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Review Analysis on Scalability of Carbon Removal Methods and Regulatory Framework for Carbon Management for Companies that sell materials to remove CO_2

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ABSTRACT

This article provides a comprehensive overview of various carbon capture and sequestration (CCS) technologies and approaches aimed at reducing atmospheric carbon dioxide (CO_2) concentrations. It evaluates the effectiveness, costs, and potential scalability of different methods proposed by companies and research organizations worldwide, including innovative technologies such as CARBiNX by Clean O_2, carbon capture by forests and trees, Direct Air Capture (DAC) systems developed by Heirloom Carbon Technologies, and geological storage solutions like Carbfix in Iceland. The article also examines the costs associated with these technologies and their capacity to remove significant amounts of CO_2 from the atmosphere. Furthermore, it explores future pathways and frameworks for achieving gigaton-scale carbon dioxide removal, emphasizing the importance of interdisciplinary collaboration and technological innovation in addressing the urgent challenge of climate change. Through a comprehensive analysis of current research and industry practices, this review aims to provide insights into the scalability of carbon removal methods and the regulatory landscape governing carbon management, focusing on companies that sell materials to remove CO_2. It discusses the challenges and opportunities associated with scaling up carbon removal technologies and explore regulatory frameworks shaping the deployment of these technologies, offering valuable insights into the future of carbon removal and regulatory compliance for companies in the carbon removal sector.

1. INTRODUCTION

Carbon removal methods and regulatory frameworks for carbon management are critical aspects of addressing climate change and achieving carbon neutrality. As the global community grapples with the urgent need to reduce greenhouse gas emissions, understanding the scalability of carbon removal methods and the regulatory landscape surrounding carbon management is paramount for companies involved in providing materials for carbon removal processes (Keohane & Stavins, 2019).

This review aims to analyze the scalability of various carbon removal methods and evaluate the regulatory frameworks governing carbon management, providing valuable insights for companies operating in this burgeoning sector. In recent years, there has been growing recognition of the importance of carbon removal technologies in mitigating the effects of climate change (Fuss et al., 2018). According to Keith et al., (2018) these technologies encompass a diverse range of approaches, including afforestation and reforestation, direct air capture, enhanced weathering, bioenergy with carbon capture and storage (BECCS), and ocean-based

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solutions such as ocean fertilization and seaweed cultivation. Each method offers unique advantages and challenges, and assessing their scalability is crucial for understanding their potential impact on carbon sequestration at a global scale (Keith et al., 2018).

Simultaneously, the regulatory landscape surrounding carbon management has evolved significantly as policymakers seek to implement frameworks that incentivize emissions reduction and carbon removal while ensuring environmental integrity and social equity. Regulatory mechanisms such as carbon pricing, cap-and-trade systems, carbon offset standards, and emissions trading schemes play a pivotal role in shaping the incentives for companies to invest in carbon removal technologies and integrate them into their operations (Pearse & Böhm, 2014).

According to IPCC report, in pursuit of achieving the ambitious goals set forth by the Paris Agreement, which aims to limit global warming to well-below 2°C and ideally pursue efforts to limit it to 1.5°C, a prevalent strategy emerging in climate mitigation scenarios involves the integration of carbon dioxide removal (CDR) technologies (Beck & Mahony, 2018). These innovative approaches to carbon management are not only envisioned as means to compensate for potential temporary overshoots in carbon budgets but also to offset emissions that are particularly costly or challenging to abate through conventional means. This underscores the growing recognition of CDR as a crucial component in the toolkit for combating climate change, offering novel avenues to address emissions reduction targets and transition towards a more sustainable future (Pathak et al., 2022). The scale-up of carbon dioxide removal (CDR) to meet the demands outlined in these scenarios necessitates the implementation of various mechanisms, including policies, incentives, obligations, and commercialization strategies (Pathak et al., 2022). Yet, the extent to which existing and proposed mechanisms will effectively drive progress towards achieving net-zero targets remains uncertain. This underscores the complexity of aligning regulatory frameworks and market dynamics with the imperative of scaling up CDR technologies to mitigate climate change effectively.

Given the persistent nature of CO_2 in the atmosphere, achieving a sustained state of net zero emissions requires that any CO_2 removed from the atmosphere is stored for a comparable duration. This underscores the importance of ensuring that carbon removal efforts are not only effective in extraction but also in long-term storage, emphasizing the necessity for solutions that guarantee enduring carbon sequestration to effectively address climate change concerns (Fankhauser et al., 2022).

Presently, disparities exist among various factors, including pricing, longevity, and advancement, between biological and geological approaches to carbon dioxide removal (CDR) (Morgan & Waskow, 2014). This highlights the significant divergence in the attributes and progress of these methods, underscoring the need for comprehensive evaluation and strategic investment to foster the development of both biological and geological CDR technologies (Morgan & Waskow, 2014). Biological carbon dioxide removal (CDR) methods typically entail shorter-term carbon storage, rendering them particularly suitable for mitigating emissions associated with land use. This distinctive characteristic positions biological CDR as a preferred option for addressing challenges related to land use emissions, emphasizing its relevance in the broader landscape of carbon management strategies (Alcalde et al., 2018).

While geological carbon dioxide removal (CDR) holds promise for permanently eliminating emissions, these methods often entail higher costs and require rigorous demonstration of efficacy and scalability. This underscores the importance of thorough assessment and validation of geological CDR techniques to ensure their viability for large-scale implementation, highlighting the necessity for robust investment and research efforts in this area (Fuss et al., 2018).

Numerous analysts assert that substantial quantities of atmospheric carbon dioxide (CO_2) must be captured and permanently sequestered in the forthcoming decades to align with international objectives aimed at halting climate change. This imperative remains pressing even in the face of aggressive measures to curtail greenhouse gas (GHG) emissions (Boyd, Joiner, Krupnick, & Toman, 2024). Meeting the demand for carbon dioxide removal (CDR) to attain net-zero GHG emissions represents a formidable technological hurdle, necessitating significant advancements in CDR capabilities and deployment strategies. Implementing CDR on the requisite scale is anticipated to be costly, particularly in the immediate future. Moreover, it

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introduces social and environmental complexities, including impacts on local communities, alterations in land use patterns, and substantial upticks in electricity consumption (Boyd et al., 2024).

In recent years, in the pursuit of restraining global warming, governments, industry pioneers, and scientific bodies have put forward an array of CO_2 reduction initiatives and technological solutions. Among these, the carbon capture and utilization or storage (CCUS) strategy emerges as a pivotal mitigation tool. This technology-driven approach transforms emitted CO2 into either stored carbon or into products with added value, thereby presenting a multifaceted solution to address the challenges of climate change (Nocito & Dibenedetto, 2020) .

