocean Alkalinization has significant risks that must not be ignored. The increase in pH value and saturation state of seawater can have a local detrimental impact on marine ecosystems. The potential release of nourishing or toxic elements and compounds can disrupt marine ecosystems. It also has mining effects. (Table 4). Therefore, it will be marked with the colour red in the SWOT table.

### Measurability

Although this study presents numerous elements, it is now difficult to make any certain statements regarding the future. An example is the MRV value (Table 4.), which quantifies the ease and precision of measuring the quantity of carbon eliminated. Regarding Ocean Alkalinization, the precision of determining the quantity of $CO_2$ that can be removed during capture and the quantity of $CO_2$ stored during storage is low. This feature will be emphasise with the colour red in the SWOT table.

### Lack of investors

CDR technologies are commonly misunderstood. From an investor's standpoint, the likelihood of recuperating costs is minimal. Additional incentives are required at both the national and international levels. Policy formulation can facilitate this procedure. For instance, in the United States, the implementation of tax credits, in the European Union and the United Kingdom, the endorsement of innovation funds, are progressively expanding the possibilities for potential investors (see chapter 6.14.) The colour orange will be used to emphasise this characteristic across all technologies.

### Scalability

The Ocean Alkalinization technology has the capacity to sequester up to 100 million tons of $CO_2$ annually *(*Table 4***)***. Consequently, this element will be designated as green in the SWOT table.

### Contribution to the below 2°C target

Due of its extremely high mitigation potential (Table 4.) this factor will ne marked with green colour in the SWOT table.

### Research and Development

In order to calculate the R&D component, data on publication and patenting activities will be utilised, as shown in ***Figure 4.*** and ***Figure 5.*** The quantity of research articles on CDR technologies has experienced exponential growth in recent years (***Figure 4***). The prevalence of publications on Ocean Alkalinization, while decreasing in recent years, remains comparatively elevated in comparison to other technologies (***Figure 4***). Regrettably, there is no patent number associated with this technique. Consequently, this feature will be indicated by using the colour orange in the SWOT table.

### Cost

The Ocean Alkalization technology is somewhat expensive compared to other technologies, as shown in Table 4. This aspect will be denoted with an orange marker in the SWOT table.

### Social acceptance

The level of acknowledgement for Soil Carbon Sequestration, as indicated by the fluctuation in the quantity of tweets seen on social media (***Figure 6.***), is presently not a comprehensively known technology. Based on the positive/negative ratio of tweets, the general public's impression of Ocean Alkalinization sequestration is highly positive (***Figure 7***). This element will be highlighted in green in the SWOT table.

### Policy making

Although there are several encouraging attempts, such as the implementation of tax credits in the United States and the allocation of funds to stimulate innovation in the European Union and the United Kingdom, there is currently limited worldwide advancement in this field (see chapter 6.14). Consequently, this factor will be emphasised by marking it in red in the SWOT table.

### The SWOT table of Ocean Alkalinization

**Table 13.** The SWOT table of Ocean Alkalinization

| Strenghts | Weaknesses |
|---|---|
| Energy requirements | Risks |
| Proven technology | Measurability |
| Durable storage | Lack of investors |
| **Opportunities** | **Threats** |

| | |
|---|---|
| Scalability | Cost |
| Contribution to the below 2°C target | Social acceptance |
| R&D | Policy making |

## 7.8. The SWOT analysis of Afforestation and Reforestation

### Proven technology

According to the data presented in Table 4. most CDR technologies have reached a high level of development. Often, in certain instances like Afforestation and Reforestation technology, the TRL value can be quite high, even reaching the maximum 9 value. It is indicated with a green colour in the SWOT table.

### Durable storage

The long-term sequestration of $CO_2$ in vegetation is significantly less compared to $CO_2$ stored in geological formations or minerals, as indicated in Table 3. However, the lifespan of trees can extend up to a century. Hence, the durable storage is highlighted in orange in the SWOT table.

### Energy requirements

Afforestation and Reforestation are classified as low-energy methods, as seen in Table 4. It will be emphasised with the colour green in the SWOT table.

### Risks

The use of Afforestation and Reforestation technology carries significant hazards, including the potential for the reversal of carbon dioxide removal (CDR) due to factors such as wildfires, diseases, and pests. If the species and biome are not suitable, it might lead to a decrease in catchment water yield and a decline in groundwater levels. The land has a limited ability to support carbon, and this ability may be decreased due to climate change (Table 4). The risks will be marked with the colour red the in the SWOT table.

### Measurability

Although this study presents numerous elements, it is now difficult to make any certain statements regarding the future. An example is the MRV value (Table 4.) which quantifies the ease and precision of measuring the quantity of carbon eliminated. In the case of Afforestation and Reforestation, the precise measurement of the quantity of $CO_2$ that can be captured during the process and the accurate estimation of the amount of $CO_2$ stored are possible. This feature will be indicated by using the colour green in the SWOT table.

