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A Comprehensive Review of Carbon Capture, Utilization, and Storage (CCUS): Technological Advances, Environmental Impact, and Economic Feasibility

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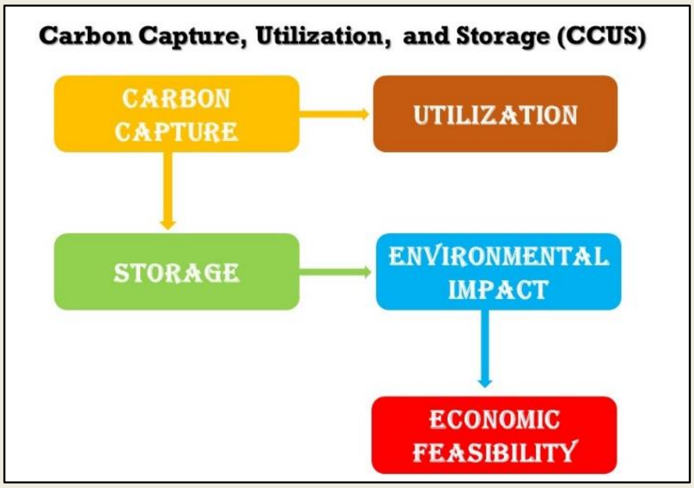
Abstract **Review Article**

Carbon capture, utilisation, and storage (CCUS) technologies are critical to reducing CO_2 exhalations on a global scale. This review study synthesizes the many elements of CCUS over 50 years, from R&D to deployment scales, in terms of their mitigation potential for global emission reductions. Next, it discusses existing and new carbon capture techniques from an automation standpoint (e.g., pre-combustion capture, post-combustion capture combustion), as well as the economic feasibility of CCUS regionally in terms of capital retail price, operating expenses, and value in the form of potential revenue streams based on CO_2, aided by significant range-scaling building blocks such as rising nation. Each technique is thoroughly evaluated in terms of its environmental impact and associated risks, and case studies are used to illustrate practical lessons learnt. The paper also discusses the arguments around what future advances may exist in CCUS technology, and opportunities to scale these up (including research needs for this support), drawing lessons past policy. The findings underscore the importance of integrating CCUS into broader climate strategies to achieve net-zero exhalations while addressing the economic and environmental challenges that remain.

Graphical Abstract:



Keywords: CCUS, carbon capture, CO_2 storage, economic feasibility, environmental impact.

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INTRODUCTION

Carbon Capture, Utilization, and Storage (CCUS) represents a suite of technologies and operations designed to capture carbon dioxide (CO_2) exhalations from various sources, particularly large industrial facilities and power plants, and either utilize the captured CO_2 for productive purposes or store it permanently to prevent its release into the atmosphere (Jiang & Ashworth, 2021; McLaughlin *et al.*, 2023). The central aim of CCUS is to mitigate the adverse impacts of anthropogenic CO_2 exhalations on global climate systems. By capturing CO_2 before it can contribute to the greenhouse effect, CCUS technologies play an important role in the transition to a low-carbon economy. These technologies are not only critical in sectors that are difficult to decarbonize, such as cement, steel, and chemical manufacture, but they also contribute to lowering the carbon intensity of fossil fuel-based energy production. The IPCC has continually highlighted the vital necessity of CCUS in meeting global climate targets (de Kleijne *et al.*, 2022). CCUS is defined as the approach of capturing CO_2 exhalations produced from industrial approaches or fossil fuel combustion, transporting it to a storage area, and depositing it where it will not enter the atmosphere, typically in underground geological formations. The potential of CCUS to mitigate climate change is immense; according to the Global Energy Agency (IEA), the widespread adoption of CCUS could contribute to the reduction of global CO_2 exhalations by approximately 15-20% by 2050, equating to around 5 to 10 gigatons of CO_2 per annum. This is particularly significant considering that global CO_2 exhalations from energy and industrial approaches were approximately 36.7 gigatons in 2022 (Ramadhan *et al.*, 2024).