Over the past decade, climate change has transitioned from a peripheral issue to a global concern of paramount importance. This shift is particularly evident given that the period from 2014 to 2018 was identified as one of the warmest on record, further underscoring the urgency of addressing climate-related challenges on a worldwide scale (Butler, 2018). During the Paris international climate summit in 2015, 177 governments collectively resolved to take unified action aimed at restricting the increase in global warming to below 2°C by the year 2030, with a further aspiration to lower it to 1.5°C by 2050 (Palermo & Hernandez, 2020). While the Paris Agreement marked a significant milestone as the first comprehensive global accord to include policy commitments addressing global warming, the trajectory for mitigating atmospheric warming traces back over three decades (Butler, 2018). This journey commenced with the establishment of the Intergovernmental Panel on Climate Change (IPCC) in 1990, followed by the inception of the United Nations Framework Convention on Climate Change (UNFCCC) in 1992, laying the groundwork for concerted international efforts to combat climate change (Palermo & Hernandez, 2020).

This review article will delve into the scalability of various carbon removal methods, examining factors such as technological maturity, cost-effectiveness, environmental impact, and potential deployment at scale. Furthermore, it will analyze the regulatory frameworks governing carbon management, exploring the effectiveness of existing policies and identifying opportunities for improvement to facilitate the widespread adoption of carbon removal technologies by businesses.

The objective of this study is to conduct a comprehensive review and analysis focusing on two key aspects crucial for companies engaged in providing materials for carbon removal: the scalability of carbon removal methods and the regulatory framework for carbon management. The research aims to evaluate the scalability of various carbon removal methods, including but not limited to biological, geological, and technological approaches. This assessment involves examining factors such as technological maturity, cost-effectiveness, environmental impact, and potential for large-scale deployment. By analyzing the scalability of different carbon removal methods, the study seeks to identify opportunities, challenges, and best practices for companies involved in the production and supply of materials used in carbon removal processes. The research seeks to analyze the regulatory landscape governing carbon management, encompassing policies, incentives, obligations, and commercialization mechanisms. This analysis aims to understand the effectiveness of existing regulatory frameworks in promoting carbon removal activities and facilitating market participation by companies offering carbon removal materials. Additionally, the study aims to identify gaps, inconsistencies, and areas for improvement in the regulatory environment to support the growth of the carbon removal industry (Keohane et al., 2019).

By synthesizing findings from the assessment of scalability and analysis of regulatory frameworks, the research aims to provide actionable insights for companies that sell materials for carbon removal. These insights may include recommendations for strategic decision-making, investment prioritization, innovation, compliance with regulations, and engagement with policymakers. The ultimate goal is to empower companies to navigate the evolving landscape of carbon removal technologies and regulatory requirements effectively, contributing to the advancement of sustainable solutions for mitigating climate change (Keith et al., 2018).

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METHODOLOGY

The research phase encompasses several components, integrating insights from past analyses alongside novel perspectives introduced in this study. The methodological framework for this research review is depicted in Figure 1 below. The design framework is based upon the companies profile line, that encompasses the major horizons of the material that was used to reduced the impact of CO_2 removal, and the cost effective approaches by each company that was set on target to remove 1 metric ton of CO_2. Moreover the paper also focus on the environmental measures adopted by the companies and what step they have taken to reduced the impact of CO_2.

Scalability Assessment

Each material-based carbon removal technology employs distinct mechanisms for capturing and storing CO_2. For example, in the case of Direct Air Capture (DAC) with Solid Sorbents, Keith et al., (2018) explore the progress made in DAC technologies, emphasizing the capacity of solid sorbents to effectively capture CO_2 from the atmosphere. However, they underscore the necessity for substantial energy input and technological enhancements to enhance efficiency and diminish costs for wides cale implementation (Keith et al., 2018).

In the study conducted by Woolf et al., (2010) delve into the significance of biochar in carbon sequestration, highlighting its capacity for long-term carbon storage within soils. They emphasize that the efficacy of biochar as a carbon removal strategy hinges on several factors, including the choice of feedstock, pyrolysis conditions, and methods of application, all of which can impact its overall efficiency in removing CO_2 and its longevity in storage (Street et al., 2011).

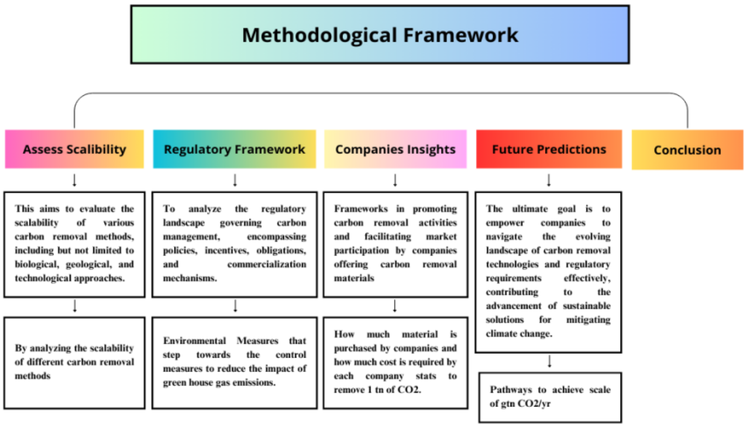

Figure 1. Methodological framework of the research.

Power et al., (2016) delve into the process of mineral carbonation, wherein CO_2 is chemically converted into stable mineral carbonates. They highlight the vast potential for CO_2 storage but also point to the energy-intensive nature of the process and the need for further research to identify more efficient pathways for mineralization at scale (Power et al., 2016).

The sustainability of carbon removal technologies is intricately linked to their resource needs and potential environmental consequences. As part of scalability assessment, evaluating energy and water usage is crucial. Realmonte et al., (2019) analyzed the energy demands of Direct Air Capture (DAC) systems, highlighting their potential in mitigating atmospheric CO2 but acknowledging limitations due to their substantial energy requirements and associated expenses. Additionally, the water footprint of these technologies, particularly in arid areas, presents sustainability concerns (Realmonte et al., 2019).

Analyzing the economic feasibility of scaling carbon removal technologies entails a thorough examination of cost projections, capital and operational expenses, and potential revenue streams. Understanding cost trajectories and reductions offers insight into the factors influencing cost reduction in DAC technology, such as technological advancements, economies

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of scale, and innovations in material science (Goeppert et al., 2012). Additionally, assessing revenue models involves exploring how companies involved in carbon removal can generate income through various avenues, including the sale of carbon credits in established markets. Moreover, delving into the economic aspects of carbon capture and storage underscores the significance of carbon pricing mechanisms and policy incentives in fostering the financial viability of these technologies (Mac Dowell et al., 2017)

Regulatory Framework

The regulatory framework governing carbon management plays a pivotal role in shaping the development, deployment, and scalability of carbon removal technologies. Effective policies, standards, and market mechanisms are indispensable in creating an environment that fosters carbon removal initiatives while upholding credibility and environmental integrity. Let us delve deeper into these components, proposing pragmatic methods for enhancement and referencing pertinent sources (Beck & Mahony, 2018).

The global response to climate change has spurred the establishment of diverse regulatory frameworks at both international and national levels, aimed at facilitating carbon removal and management. Notably, the Paris Agreement stands out as a monumental global endeavor to combat global warming, urging nations to strive for carbon neutrality through various means, including the adoption of carbon removal technologies. Each participating country outlines its nationally determined contributions (NDCs) toward curbing global greenhouse gas emissions (Realmonte et al., 2019).