### Lack of investors

CDR technologies are commonly misunderstood. From an investor's standpoint, the likelihood of recuperating costs is minimal. Additional incentives are required at both the national and international levels. Policy formulation can facilitate this procedure. For instance, in the United States, the implementation of tax credits, in the European Union and the United Kingdom, the endorsement of innovation funds, are progressively expanding the possibilities for potential investors (see chapter 6.14.) The colour orange will be used to emphasise this characteristic across all technologies.

### Scalability

Based on the mitigation potential (Table 4.) we can infer the feasibility of the technology in the future. The Afforestation and Reforestation technology has the capacity to sequester up to 18 million tons of $CO_2$ annually. Consequently, this element will be designated as green in the SWOT table.

### Contribution to the below 2°C target

Due of its extremely high mitigation potential (Table 4.) this factor will be marked with the colour green in the table.

### Research and Development

In order to calculate the R&D component, data on publication and patenting activities will be utilised, as shown in ***Figure 4.*** and ***Figure 5.*** The quantity of research articles on CDR technologies has experienced exponential growth in recent years (***Figure 4***). The quantity of papers pertaining to Afforestation and Reforestation is exceedingly substantial ***(Figure 4)***. Due to its low number of patents ***(Figure 5.)*** This feature will be designated with the colour orange in the SWOT table.

### Cost

The Afforestation and Reforestation technology is somewhat expensive compared to other technologies, as shown in Table 4. This aspect will be marked with an orange marker in the SWOT table.

### Social acceptance

The level of acceptance of Afforestation and Reforestation is categorised as medium-high based on the fluctuation in the number of tweets recorded on social media ***(Figure 7).*** Based on the positive/negative ratio of tweets, the general public's impression of Afforestation and Reforestation is highly positive, as shown in Figure 10. Upon analysing the two sets of data, this particular element will be designated as green in the SWOT table.

### Policy making

Although there are several encouraging attempts, such as the implementation of tax credits in the United States and the allocation of funds to stimulate innovation in the European Union and the United Kingdom, there is currently limited worldwide advancement in this field (see chapter 6.14). Consequently, this factor will be emphasised by marking it in red in the SWOT chart.

### The SWOT table of Afforestation and Reforestation

**Table 14.** The SWOT table of Afforestation and Reforestation

| Strenghts | Weaknesses |
|---|---|
| Energy requirements | Risks |
| Proven technology | Measurability |
| Durable storage | Lack of investors |
| **Opportunities** | **Threats** |
| Scalability | Cost |
| Contribution to the below 2°C target | Social acceptance |
| R&D | Policy making |

# 8. Summary of SWOT analysis of CDR technologies

**Table 15**. Summary of SWOT analysis of CDR technologies

| Technologies | Strenghts | | | Weaknesses | | | Opportunities | | | Threats | | | Relative potential of CDR techologies |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Energy requirements | Proven technology | Durable storage | Risks | Measurability | Lack of investors | Scailability | Contribution to the below 2°C target | R&D | Cost | Social acceptance | Policy making | |
| DACCS | 0 | 3 | 3 | 3 | 3 | 1 | 3 | 3 | 1 | 0 | 1 | 0 | 21 |
| BECCS | 3 | 3 | 3 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 15 |
| Biochar | 3 | 3 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 15 |
| Enhanced Rock Weathering | 1 | 0 | 3 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 5 |
| Ocean Alkalinization | 3 | 0 | 3 | 0 | 0 | 1 | 3 | 3 | 1 | 1 | 3 | 0 | 18 |
| Ocean Fertilisation | 3 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 4 |
| Afforestation and Reforestation | 3 | 3 | 1 | 0 | 3 | 1 | 3 | 3 | 1 | 1 | 3 | 0 | 22 |
| Soil Carbon Sequestration | 3 | 3 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 3 | 3 | 0 | 18 |

| | | |
|---|---|---|
| 0 | 1 | 3 |

### Relative potential of CDR technologies

This thesis assigned distinct numerical values to each hue, enabling the use of a bar chart to assess the relative potential of each CDR technology in achieving the aim of the research question of this thesis. The relative numerical values ascribed to the factors were weighted in accordance with the data analysed in the SWOT analysis. The colour red was assigned a numerical value of 0, orange a value of 1, and green a value of 3. Finally, the values for the various technologies were added together. The greater the overall score of a technology, the greater its relative potential.