The importance of CCUS in climate mitigation cannot be overstated. While renewable energy technologies such as wind, solar, and hydropower are essential for reducing exhalations in the energy sector, they are not sufficient alone to address the exhalations from industrial approaches. For example, the production of cement and steel together accounts for nearly 15% of global CO_2 exhalations, and these approaches inherently produce CO_2 as a byproduct (Ostovari *et al.*, 2021). CCUS offers a viable solution for capturing these exhalations at the source, thereby enabling continued industrial activity without contributing to global warming. Moreover, CCUS is one of the few technologies capable of delivering "negative exhalations" when combined with bioenergy (BECCS), where CO_2 is removed from the atmosphere and sequestered, potentially reversing some of the damage caused by previous exhalations (Ostovari *et al.*, 2021). The idea of capturing CO_2 and storing it underground has been around for decades, but it gained traction in the late twentieth century as scientific consensus on climate change grew. Early research on CCUS began in the 1970s, largely focusing on Enhanced Oil Recovery (EOR) as a method of exploiting captured CO_2 to boost oil production (Magzymov *et al.*, 2022). The first large-scale application of CO_2 EOR was initiated in the Permian Basin in Texas, USA, in 1972. This program successfully demonstrated that CO_2 could be injected into oil fields to enhance oil recovery while simultaneously storing the CO_2 underground. By the 1990s, the urgency of addressing climate change led to increased interest in the potential of CCUS to mitigate CO_2 exhalations on a larger scale.

The technological evolution of CCUS has been marked by significant advancements in both capture and storage techniques. In the early stages, carbon capture was primarily explored through post-combustion techniques, where CO_2 is separated from flue gases after combustion. This technique, while effective, was energy-intensive and costly, with a capture retail price ranging from \$100 to \$150 per ton of CO_2 (Gür, 2022). However, advances in solvent automation, particularly the progress of amine-based solvents, have significantly reduced these retail prices. For instance, second-generation amine solvents can reduce energy requirements by 20-30%, bringing capture retail price down to \$50-\$100 per ton of CO_2. In parallel, pre-combustion capture and oxy-fuel combustion technologies have been developed and refined. Pre-combustion capture involves gasifying fossil fuels to produce a mixture of hydrogen and CO_2, with the latter being captured before combustion. This technique has the edge of producing a pure stream of CO_2, which simplifies the capture approach (Kheirinik *et al.*, 2021). Oxy-fuel combustion, on the other hand, involves burning fossil fuels in an environment rich in oxygen rather than air, resulting in flue gases that are primarily composed of CO_2 and water vapors. This technique can achieve nearly 100% CO_2 capture efficiency, making it highly attractive for power generation applications.

Transporting captured CO_2 to storage areas has also seen significant advancements. Early transportation techniques relied on existing natural gas pipelines, but these were often unsuitable due to the corrosive nature of CO_2 when combined with water. The progress of dedicated CO_2 pipelines, designed with materials resistant to corrosion and capable of handling high-pressure CO_2, has enabled the secure and efficient transport of captured CO_2 over long distances. As of 2023, there are over 8,000 kilometres of CO_2 pipelines in operation worldwide, primarily in North America, transporting more than 80 million metric tons of CO_2 per annum (McLaughlin *et al.*, 2023).

Storage technologies have similarly evolved, with geological storage in deep saline aquifers and depleted oil and gas fields being the most mature and widely used techniques. The Sleipner Program in the North Sea, initiated in 1996, was the first commercial-scale geological storage program and has since sequestered over 20 million metric tons of CO_2. This program revealed that CO_2 may be injected into deep saline aquifers and confined by impermeable rock strata. Subsequent initiatives, such as the In Salah program in Algeria and the Gorgon program in Australia, have further perfected the systems for monitoring and verification of CO_2 storage, ensuring long-term containment.

The progress and deployment of CCUS technologies have been heavily influenced by economic and policy factors. The high initial retail price of CCUS, particularly for capture technologies, has been a significant barrier to widespread adoption. However, government incentives, such as tax credits for CO_2 storage in the United States under Section 45Q, and carbon pricing mechanisms, such as the European Union's Exhalations Trading System (EU ETS), have begun to tip the economic balance in favours of CCUS (Bacci, 2023). Under Section 45Q, for instance, facilities can receive up to $50 per ton of CO_2 stored, making many CCUS programs economically viable.