Moreover, attention must be directed towards national policies tailored to individual countries. Policies such as the United States' 45Q tax credit for carbon capture, utilization, and storage (CCUS) activities, and the European Green Deal, endeavor to slash net emissions through innovative approaches and economic incentives (Pathak et al., 2022). Regulatory framework also encompasses carbon pricing mechanisms, which can be implemented through carbon taxes or cap-and-trade systems. These mechanisms internalize the costs associated with carbon emissions, compelling companies to invest in carbon removal or reduce their emissions (Boyd et al., 2024).

In essence, a well-crafted regulatory framework serves as the linchpin for advancing carbon management strategies, ensuring alignment with global climate goals and fostering a conducive environment for the widespread adoption and scaling of carbon removal technologies (Morgan & Waskow, 2014).

Carbon pricing mechanisms play a fundamental role in shaping the economics of carbon removal. For instance, cap-and-trade systems establish a limit on total emissions while enabling the trading of emission allowances, fostering a carbon market that encourages cost-effective strategies for carbon reduction. Similarly, carbon taxes impose a tax on each ton of emitted CO_2, motivating companies to either reduce emissions or invest in carbon removal technologies to mitigate the tax burden (Pathak et al., 2022).

The reliability of carbon removal assertions relies heavily on robust standards and verification processes. This entails the development of comprehensive standards, such as those being developed by the International Organization for Standardization (ISO) and similar entities, specifically targeting carbon capture, utilization, and storage (CCUS). The aim is to ensure that activities within this sector are measurable, reportable, and verifiable (Pathak et al., 2022). Third-party verification of carbon removal and storage claims is indispensable for maintaining the credibility of the carbon market. Independent verification guarantees that claimed carbon reductions are authentic, permanent, and additional (Morgan & Waskow, 2014).

The urgent threat of climate change has spurred efforts to explore innovative approaches aimed at reducing atmospheric carbon dioxide (CO_2) levels (Beck & Mahony, 2018). Among these strategies, carbon removal methods have emerged as pivotal tools in the fight against global warming. From direct air capture (DAC) utilizing solid sorbents to techniques like biochar and mineralization, a diverse array of methods holds promise for achieving carbon neutrality. However, the scalability of these technologies is intricately linked to a myriad of factors,

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encompassing technical feasibility, resource demands, economic viability, and notably, the regulatory landscape governing carbon management (Goeppert et al., 2012).

This review analysis explores the scalability of carbon removal methods with a specific focus on companies engaged in the development and sale of materials aimed at capturing and eliminating CO_2 from the atmosphere. It scrutinizes the present status of carbon removal technologies, evaluating their effectiveness, durability, and the technological innovations required for extensive implementation. Additionally, it delves into the economic aspects driving these technologies, including the trajectory of costs, operational expenditures, and potential revenue models bolstered by policy incentives and carbon credit markets (Minx et al., 2018). At the core of this analysis lies the examination of the regulatory framework influencing the carbon management sector (Zeman & Keith, 2008). International and national policies, along with market mechanisms like cap-and-trade systems and carbon taxes, are pivotal in either fostering or impeding the advancement of carbon removal solutions (Lehmann, 2007). Emphasis is placed on the significance of standardization and verification processes to uphold the credibility of carbon removal claims, crucial for the integrity and scalability of carbon markets (Minx et al., 2018).

This review also anticipates future regulatory and market advancements crucial for scaling carbon removal methods, emphasizing international collaboration, enhanced carbon trading markets, and supportive public policies to meet climate targets. Through this comprehensive analysis, it aims to provide valuable insights and a roadmap for companies, policymakers, and stakeholders in the carbon management sector (Zeman & Keith, 2008). Carbon removal methods encompass biological, geological, and technological categories, each delineating distinct mechanisms, potentials, limitations, and scalability impacts. This analysis delves into these varied approaches, furnishing a holistic view of their scalability amidst contemporary technological progress, economic viability, and regulatory paradigms.

Biological carbon removal methods

Biological approaches harness natural processes to capture carbon, employing methods such as afforestation and reforestation, soil carbon sequestration, and bioenergy with carbon capture and storage (BECCS) (Realmonte et al., 2019). Afforestation and Reforestation involve planting trees on non-forested land or replanting deforested areas, offering significant scalability potential globally (Goeppert et al., 2012). Challenges include land competition with agriculture, water usage, and the long-term permanence of carbon storage (Realmonte et al., 2019).

Table 1. Table highlights the difference between current available biological CO_2 removal technologies.

Variables	Biochar	Afforestation	BECCS	DAC	Weathering
Land	Existing	Re-planting	Displaced crops	Small	Existing
CAPEX	Low	Low	High	High	Low
OPEX	Low	Low	High	High	Low
Readiness	Now	Now	>5yrs	Not yet	Not yet
Permanence	100-1000 yrs	Not graunteed	Unproven	Unproven	Unproven
Scale	Limited by material	Limited by land	Limited by material	High	Limited by land

***BECCS** – (Bioenergy carbon capture & storage)* ***DAC** – (Direct air capture)*

Soil Carbon Sequestration methods like no-till farming, cover cropping, and biochar application enhance carbon storage in soils. While highly scalable across diverse agricultural landscapes, variability in soil types and farming practices can influence carbon sequestration levels. Bioenergy with Carbon Capture and Storage (BECCS) integrates biomass energy generation with carbon capture and storage, presenting the opportunity for negative emissions (Fankhauser et al., 2022). However, scalability is hindered by biomass availability, energy conversion efficiency, and the necessity for substantial investments in CCS infrastructure (Power et al., 2016).

In comparison to other carbon removal methods, biochar presents an immediate, cost-effective, and permanent solution (Realmonte et al., 2019). In China, advancements in gasifier

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equipment have led to the development of continuous carbonizers, facilitating high-volume production suitable for addressing crop burning pollution (Zeman & Keith, 2008).

Cost-effectiveness is evident in soil sequestration of pyrolyzed carbon, which offers a relatively inexpensive option compared to alternative techniques. Additionally, the independent value of biochar makes its adoption financially feasible, aligning with current market prices on CO_2 exchanges (Lehmann, 2007).

Evidence, such as the discovery of black Terra Preta soils in the Amazon, suggests the enduring nature of carbon char within soils. This condensed ring form of carbon withstands natural soil processes and exhibits compatibility with typical soil organic matter, demonstrating its long-term effectiveness as a carbon removal solution (Minx et al., 2018).

The concern for nature biocycle – the biggest carbon stream

The largest carbon stream, accounting for approximately 120 GtC/year or 440 $GtCO_2$/year, is attributed to the photosynthesis process occurring in plants (Cho, 2018). However, only about 2%-3% of this carbon remains stored in the ground for decades, with the rest being released back into the atmosphere. Utilizing this natural biological cycle presents an opportunity to absorb more atmospheric carbon and store it effectively (Cho, 2018). This could involve a combination of strategies such as enhancing carbon sequestration on land and generating negative emissions.