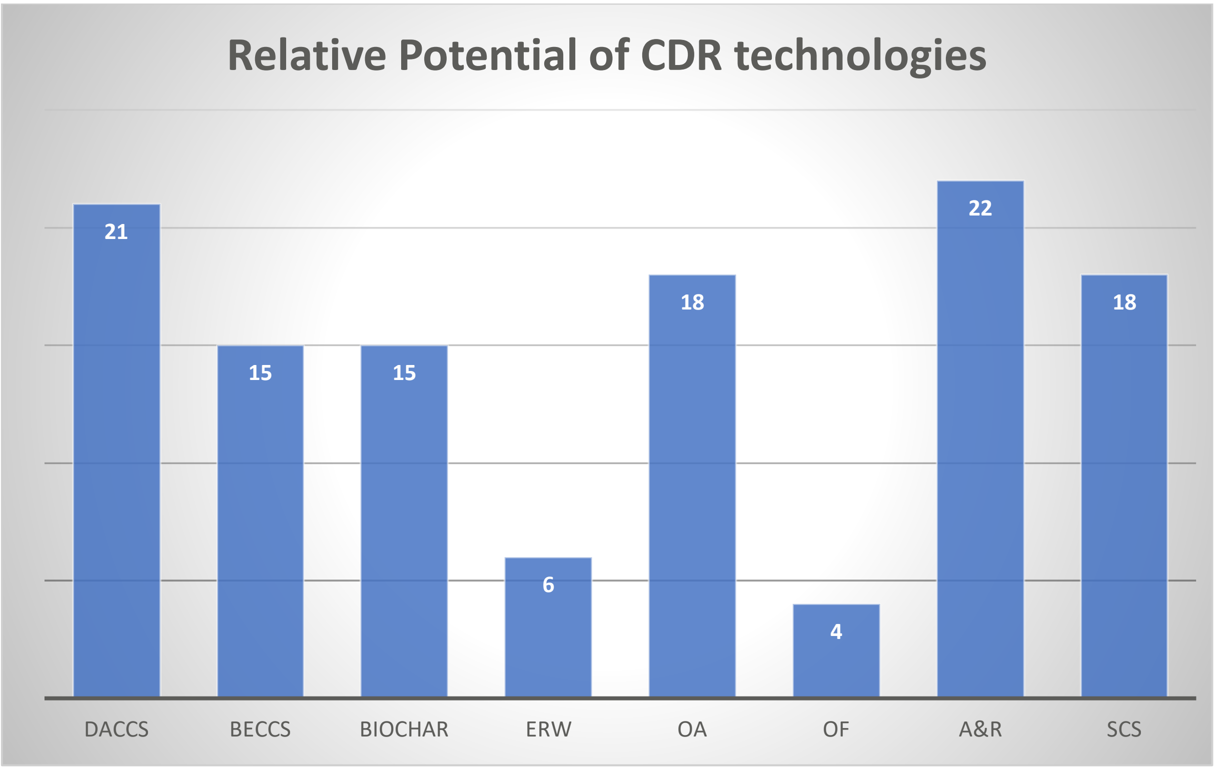


**Figure 10.** Relative potential of CDR technologies

According to the graph, Direct Air Capture with Carbon Storage (DACCS) and Afforestation and Reforestation (AF&RF) technologies received the highest scores through the SWOT analysis. Ocean Alkalinization (OF) and Soil Carbon Sequestion technologies received a relatively high score. Bioenergy with Carbon Capture and Storage (BECCS) and Biochar technologies achived a relatively medium high score. Enhanced Rock Weathering and Ocean Fertilisation achived a relatively low score after the SWOT analysis.

# 9. Conclusion and outlook

As a consequence of the SWOT analysis, few technologies are thought to be promising. The SWOT analysis was certainly suitable for the classification of CDR technologies.

By conducting a SWOT analysis, this thesis was able to evaluate various CDR technologies. From this perspective, the SWOT analysis was employed has demonstrated its appropriateness in effectively comparing the efficacy of CDR technologies.

Following the analysis, there are more promising technologies, such as Direct Air Capture with Carbon Storage (DACCS), Afforestation and Reforestation (AF&RF), Ocean Alkalinization (OF), and Soil Carbon Sequestration. These technologies received a relatively high score. Additionally, there are technologies that are less promising, such as Ocean Fertilisation and Enhanced Rock Weathering, which received a relatively low score following the SWOT analysis. According to the SWOT analysis Enhanced Rock Weathering and Ocean Fertilisation technologies will not be able to make a significant contribution to achieving the aim of the Paris Agreement because of their high risks, their high cost and their measurability is extremely low. Ocean Alkalinization (OF) can be promising due to its long-term storage potential and scalability, and the Soil Carbon Sequestion technology due to its very low energy requirements. Regarding DACCS and Forestration and Deforestation methods, were identified the most favourable aspects in relation to the purpose of limiting global warming to below 2°C, as outlined in the Paris Agreement. Both technologies are deemed secure and technologically robust. Both DACCS and Forestration and Deforestation technologies have significant potential for capacity expansion. These methods have the potential to individually or collectively absorb and store the present yearly amount of around 40 million tons or more of anthropogenic $CO_2$ sequestration, especially after capacity improvements. In the view of DACCS technologies, despite the current high maintenance costs, it is projected that these expenses could be reduced by 50% by the year 2030, owing to various promising technology advancements. Geological storage has the potential to offer secure and long-lasting storage for thousands of years.

Therefore, this research concludes that there are currently available carbon dioxide removal (CDR) technology that can effectively and consistently decrease atmospheric $CO_2$ levels in the near future, making a meaningful contribution to achieving the Paris Agreement's aim of keeping global warming below 2°C?

Overall, the development of laws to encourage the implementation of carbon dioxide removal (CDR) technology is still in its early stages. Additional advancements are required in this domain, which would likely significantly enhance investment attraction.

It may be beneficial to periodically review the SWOT analysis utilised in this thesis as further comprehensive data becomes accessible in the literature. This will ensure a thorough and precise method of evaluating the future efficacy of CDR technologies.

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