Additionally, policy foundation at both national and global levels have played a crucial role in promoting CCUS progress. The Paris Agreement, adopted in 2015, explicitly recognizes the role of CCUS in achieving global climate goals, and many countries have incorporated CCUS into their Nationally Determined Contributions (NDCs). The United Kingdom, for example, has committed to establishing several CCUS clusters by 2030, to capture and store 10 million metric tons of CO_2 per annum by that date (Bolscher *et al.*, 2023).

Despite these developments, CCUS still faces significant hurdles that must be overcome in order to reach large-scale deployment. One of the most significant hurdles is the expense, particularly the large capital investment required for the building of capture facilities and transportation infrastructure. While retail prices have been lowering, additional technological innovation is required to make CCUS more competitive with other low-carbon technologies (Araújo & de Medeiros, 2021). Additionally, public acceptance of CO_2 storage, particularly in regions with a history of seismic activity, remains a significant hurdle. Effective communication and community engagement are essential to addressing these concerns.

CCUS's future depends on scale economies, ongoing technological innovation, and CCUS's integration with other low-carbon technologies. One interesting area of research is the development of Direct Air Capture (DAC) devices, which extract CO2 straight from the atmosphere. DAC is still in its infancy, but if implemented widely, it would be able to absorb billions of metric tons of CO2 annually. Additionally, combining CCUS and bioenergy (BECCS) may help pave the road for negative exhalations, which are necessary to satisfy long-term climate targets (Hayat *et al.*, 2024).

Therefore, Carbon Capture, Utilization, and Storage (CCUS) have evolved significantly over the past few decades, from early concepts of CO_2 injection for Enhanced Oil Recovery (EOR) to advanced technologies capable of capturing and storing CO_2 at commercial scales (Bajpai *et al.*, 2022; McLaughlin *et al.*, 2023). The potential for CCUS to cut global CO2 emissions by up to 20% by 2050 highlights how crucial it is for reducing climate change. Although there are still obstacles to overcome, mostly related to affordability and public acceptance, the steady advancement of CCUS technology, coupled with a supportive economic and policy environment, presents a viable route towards accomplishing global climate goals (Ullah, Qasim, *et al.*, 2024). This suite of technologies is expected to play an increasingly important part in the shift to a low-carbon economy as CCUS continues to evolve due to technical innovation and the pressing need to address climate change.

The pre-dominant objective of this review is to contribute a comprehensive examination of the current state of Carbon Capture, Utilization, and Storage (CCUS) technologies, with a particular focus on recent technological advancements, their environmental impact, and the economic feasibility of their widespread adoption. This review aims to synthesize and critically analyze the most up-to-date research and progress in CCUS, offering insights into how these technologies have evolved to become more efficient, cost-effective, and environmentally sustainable. The scope of the review encompasses an in-depth exploration of the various carbon capture techniques, including pre-combustion, post-combustion, and oxy-fuel combustion techniques, as well as emerging technologies like Direct Air Capture (DAC). Additionally, the review will assess the different pathways for carbon utilization, such as Enhanced Oil Recovery (EOR) and chemical production, and the long-term storage options, particularly geological storage and mineralization, which are crucial for ensuring the permanent removal of CO_2 from the atmosphere. Environmental impacts, including potential threats and benefits of CCUS deployment, will be evaluated to understand how these technologies contribute to or mitigate environmental challenges such as groundwater contamination, ecosystem disruption, and the overall reduction of greenhouse gas exhalations (Fatima *et al.*, 2024). Furthermore, the economic aspects of CCUS will be rigorously analyzed, considering the retail price associated with capture, transportation, and storage, as well as the economic incentives and policies that can drive the adoption of these technologies on a global scale. Key questions addressed in this review include: What are the latest technological innovations in carbon capture and how do they compare in terms of efficiency and cost? How do the different carbon utilization and storage techniques impact environmental sustainability? What are the economic challenges and opportunities associated with scaling up CCUS, and how can policy foundation support this approach? By addressing these questions, the review aims to contribute a detailed and nuanced understanding of CCUS as a critical component in the global effort to mitigate climate change, offering recommendations for future research, progress, and policy initiatives.