Additionally, maximizing the potential benefits of increased food, biofeed, and fiber crop production, which hold commercial value, is crucial (Mulligan et al., 2020). Research utilizing genetic engineering and other techniques to improve photosynthetic efficiency in crops for various purposes, including food, bioenergy, and reforestation, is underway (Mulligan et al., 2020). It's essential to ensure that these advancements require no additional input resources like freshwater, fertilizer, and pesticides. Furthermore, approaches focusing on organic soil breakdown and minimizing N_2O emissions are necessary to enhance carbon sequestration (Cho, 2018). Developing deeper lignin roots in the rhizosphere, coupled with no-till agriculture, can further stabilize soil carbon. However, it's imperative to thoroughly analyze and document the direct and indirect effects of implementing no-till agriculture on land usage and production to ensure sustainability (Lehmann, 2007).

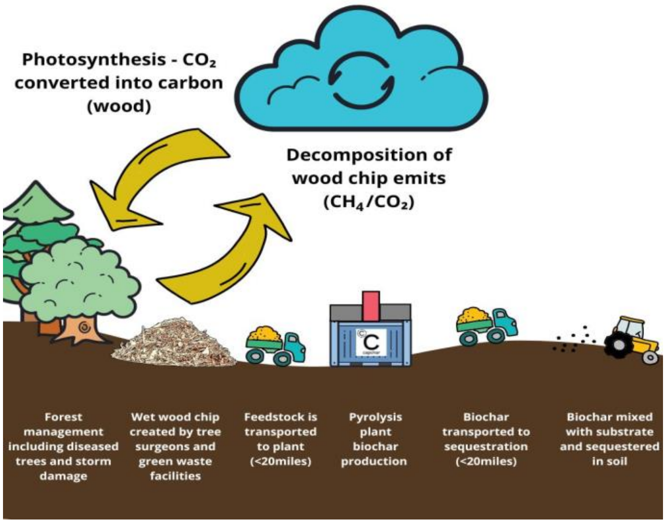

Figure 2. Demonstration of carbon removal using biochar method.

Geological carbon removal methods

Geological approaches involve storing carbon underground or through mineralization. Carbon Capture and Storage (CCS) technology captures CO_2 emissions and stores them underground, facing challenges like infrastructure development and leakage risks. Enhanced

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Weathering accelerates mineral weathering to capture CO_2 but encounters scalability issues due to energy-intensive processes and slow sequestration rates (McGrath, 2018).

Weathering represents a fundamental geological phenomenon wherein carbon dioxide present in the atmosphere interacts with rainwater, leading to the partial dissolution of rocks and soils (as illustrated by Eq. 1 and Eq. 2) (James & Menzies, 2022). This interaction results in the conversion of CO_2 into hydrogen carbonate ions, known as alkalinity, which ultimately find their way into the ocean, where they undergo secure storage for periods exceeding 100,000 years. Certain conditions may facilitate these hydrogen carbonate ions as carbonate minerals, a process referred to as carbon mineralization (as depicted in Eq. 3). These carbonate minerals exhibit stability over more than 10,000 years (James & Menzies, 2022).

$$CaSiO3 + 2CO2 + 3H2O \rightarrow Ca2+ + 2HCO3- + H4SiO4 \quad (1)$$

$$CaCO3 + H2O + CO2 \rightarrow Ca2+ + 2HCO3- \quad (2)$$

$$Ca2+ + 2HCO3- \rightarrow CaCO3 + CO3 + H2O \quad (3)$$

It's important to note that during the precipitation of carbonates, only half of the CO_2 captured by silicate minerals and all of the CO_2 captured by carbonate minerals are subsequently released back into the atmosphere (as described in Eq. 3) (James & Menzies, 2022). Consequently, while carbon mineralization of silicates is only half as effective as mineral dissolution (weathering) for CO_2 removal, the dissolution and re-precipitation of carbonate minerals have no net impact on atmospheric CO_2 levels (Taylor et al., 2016).

On a global scale, natural weathering removes approximately 1 Gt of CO_2 annually, playing a significant role in the Earth's long-term climate regulation. However, these processes operate over extended timeframes. To achieve substantial reductions in atmospheric CO_2 levels by the end of the century, geologists are exploring methods to accelerate weathering and carbon mineralization processes (Taylor et al., 2016).

Enhanced rock weathering is a CO_2 removal method that involves incorporating crushed calcium- and magnesium-rich silicate rocks into agricultural soils to accelerate weathering rates, aided by the photosynthetic activity of crops. Environmental factors such as water availability, temperature, and soil properties like mineralogy, grain size, porosity, and permeability influence weathering rates (Taylor et al., 2016).

In Fig.3 modeling studies by Taylor et al., (2016) suggest that applying 1–5 kg m^2 per year of pulverized silicate rock (basalt and harzburgite) to all agricultural land within 30° of the equator (~20 x 106 km^2) could potentially reduce atmospheric CO_2 levels by 30 to 300 ppm by the century's end, depending on the rock type and application rate. Additionally, these simulations indicate that enhanced rock weathering could counteract ocean acidification effects by delivering sufficient alkalinity to the oceans (Taylor et al., 2016).

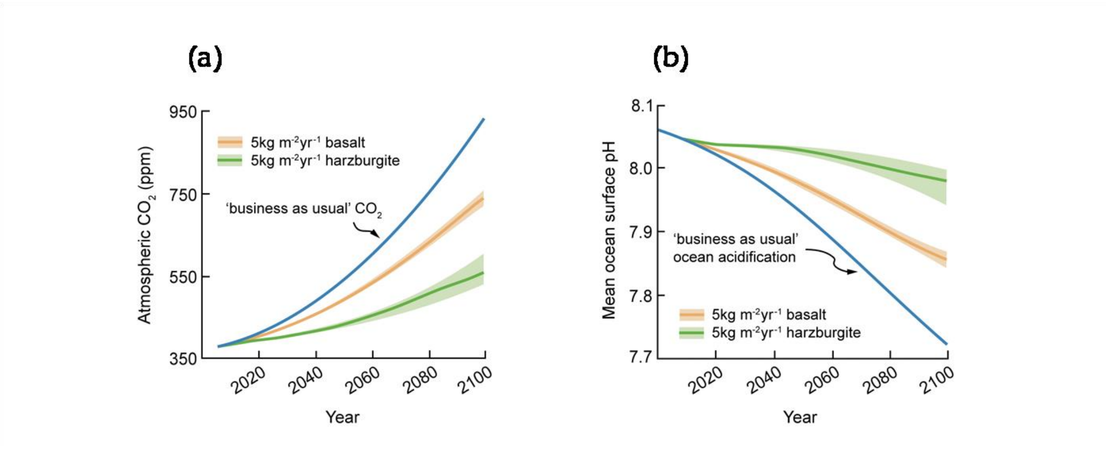

Figure 3. Modeled simulations illustrate the impact of applying pulverized basalt or harzburgite to agricultural land on (a) atmospheric CO2 levels and (b) ocean surface pH. The projected atmospheric CO2 concentrations follow the "business as usual" trajectory (RCP8.5), with the blue line representing the RCP8.5 projection without enhanced rock weathering (Taylor et al., 2016).

doi: 10.34312/jage.v3i1.25695

A crucial aspect of achieving negative emissions involves geological storage of CO_2, offering the potential to store vast quantities of carbon dioxide at the gigaton (GT) scale (Bui et al., 2018). Over the past decade, numerous projects have been initiated to study Research, Development, and Deployment (RD&D) of carbon storage in saltwater aquifers. Despite lacking commercial value inherently, traditional enhanced oil recovery (EOR) techniques utilize CO_2 with commercial value. However, existing EOR incentives prioritize limiting CO_2 usage and maximizing hydrocarbon recovery due to the purchase costs associated with CO_2 (Majumdar & Deutch, 2018).

Can a non-traditional approach to EOR be established to estimate CO_2 storage, possibly reaching GT scale, while maintaining a commercial value for the produced hydrocarbons? This could be achieved by altering incentives, perhaps through a carbon charge (Majumdar & Deutch, 2018). Such unconventional EOR methods could potentially result in a net decrease in CO_2 emissions. Additionally, focusing on fundamental research is essential, particularly on pore-scale CO_2 migration, co-optimization of hydrocarbon and saline reservoirs for CO_2 storage, and understanding the geo-mechanical and geochemical impacts of CO_2 transportation and mineralization (Cho, 2018).

Research efforts must also target reducing the energy-intensive costs associated with CO_2 extraction from gas mixtures. Identifying new, inexpensive CO_2 sorbents with favorable binding properties and developing low-cost, low-viscosity liquid solutions are critical (McGrath, 2018). Furthermore, innovative materials and techniques are necessary for separating miscible liquid combinations and designing reactors that efficiently collect CO_2 at the GT scale (Cho, 2018). In summary, advancements in CO_2 sorbents, along with improved techniques for CO_2 extraction and storage, are crucial for addressing the challenges of carbon removal and achieving negative emissions targets.

The weathering of silicate minerals yields calcium, magnesium, and hydrogen carbonate ions, which can subsequently undergo precipitation as carbonate minerals. This natural process occurs during the weathering of ultramafic to mafic rocks, such as mantle peridotites and basalts. Peridotites undergo hydration (serpentinization) and carbonation reactions at relatively rapid rates and low temperatures geologically. While mafic and ultramafic rocks possess the potential to sequester tens of gigatonnes of CO2 globally, the extent of carbonation is also influenced by factors such as CO2 availability, chemical conditions (pH, salinity, temperature, pressure), and the permeability of the storage formation (Bullock et al., 2021).

Engineered carbon mineralization is integral to efficient CO_2 removal and can be achieved through three main methods: (1) ex-situ mineralization, involving the reaction of calcium- and/or magnesium-rich silicate minerals with CO_2-rich fluid or gas in a reactor; (2) in-situ mineralization, where CO_2 gas or CO_2-bearing fluids are injected into appropriate subsurface reservoirs for geologic storage; and (3) surficial mineralization utilizing CO_2 from the air, employing mafic to ultramafic mine tailings or alkaline industrial waste material (Bullock et al., 2021).

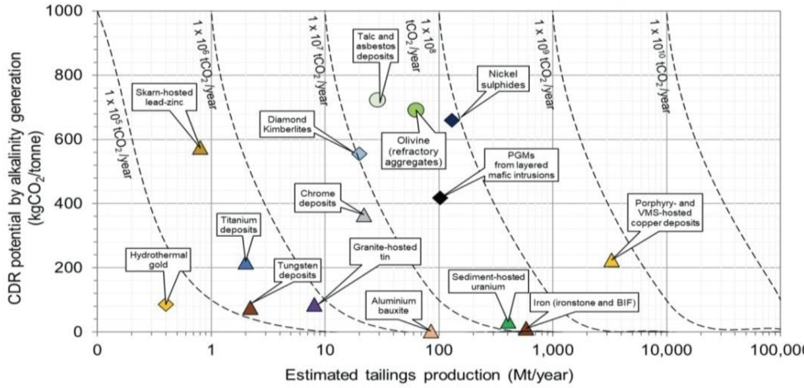

Figure 4. Comparison of the yearly output of mine tailings to the calculated potential for CO_2 removal through weathering and alkalinity generation per ton of rock across various ore deposit types. The contours depict the total amount of CO_2 removal in tons per year (Bullock et al., 2021).

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ANALYSIS AND DISCUSSION

Analysis

In the global effort to combat climate change, carbon management has emerged as a critical area of focus, prompting companies worldwide to develop innovative solutions for removing carbon dioxide (CO_2) from the atmosphere. Among these companies, BeZero Carbon from the UK, Clean O_2 from Canada, the World Resources Institute (WRI) from the US, Heirloom Carbon Technologies from the US, and Carbfix from Iceland have garnered significant attention for their contributions to the field. This paper aims to explore the regulatory frameworks surrounding carbon management, particularly for companies that sell materials designed to remove CO_2. By examining the approaches and technologies employed by these companies, as well as the regulatory landscape in which they operate, we can gain valuable insights into the challenges and opportunities facing the carbon removal industry. Through this analysis, we seek to identify key regulatory considerations and potential avenues for future policy development to support the growth and scalability of carbon removal efforts on a global scale.

BeZero Carbon (UK)

BeZero Carbon, a rapidly growing UK-based ratings agency in the voluntary carbon market, is dedicated to creating the information architecture essential for scaling climate action. With a mission to lead in providing carbon credit ratings, research, and analytics, BeZero Carbon aims to equip Voluntary Carbon Market participants with the insights needed to accurately price and manage risk (Warnecke et al., 2019).

BeZero Carbon's strategic approach, embedded within the United Kingdom's comprehensive climate policy framework, exemplifies a pioneering model for enhancing the efficacy, transparency, and accountability within the carbon offset market (Cullenward & Victor, 2020). Their carbon credit rating system emerges as a crucial tool, potentially aiding both corporate entities and regulatory bodies by offering a transparent and reliable metric for carbon offsets. This system is essential for ensuring that carbon credits used to meet regulatory or corporate sustainability goals genuinely contribute to carbon mitigation efforts (Roe et al., 2019). BeZero Carbon addresses the prevalent challenge in the carbon market, the variability in project efficacy and verification rigor (Gillenwater, 2012). By implementing a comprehensive rating system, BeZero Carbon aims to elevate industry standards, encouraging project developers to adopt methodologies and technologies that ensure genuine, additional, and lasting carbon sequestration or abatement (Kollmuss et al., 2015). The scalability of BeZero Carbon's framework is key to its potential global impact. Proving its effectiveness within the UK's regulatory and market framework could pave the way for international replication or adaptation, aiming to standardize criteria for carbon offset projects worldwide. Such an expansion could create a robust, transparent international carbon market. The cost required for their carbon credit rating tool is $ 50 million (Michaelowa et al., 2021).

In conclusion, BeZero Carbon's strategies for selling products to reduce CO_2 impact have made significant strides in improving transparency, driving market shifts towards high-quality projects, and fostering technological advancements. While challenges remain, the opportunities for global scalability and innovation are substantial. Through international collaboration and continued focus on quality and transparency, BeZero Carbon can play a pivotal role in the global effort to mitigate climate change.