Carbon Capture Technologies

Pre-Combustion Carbon Capture

Pre-combustion carbon capture automation involves the removal of carbon dioxide (CO_2) from fossil fuels before combustion. This approach typically begins with the gasification of coal, natural gas, or biomass, resulting in a synthesis gas (syngas) composed primarily of hydrogen (H2), carbon monoxide (CO), and CO_2 (Ibigbami *et al.,* 2024; Siddiqui *et al.,* 2022). The CO is then subjected to a water-gas shift reaction, converting it into additional CO_2 and H2. The CO_2 is separated from the H2 using physical or chemical solvents, such as Selexol or Rectisol, and then captured for storage or utilization (Zhang, 2023). The hydrogen produced in this approach can be used as a clean fuel in power generation or industrial applications, making pre-combustion capture particularly attractive in integrated gasification combined cycle (IGCC) power plants. The efficiency of pre-combustion capture is generally high, with capture rates exceeding 90%. However, the approach is complex and requires substantial modifications to existing infrastructure, which can be a barrier to its widespread adoption.

Post-Combustion Carbon Capture

Post-combustion carbon capture involves the removal of CO_2 from the flue gases produced by the combustion of fossil fuels in power plants and industrial facilities. The most common technique for post-combustion capture is the use of chemical absorption, where flue gases are passed through an aqueous amine solution that selectively absorbs CO_2. The CO_2-laden solvent is then heated to release the captured CO_2, which can be compressed and stored. Amines such as monoethanolamine (MEA) are widely used due to their high reactivity with CO_2 (Behbahani & Green, 2023). The efficiency of post-combustion capture typically ranges from 85% to 95%, depending on the specific automation and operational conditions. However, the energy penalty associated with regenerating the solvent and compressing the captured CO_2 is significant, often resulting in a 25-30% reduction in the net efficiency of the power plant. The cost of post-combustion capture is also relatively high, with estimates ranging from $50 to $100 per metric ton of CO_2 captured.

Oxy-Fuel Combustion Carbon Capture

Oxy-fuel combustion is an approach in which fossil fuels are burned in an environment rich in oxygen rather than air, resulting in a flue gas composed primarily of CO_2 and water vapor. By eliminating nitrogen from the combustion approach, oxy-fuel combustion simplifies the capture of CO_2, as the flue gas requires minimal processing to separate CO_2 from water vapor. The water is condensed, leaving a nearly pure stream of CO_2 that can be captured and stored. Oxy-fuel combustion offers a CO_2 capture efficiency of nearly 100%, making it one of the most effective carbon capture technologies (Dods *et al.,* 2022; Yadav & Mondal, 2022). However, the production of pure oxygen required for this approach is energy-intensive, contributing to an energy penalty of 15-20%. The cost of implementing oxy-fuel combustion is estimated to be between $30 and $50 per metric ton of CO_2 captured, making it a potentially cost-effective option in certain applications, particularly in retrofitting existing power plants.

Energy Penalties in Carbon Capture Technologies

The implementation of carbon capture technologies introduces significant energy penalties, which are critical factors in evaluating their overall feasibility and effectiveness. In pre-combustion capture, the energy penalty primarily arises from the gasification approach and the subsequent separation of CO_2 from the syngas. This energy requirement can reduce the net efficiency of IGCC power plants by approximately 10-15%. In post-combustion capture, the energy penalty is largely due to the regeneration of the solvent used in chemical absorption and the compression of the captured CO_2 (Waseem *et al.,* 2023). This can lead to a 25-30% reduction in the overall efficiency of the power plant. Oxy-fuel combustion also incurs an energy penalty, primarily from the energy-intensive air separation unit required to produce pure oxygen, which can reduce plant efficiency by 15-20%. These energy penalties not only impact the economic viability of carbon capture technologies but also influence their environmental benefits, as increased energy consumption may offset some of the CO_2 exhalation reductions achieved (Cao *et al.,* 2021).