Clean O_2 (Canada)

Clean O_2's operational model, centered around carbon capture technology and the conversion of CO_2 into commercially viable products, presents a novel approach within the broader context of carbon management strategies (Bocken & Short, 2016). Calgary-based Clean O_2 has engineered a compact carbon capture device, comparable in size to a home air conditioner, which attaches to a natural gas boiler to capture CO_2 from flue gas. Known as CARBiNX, this innovative device converts CO_2 into potash, which can then be used to produce detergents, soaps, and fertilizers. Impressively, Clean O_2 states that every four-liter container of its biodegradable liquid hand soap recycles 1.2 kg of CO_2 (Majumdar & Deutch, 2018).

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Clean O_2 Company has achieved groundbreaking cost efficiency in carbon emission management, removing 1,000 metric tons of carbon dioxide at less than $50 per ton. This represents the most cost-effective carbon removal strategy implemented by any company to date (Majumdar & Deutch, 2018). CleanO_2's technology aligns with Canada's strategic objectives as outlined in the Pan-Canadian Framework on Clean Growth and Climate Change, which advocates for the reduction of greenhouse gas emissions through innovation and clean technologies (Bocken & Short, 2016).

The companies also focuses on capturing carbon from heating systems and its subsequent conversion into valuable products like soap dovetails with the country's carbon pricing strategy and the incentives provided for carbon capture, utilization, and storage (CCUS) technologies at the cost of $40 per ton (Leung et al., 2014).

Clean O_2's approach exemplifies a circular economy model, wherein carbon emissions, typically considered waste, are transformed into valuable commodities. This not only mitigates carbon emissions but also reduces waste and generates economic value from what would otherwise be an environmental liability. The company's innovative use of captured CO_2 in consumer products could serve as a blueprint for other industries aiming to achieve sustainability through waste reduction and resource optimization (Mac Dowell et al., 2017). The scalability of Clean O_2's technology is critical for its potential global impact. As the technology matures and demonstrates success in Canada's regulatory and market environment, there is the possibility for international expansion (Minx et al., 2018). This could be particularly relevant in regions with similar regulatory incentives for carbon management technologies, facilitating a global shift towards innovative carbon utilization practice.

Clean O_2's integration of carbon capture technology with the production of economically valuable products represents a forward-thinking approach to carbon management (Majumdar & Deutch, 2018). Set within Canada's supportive regulatory framework, the company exemplifies how innovation can align environmental sustainability with economic viability. The trajectory of Clean O_2's impact hinges on technological scalability, market acceptance, and collaborative engagement across sectors, promising a significant contribution to global efforts in carbon reduction and sustainability (Mac Dowell et al., 2017).

World Resource Institute (US)

The World Resources Institute (WRI) is a global research organization dedicated to collaborating with governments, businesses, multilateral institutions, and civil society to develop practical solutions that improve lives while safeguarding the environment (McGrath, 2018). We focus our efforts on seven critical global issues: Food, Forests, Water, Energy, Climate, the Ocean, and Cities. Our four Centers of Excellence provide insights on these challenges from the perspectives of business, economics, finance, and governance (Bui et al., 2018).

The World Resources Institute (WRI) estimates that forests and trees outside of forests in the United States have the potential to remove over 1,000 gigatons of CO_2 annually, matching the country's total yearly agricultural emissions. Compared to other carbon removal methods, utilizing trees for CO_2 sequestration is highly cost-effective, often costing less than $50 per metric ton, while also providing the added benefits of cleaner water and air. (The cost required to World Resource Institute for removing 1000 tons of carbon dioxide is approximately $50 per ton (Bui et al., 2018).

WRI's focus extends beyond carbon management to encompass broader sustainability challenges, including water security, forest restoration, and urban planning (Friedman et al., 2022). This holistic approach recognizes the interconnectedness of these issues with global climate resilience and carbon cycles. By advocating for integrated policy solutions that address multiple environmental challenges simultaneously, WRI contributes to the development of a more sustainable and resilient global ecosystem (Hale & Roger, 2017).

Heirloom Carbon Technologies (US)

Heirloom Carbon Technologies represents a pioneering effort in the field of Direct Air Capture (DAC) technology, focusing on refining the efficiency and affordability of atmospheric CO_2 extraction (Minx et al., 2018). Their innovative use of limestone as a CO_2 capture medium

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underlines the potential for scalable, cost-effective carbon removal solutions. This segment examines Heirloom's integration with U.S. regulatory incentives and explores potential pathways for future development and impact within the carbon capture sector (Realmonte et al., 2019).

By 2035, they aim to capture 1 billion tons of CO_2 using natural processes to develop the world's most cost-effective Direct Air Capture system (Lehmann, 2007). This innovative approach leverages abundant, low-cost minerals that naturally bond with CO_2 at ambient temperatures. Instead of relying on energy-intensive air contactors, they passively expose these minerals to the air. The captured CO_2 is then collected and treated before being injected underground into geological formations with the help of their partners, ensuring permanent and secure sequestration (James & Menzies, 2022).

Their method is designed to minimize resource extraction and avoid secondary environmental impacts. This includes creating a recycling loop for the minerals, which reduces the need for mining and overall resource consumption. Additionally, they are committed to using 100% renewable energy, thereby eliminating reliance on fossil fuels (Bui et al., 2018).

Founded with the mission to combat climate change, Heirloom Carbon Technologies aims to harness minerals for capturing carbon dioxide directly from the atmosphere. As one of the pioneering commercial ventures employing enhanced weathering techniques, the company projects that, upon scaling, it could remove 1000 tons of CO_2 for just $50 significantly lower than previous industrial estimates. By 2035, Heirloom aspires to eliminate one billion metric tons of CO_2, the predominant greenhouse gas, from the environment (Minx et al., 2018).

Carbfix (Iceland)

Carbfix, based in Iceland, exemplifies innovative strides within the carbon capture and storage (CCS) sector through its unique method of converting CO_2 into mineral forms within basalt rock formations. This pioneering approach not only offers a potentially permanent solution to carbon storage but also aligns with global efforts to mitigate climate change impacts. This section delves into Carbfix's methodology, its symbiosis with Iceland's regulatory and natural landscape, and the broader implications for CCS technologies (Scott et al., 2015).

Matter et al., (2016) suggests that Carbfix excels in carbon capture at a lower cost compared to purchasing carbon credits. Their method averages approximately $25 per ton, contrasting with the approximately 40 euros ($48) per ton for removing 1000 tons of CO_2 through the EU's Emissions Trading System, the primary policy tool for emission reduction within the block (Matter et al., 2016).

The Carbfix project not only contributes to the advancement of CCS technology but also aligns with global climate objectives, such as those outlined in the Paris Agreement. By offering a potentially scalable and permanent solution for CO_2 storage, Carbfix's approach can play a crucial role in global strategies to reduce atmospheric CO_2 levels and mitigate climate change. Its success in Iceland suggests the potential for replication in other regions with similar geological and regulatory conditions, thereby expanding the impact of this technology on a global scale (Daly et al., 2015).

Table 2. Companies insights for the product they sell to remove CO_2 emissions at GT scale per ton by different process.

Companies	**Products**	**Removal Cost for CO_2 (per/ton)**	**Process**
BeZero Carbon	Carbon credits	$ 100	BECCS, DAC
Clean O2	Detergents, Soaps, Fertilizers & Nano-onions	$45	DAC
WRI	Agro-organic	$55	Ocean Mineralization
Heirloom CT	Limestone & other minerals	$50	Weathering, DAC
Carbfix	Smokestackes & Nano tubes	$45	DAC

****Scale - Limited by material (mostly GT)*
***BECCS**- (Bioenergy carbon capture & storage)*
***DAC**- Direct Air Capture*

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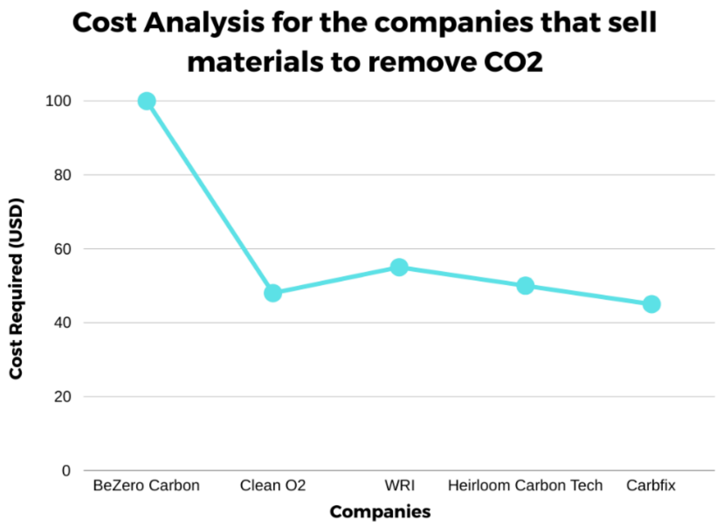

Figure 5. Graph showing cost analysis for the companies that sell materials to remove CO_2.

Discussion

Among companies focusing on carbon dioxide removal through various materials, the Canadian-based company specializing in converting CO_2 into nanotubes, soaps, and fertilizers appears to offer the most cost-effective solution. Large-scale purchases of these materials are estimated to cost between $50-70 per ton (Cho, 2018). Climate change, primarily driven by excessive CO_2 emissions, necessitates urgent action. Planting trees and employing direct air capture are effective methods to combat pollution globally, at any time and in any location (Majumdar & Deutch, 2018). The cost of capturing one million tons of CO_2 from the atmosphere ranges from $100 to $1,000 annually, with a minimum cost of $50 per ton (Butler, 2018). Advancements in agricultural and forestry practices, such as plant engineering and improved land management aimed to increase soil carbon sequestration, but also have led to a significant increase in carbon content, resulting in a net increase in carbon emissions at an alarming rate that threatens to undermine climate change mitigation efforts, emphasizing the importance to resolve these problems is necessary. . Research into new sorbents and reactor systems can reduce the cost of capturing CO_2 from dilute sources (Power et al., 2016).

Investing in techniques to convert CO_2 into cost-competitive carbon-based compounds and fuels is essential, given the availability of low-cost renewable energy. Additionally, studying non-traditional refined oil recovery methods that store carbon in geological formations is crucial (Cho, 2018). A systemic approach is necessary to analyze the impact of different measures and explore potential scenarios for addressing this global-scale problem. Mitigation strategies, including reducing emissions and enhancing CO_2 absorption rates, are crucial in combating the adverse effects of anthropogenic greenhouse gas emissions (Friedman et al., 2022). The atmospheric emission rate currently stands at 3200 $GtCO_2$ annually, emphasizing the need for measures on a gigaton scale is crucial. Discussions often use the term "1,000,000,000 gigatonnes" to represent emissions, roughly equivalent to the mass of all land animals worldwide, excluding humans, as depicted in the comic strip (Realmonte et al., 2019).

FUTURE OUTCOMES

A recent study by Southampton University, United Kingdom predicts unprecedented levels of atmospheric carbon dioxide within the next 100-200 years, reaching concentrations not seen since the Triassic epoch (200 million years ago), with CO_2 levels projected to reach 550 ppm by 2050 (Mulligan et al., 2020). The Secretary of Energy's Task Force (TF) emphasizes the urgency of accelerating evaluation and deployment of gigaton-scale (GT) solutions to address climate change. This calls for enhanced technological readiness and policy measures to facilitate deployment, particularly in the power sector, where emissions reductions are more feasible.

Negative emissions technologies are highlighted as crucial counteractive measures, capable of lowering atmospheric CO_2 concentrations even below hazardous thresholds despite zero net emissions (Cho, 2018).

CONCLUSION

In conclusion, the exploration of various companies' efforts in carbon management, including BeZero Carbon, $CleanO_2$, WRI, Heirloom Carbon Technologies, and Carbfix, underscores the critical role of innovation and collaboration in combating climate change. These companies have developed pioneering technologies and strategies aimed at removing carbon dioxide from the atmosphere, contributing to global efforts to mitigate greenhouse gas emissions.

BeZero Carbon's commitment to transparency and accountability within the carbon offset market, $CleanO_2$'s innovative carbon capture and utilization approach, WRI's holistic approach to sustainability, Heirloom Carbon Technologies' advancements in Direct Air Capture technology, and Carbfix's unique carbon storage method in basalt formations all represent significant strides in the field of carbon management. The regulatory frameworks surrounding carbon management play a crucial role in shaping the development and deployment of these technologies. Policy measures that support research, innovation, and scalability are essential for driving progress in carbon removal efforts on a global scale.

As climate change continues to pose fomidable challenges, it is imperative to accelerate the evaluation and implementation of gigaton-scale solutions. Negative emissions technologies, such as carbon capture and utilization, offer promising avenues for lowering atmospheric CO_2 concentrations and mitigating climate change impacts. Overall, the diverse approaches and technologies discussed in this paper highlight the multifaceted nature of carbon management and the need for comprehensive strategies that integrate technological innovation, policy support, and international collaboration. By addressing these challenges collectively, we can work towards a more sustainable and resilient future for generations to come.

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REFERENCES

Alcalde, J., Flude, S., Wilkinson, M., Johnson, G., Edlmann, K., Bond, C. E., . . . Haszeldine, R. S. (2018). Estimating geological CO2 storage security to deliver on climate mitigation. *Nature communications, 9*(1), 2201.

Andonova, L. B., Hale, T. N., & Roger, C. B. (2017). National policy and transnational governance of climate change: Substitutes or complements? *International Studies Quarterly, 61*(2), 253-268.

Beck, S., & Mahony, M. (2018). The IPCC and the new map of science and politics. *Wiley Interdisciplinary Reviews: Climate Change, 9*(6), e547.

Bocken, N. M., & Short, S. W. (2016). Towards a sufficiency-driven business model: Experiences and opportunities. *Environmental innovation societal transitions, 18*, 41-61.

Boyd, J., Joiner, E., Krupnick, A., & Toman, M. (2024). Policy Incentives to Scale Carbon Dioxide Removal: Analysis and Recommendations.

Bui, M., Adjiman, C. S., Bardow, A., Anthony, E. J., Boston, A., Brown, S., . . . Hackett, L. A. (2018). Carbon capture and storage (CCS): the way forward. *Energy Environmental Science, 11*(5), 1062-1176.