Cost Implications of Carbon Capture Technologies

The cost of carbon capture technologies is a critical consideration in their deployment, particularly in large-scale applications. Pre-combustion capture, while highly efficient, requires significant capital investment in gasification infrastructure and CO_2 separation units. The cost of pre-combustion capture is estimated to range from $40 to $60 per metric ton of CO_2, depending on the scale and complexity of the facility. Post-combustion capture, on the other hand, is generally more expensive due to the energy-intensive nature of the solvent regeneration approach and the need for large volumes of solvent (Haidri *et al.,* 2024). The cost of post-combustion capture can vary widely, with estimates ranging from $50 to $100 per metric ton of CO_2, depending on the specific automation and operational conditions. Oxy-fuel combustion, while offering nearly complete CO_2 capture, also entails a substantial retail price, particularly in the production of pure oxygen. The cost of oxy-fuel combustion is estimated to be between $30 and $50 per metric ton of CO_2, making it potentially more cost-effective than other capture techniques in certain applications (Raganati & Ammendola, 2024; Tozzi, 2022).

Challenges in Carbon Capture Technologies

Despite significant advancements in carbon capture technologies, several challenges remain that hinder their widespread adoption. One of the pre-dominant challenges is the high capital and operational retail price associated with these technologies, which can make them economically unfeasible in the absence of strong policy incentives or carbon pricing mechanisms. Additionally, the energy penalties associated with carbon capture reduce the overall efficiency of power plants and industrial facilities, potentially leading to increased fuel consumption and higher operational retail prices (Ummer *et al.,* 2023). Another challenge is the need for large-scale infrastructure to transport and store captured CO_2, which requires significant investment and careful planning to ensure long-term security and reliability. Furthermore, public perception and acceptance of carbon capture and storage (CCS) technologies can be a barrier, particularly in regions where concerns about the security of CO_2 storage and potential environmental impacts are prevalent (Fikru & Nguyen, 2024; Witte, 2021).

Current Research Directions in Pre-Combustion Capture

Current research in pre-combustion capture is focused on improving the efficiency and cost-effectiveness of gasification approaches and CO_2 separation techniques. Advances in membrane automation, for example, are being explored as a potential alternative to traditional solvent-based separation techniques. Membranes can selectively separate CO_2 from the syngas with lower energy requirements and potentially lower retail prices. Additionally, research is ongoing to develop more efficient gasification technologies, such as pressurized gasification, which can operate at higher temperatures and pressures, resulting in more efficient conversion of fuel to syngas and improved CO_2 capture rates. Another area of research is the integration of pre-combustion capture with renewable energy sources, such as biomass gasification, which can further reduce the carbon footprint of the approach.

Current Research Directions in Post-Combustion Capture

In post-combustion capture, research efforts are focused on developing advanced solvents with higher CO_2 absorption capacities and lower regeneration energy requirements. For example, amine-based solvents such as MEA are being modified to improve their thermal stability and reduce the energy required for regeneration. Additionally, alternative solvents, such as ionic liquids and solid sorbents, are being investigated for their potential to achieve higher CO_2 capture efficiencies with lower energy penalties (Ullah, Munir, *et al.*, 2024). Another area of research is the progress of novel capture technologies, such as cryogenic separation and adsorption-based approachs, which have the potential to reduce the cost and energy requirements of post-combustion capture. Furthermore, research is being conducted to optimize the integration of post-combustion capture systems with power plants, aiming to minimize the impact on overall plant efficiency and reduce operational retail price.

Current Research Directions in Oxy-Fuel Combustion

Research in oxy-fuel combustion is primarily focused on improving the efficiency of the air separation unit (ASU) and reducing the energy penalty associated with oxygen production. Advanced cryogenic air separation technologies are being developed to achieve higher purity oxygen with lower energy consumption. Additionally, alternative oxygen production techniques, such as chemical looping combustion (CLC), are being explored as a potential means of reducing the energy requirements of oxy-fuel combustion. In CLC, oxygen is transferred from an air reactor to a fuel reactor using a metal oxide, eliminating the need for an ASU and potentially reducing the energy penalty of the approach (Baig *et al.,* 2024; Czakiert *et al.,* 2022). Another area of research is the optimization of burner designs and combustion approachs to maximize CO_2 capture efficiency and minimize the formation of pollutants such as nitrogen oxides (NOx) and sulfur oxides (SOx) (Asghar *et al.,* 2021). Furthermore, research is being conducted to explore the feasibility of retrofitting existing power plants with oxy-fuel combustion automation, to reduce the cost and complexity of implementation.

Integrated Carbon Capture Systems

In addition to research focused on individual carbon capture technologies, there is a growing interest in the progress of integrated systems that combine multiple capture techniques to achieve higher overall efficiencies and cost savings. For example, hybrid systems that combine pre-combustion and post-combustion capture technologies are being explored as a means of optimizing CO_2 capture across different stages of the power generation approach (Akeeb *et al.,* 2022). These integrated systems have the potential to achieve capture efficiencies exceeding 95% while minimizing the energy penalties and retail price associated with traditional capture techniques. Additionally, integrated systems that combine carbon capture with renewable energy sources, such as wind or solar power, are being investigated as a means of reducing the carbon footprint of the capture approach and enhancing the overall sustainability of power generation.

Therefore, carbon capture technologies, including pre-combustion, post-combustion, and oxy-fuel combustion, represent critical components of global efforts to mitigate CO_2 exhalations and combat climate change. While each automation offers distinct edges in terms of efficiency and applicability, they also face significant challenges related to cost, energy penalties, and infrastructure requirements. Ongoing research and progress efforts are focused on addressing these challenges through the progress of advanced materials, improved approach designs, and the integration of capture systems with renewable energy sources (Abbas *et al.*, Gür, 2022). As these technologies continue to evolve, they have the potential to play a central role in the transition to a low-carbon economy, contributing that the economic, technical, and social barriers to their deployment can be overcome. The future of carbon capture lies in the successful integration of these technologies into existing and new infrastructure, supported by robust policy foundation and economic incentives that drive large-scale adoption and investment in carbon capture and storage (CCS) solutions.

Table 1: Comparative Analysis of Carbon Capture Technologies

Automation	**CO_2 Capture Efficiency (%)**	**Energy Penalty (%)**	**Cost per Ton of CO_2 Captured ($)**
Pre-Combustion Capture	90-95%	10-15%	$40 - $60
Post-Combustion Capture	85-95%	25-30%	$50 - $100
Oxy-Fuel Combustion	~100%	15-20%	$30 - $50

This table contributes a comparative analysis of the three main carbon capture technologies: pre-combustion, post-combustion, and oxy-fuel combustion. The table includes key metrics such as CO2 capture efficiency, energy penalty, and the cost per ton of CO_2 captured. These metrics are crucial for understanding the performance, economic viability, and energy impact of each automation in reducing carbon exhalations from industrial and power generation approachs.

Explanation of Metrics:

- **CO_2 Capture Efficiency (%):** This represents the percentage of CO_2 exhalations captured by each automation. Higher efficiency indicates more effective capture of CO_2.
- **Energy Penalty (%):** Reflects the percentage reduction in net efficiency of the power plant or industrial approach due to the additional energy required for carbon capture. A lower penalty suggests a less significant impact on overall energy production.
- **Cost per Ton of CO_2 Captured ($):** Indicates the economic cost associated with capturing one metric ton of CO_2. Lower retail prices make automation more economically feasible for large-scale deployment.

Carbon Utilization Pathways

Enhanced Oil Recovery (EOR)

Enhanced Oil Recovery (EOR) is one of the most prominent and mature pathways for carbon utilization, involving the injection of captured CO_2 into depleted oil fields to increase the extraction of crude oil (Kumar *et al.,* 2023). The mechanism of EOR is based on the ability of CO_2 to mix with crude oil, reducing its viscosity and enhancing its flow through the reservoir. This approach is particularly effective in reservoirs where pre-dominant and secondary recovery techniques have exhausted easy-to-extract oil. CO_2-EOR can enhance oil recovery by an additional 10-20% of the original oil in place (OOIP), depending on reservoir conditions and the CO_2 injection strategy (Dutta *et al.*, 2024). The efficiency of EOR, measured as the ratio of incremental oil recovered to CO_2 injected, can vary from 0.2 to 0.5 barrels of oil per metric ton of CO_2, with the CO_2 storage efficiency in these operations ranging from 90-99%. This dual benefit of oil recovery and CO_2 storage makes EOR a critical component of integrated carbon management strategies.