Bullock, L. A., James, R. H., Matter, J., Renforth, P., & Teagle, D. A. (2021). Global carbon dioxide removal potential of waste materials from metal and diamond mining. *Frontiers in Climate, 3*, 694175.

Butler, C. D. (2018). Climate change, health and existential risks to civilization: A comprehensive review (1989–2013). *International journal of environmental research public health, 15*(10), 2266.

Cho, R. (2018). Can Removing Carbon From the Atmosphere Save Us From Climate Catastrophe? *State of the Planet*.

doi: 10.34312/jage.v3i1.25695 ejurnal.ung.ac.id/index.php/jage

Cullenward, D., & Victor, D. G. (2020). *Making climate policy work*: John Wiley & Sons.

Daly, H. E., Scott, K., Strachan, N., & Barrett, J. (2015). Indirect CO2 emission implications of energy system pathways: linking IO and TIMES models for the UK. *Environmental Science Technology, 49*(17), 10701-10709.

Fankhauser, S., Smith, S. M., Allen, M., Axelsson, K., Hale, T., Hepburn, C., . . . Mitchell-Larson, E. (2022). The meaning of net zero and how to get it right. *Nature climate change, 12*(1), 15-21.

Friedman, H., Huang, K., & Wu, K. (2022). ESG Attention in Capital Markets: Evidence from China's Carbon Neutrality Pledge Announcement.

Fuss, S., Lamb, W. F., Callaghan, M. W., Hilaire, J., Creutzig, F., Amann, T., . . . Khanna, T. (2018). Negative emissions—Part 2: Costs, potentials and side effects. *Environmental research letters, 13*(6), 063002.

Gillenwater, M. (2012). What is wrong with 'real'carbon offsets? *Greenhouse Gas Measurement Management, 2*(4), 167-170.

Goeppert, A., Czaun, M., Prakash, G. S., & Olah, G. A. (2012). Air as the renewable carbon source of the future: an overview of CO 2 capture from the atmosphere. *Energy Environmental Science, 5*(7), 7833-7853.

James, N., & Menzies, M. (2022). Global and regional changes in carbon dioxide emissions: 1970–2019. *Physica A: Statistical Mechanics its Applications, 608*, 128302.

Keith, D. W., Holmes, G., Angelo, D. S., & Heidel, K. (2018). A process for capturing CO2 from the atmosphere. *Joule, 2*(8), 1573-1594.

Keohane, N. O., Revesz, R. L., & Stavins, R. N. (2019). The choice of regulatory instruments in environmental policy. *Environmental law*, 491-545.

Kollmuss, A., Schneider, L., & Zhezherin, V. (2015). *Has joint implementation reduced GHG emissions?: lessons learned for the design of carbon market mechanisms*: JSTOR.

Lehmann, J. (2007). A handful of carbon. *Nature, 447*(7141), 143-144.

Leung, D. Y., Caramanna, G., & Maroto-Valer, M. M. (2014). An overview of current status of carbon dioxide capture and storage technologies. *Renewable sustainable energy reviews, 39*, 426-443.

Mac Dowell, N., Fennell, P. S., Shah, N., & Maitland, G. C. (2017). The role of CO2 capture and utilization in mitigating climate change. *Nature climate change, 7*(4), 243-249.

Majumdar, A., & Deutch, J. (2018). Research Opportunities for CO2 Utilization and Negative Emissions at the Gigatonne Scale. *Joule, 2*(5), 805-809. doi:https://doi.org/10.1016/j.joule.2018.04.018

Matter, J. M., Stute, M., Snæbjörnsdottir, S. Ó., Oelkers, E. H., Gislason, S. R., Aradottir, E. S., . . . Gunnlaugsson, E. (2016). Rapid carbon mineralization for permanent disposal of anthropogenic carbon dioxide emissions. *Science, 352*(6291), 1312-1314.

McGrath, M. (2018). Climate change: Five cheap ways to remove CO2 from the atmosphere. *BBC*.

Michaelowa, A., Michaelowa, K., Shishlov, I., & Brescia, D. (2021). Catalysing private and public action for climate change mitigation: the World Bank's role in international carbon markets. *Climate Policy, 21*(1), 120-132.

Minx, J. C., Lamb, W. F., Callaghan, M. W., Fuss, S., Hilaire, J., Creutzig, F., . . . Hartmann, J. (2018). Negative emissions—Part 1: Research landscape and synthesis. *Environmental Research Letters, 13*(6), 063001.

Morgan, J., & Waskow, D. (2014). A new look at climate equity in the UNFCCC. *Climate Policy, 14*(1), 17-22.

Mulligan, J., Ellison, G., Levin, K., Lebling, K., & Rudee, A. (2020). 6 Ways to Remove Carbon Pollution from the Sky. *World Resources Institute*.

Nocito, F., & Dibenedetto, A. (2020). Atmospheric CO2 mitigation technologies: carbon capture utilization and storage. *Current Opinion in Green Sustainable Chemistry, 21*, 34-43.

Palermo, V., & Hernandez, Y. (2020). Group discussions on how to implement a participatory process in climate adaptation planning: a case study in Malaysia. *Ecological Economics, 177*, 106791.

doi: 10.34312/jage.v3i1. 25695 ejurnal.ung.ac.id/index.php/jage

Pathak, M., Slade, R., Pichs-Madruga, R., Ürge-Vorsatz, D., Shukla, R., & Skea, J. (2022). Climate Change 2022 Mitigation of Climate Change: Technical Summary.

Pearse, R., & Böhm, S. (2014). Ten reasons why carbon markets will not bring about radical emissions reduction. *Carbon Management, 5*(4), 325-337.

Power, I. M., Harrison, A. L., & Dipple, G. M. (2016). Accelerating mineral carbonation using carbonic anhydrase. *Environmental Science Technology, 50*(5), 2610-2618.

Realmonte, G., Drouet, L., Gambhir, A., Glynn, J., Hawkes, A., Köberle, A. C., & Tavoni, M. (2019). An inter-model assessment of the role of direct air capture in deep mitigation pathways. *Nature communications, 10*(1), 3277.

Roe, S., Streck, C., Obersteiner, M., Frank, S., Griscom, B., Drouet, L., . . . Hasegawa, T. (2019). Contribution of the land sector to a 1.5 C world. *Nature climate change, 9*(11), 817-828.

Street-Perrott, A., Woolf, D., Amonette, J. E., Street-Perrott, F. A., Lehmann, J., & Joseph, S. (2011). Sustainable biochar to mitigate global climate change.

Taylor, L. L., Quirk, J., Thorley, R., Kharecha, P. A., Hansen, J., Ridgwell, A., . . . Beerling, D. J. (2016). Enhanced weathering strategies for stabilizing climate and averting ocean acidification. *Nature Climate Change, 6*(4), 402-406.

Warnecke, C., Schneider, L., Day, T., La Hoz Theuer, S., & Fearnehough, H. (2019). Robust eligibility criteria essential for new global scheme to offset aviation emissions. *Nature climate change, 9*(3), 218-221.

Zeman, F. S., & Keith, D. W. (2008). Carbon neutral hydrocarbons. *Philosophical Transactions of the Royal Society A: Mathematical, Physical Engineering Sciences, 366*(1882), 3901-3918.