Mechanisms and Efficiency of EOR

The efficiency of CO_2-EOR is governed by several factors, including reservoir characteristics, CO_2 injection rates, and the miscibility of CO_2 with the reservoir oil. The miscibility of CO2 with oil is a key determinant of the approach's success, as it allows for the reduction of oil viscosity and interfacial tension, facilitating the flow of oil to production wells (Eyinla *et al.*, 2023). The approach can be described by the following figured equation, which relates the amount of oil recovered (R_{oil}) to the volume of CO_2 injected (V_{CO2}) and the efficiency of the approach (η_{EOR}):

$$R_{oil} = \eta_{EOR} \times V_{CO2}$$

Where η_{EOR} represents the efficiency factor, typically ranging between 0.2 and 0.5. The optimization of injection parameters, such as pressure and temperature, can enhance miscibility and improve the overall efficiency of CO_2-EOR. Furthermore, CO_2 injection strategies, such as continuous or alternating water and CO_2 injection (WAG), are employed to maximize oil recovery and CO_2 storage. Continuous CO_2 injection ensures a constant supply of CO_2 to the reservoir, while WAG injection alternates between CO_2

and water, improving sweep efficiency and reducing the amount of CO_2 required per barrel of oil recovered.

Environmental Impact of EOR

While EOR contributes a significant opportunity for CO_2 utilization, it also raises environmental concerns that must be carefully managed. The pre-dominant environmental benefit of CO_2-EOR is its potential to sequester CO_2 in geological formations, effectively preventing it from entering the atmosphere (Cao *et al.,* 2020; Kumar *et al.*, 2023). However, the environmental impact of EOR depends on the net CO_2 balance, which considers the amount of CO_2 injected and stored versus the CO_2 exhalations associated with the additional oil produced and consumed (Sminchak *et al.*, 2020). Studies have shown that the net CO_2 storage in EOR operations can range from 0.5 to 1.5 metric tons of CO_2 per barrel of oil produced, depending on the efficiency of the approach and the lifecycle exhalations of the oil (Novak Mavar *et al.,* 2021).

The potential threats associated with CO_2 leakage from storage areas also pose environmental challenges. Although the risk of leakage is considered low, with well-sealed reservoirs and appropriate monitoring, it remains a critical area of concern. Advanced monitoring techniques, such as seismic imaging and tracer studies, are employed to ensure the integrity of CO_2 storage and mitigate the risk of leakage. Additionally, the increased production of oil through EOR can lead to higher CO_2 exhalations during refining and combustion, potentially offsetting the benefits of CO_2 sequestration. Therefore, the overall environmental impact of EOR must be carefully assessed within the context of its contribution to reducing net CO_2 exhalations.

Chemical Production and CO_2 Utilization

CO_2 utilization in chemical production represents another significant pathway for reducing industrial carbon exhalations (Gabrielli *et al.,* 2020). CO_2 can be used as a feedstock for producing a variety of chemicals, including urea, methanol, and polycarbonate. The utilization of CO_2 in these approachs not only reduces the demand for fossil fuel-derived raw materials but also contributes a means of recycling CO_2 into value-added products. For example, the production of urea, a key component in fertilizers, involves the reaction of CO_2 with ammonia, resulting in the formation of urea and water:

$$2NH_3+CO_2 \rightarrow (NH_2)_2CO+H_2O$$

This approach consumes approximately 0.75 metric tons of CO_2 per metric ton of urea produced, offering a direct and scalable technique of CO_2 utilization. Similarly, CO_2 can be hydrogenated to produce methanol, a versatile chemical used in fuels, plastics, and pharmaceuticals (Singh & Pöllmann, 2021). The production of methanol from CO_2 and hydrogen can be represented by the following equation:

$$CO_2+3H_2 \rightarrow CH_3OH+H_2O$$

This reaction, known as the hydrogenation of CO_2, consumes 1.37 metric tons of CO_2 per metric ton of methanol produced (Yang *et al.*, 2020). The efficiency of this approach is highly dependent on the availability of low-cost, renewable hydrogen, as well as the progress of catalysts that can operate under mild conditions and with high selectivity.

Mineralization as a Carbon Utilization Pathway

Mineralization, or the conversion of CO_2 into stable carbonates, is another promising technique for CO_2 utilization. This approach involves reacting CO_2 with naturally occurring minerals, such as magnesium or calcium silicates, to form stable carbonates, which can be used in construction materials, such as cement and concrete. The overall reaction for the mineralization of CO_2 with calcium silicate can be represented as:

$$CaSiO_3+CO_2 \rightarrow CaCO_3+SiO_2$$

This reaction sequesters CO_2 in a solid, stable form, effectively removing it from the atmosphere and providing a durable material for construction applications (Humphries *et al.*, 2024; Kherbeche, 2020). The efficiency of mineralization operations varies depending on the type of mineral and the conditions under which the reaction occurs. For example, the mineralization of CO_2 with magnesium silicate can sequester up to 1.5 metric tons of CO_2 per metric ton of silicate operation. However, the kinetics of these reactions are often slow, requiring high temperatures and pressures to achieve practical rates of CO_2 conversion, which can increase the energy requirements and retail price associated with mineralization.

Overview of CO2 Utilization in Industrial Operations

The utilization of CO_2 in industrial operations offers a pathway to reduce greenhouse gas exhalations while producing valuable products. In addition to EOR and chemical production, CO_2 can be used in a variety of other industrial applications, including the production of synthetic fuels, the carbonation of beverages, and the manufacture of building materials (Kim *et al.,* 2022). For instance, the production of synthetic fuels, such as synthetic natural gas (SNG) and Fischer-Tropsch liquids, involves the conversion of CO_2 and hydrogen into hydrocarbons, which can be used as substitutes for fossil fuels. The synthesis of SNG from CO_2 and hydrogen can be represented by the following equation:

$$CO_2+4H_2 \rightarrow CH_4+2H_2O$$

This operation, known as the Sabatier reaction, consumes 2.75 metric tons of CO_2 per metric ton of SNG produced (Neubert, 2020). The utilization of CO_2 in these operations not only reduces the reliance on fossil fuels but also contributes a means of storing renewable energy in the form of chemical energy, which can be used when renewable generation is low.

Emerging Utilization Technologies

Emerging technologies for CO_2 utilization are focused on improving the efficiency, scalability, and economic viability of existing operations, as well as developing new pathways for CO_2 conversion. One area of active research is the progress of electrochemical reduction technologies, which use electricity to convert CO_2 into valuable chemicals and fuels. For example, the electrochemical reduction of CO_2 to formic acid (*HCOOH*) is a promising pathway for producing a high-value chemical with a wide range of industrial applications. The overall reaction can be represented as:

$$CO_2+2H^++2e^-\rightarrow HCOOH$$

The efficiency of this operation is highly dependent on the progress of advanced catalysts that can operate at low over potentials and with high selectivity for the desired product (Sun *et al.,* 2024). Additionally, the use of renewable electricity to power these reactions can further enhance the sustainability of electrochemical CO_2 reduction, providing a means of coupling CO_2 utilization with renewable energy generation.

Biological CO_2 Utilization

Another emerging automation for CO_2 utilization is biological conversion, which involves the use of microorganisms to convert CO_2 into biofuels and biochemical. Algae and cyanobacteria, for example, can photosynthesize CO_2 into biomass, which can be operated into biofuels, such as biodiesel, or bioplastics. The overall efficiency of biological CO_2 conversion is governed by the photosynthetic efficiency of the microorganisms and the conditions under which they are cultured (Agarwal *et al.,* 2022; Kajla *et al.,* 2022). The potential of biological CO_2 utilization is significant, with estimates suggesting that algae-based biofuels could capture and convert up to 1.8 metric tons of CO_2 per metric ton of dry algae produced.

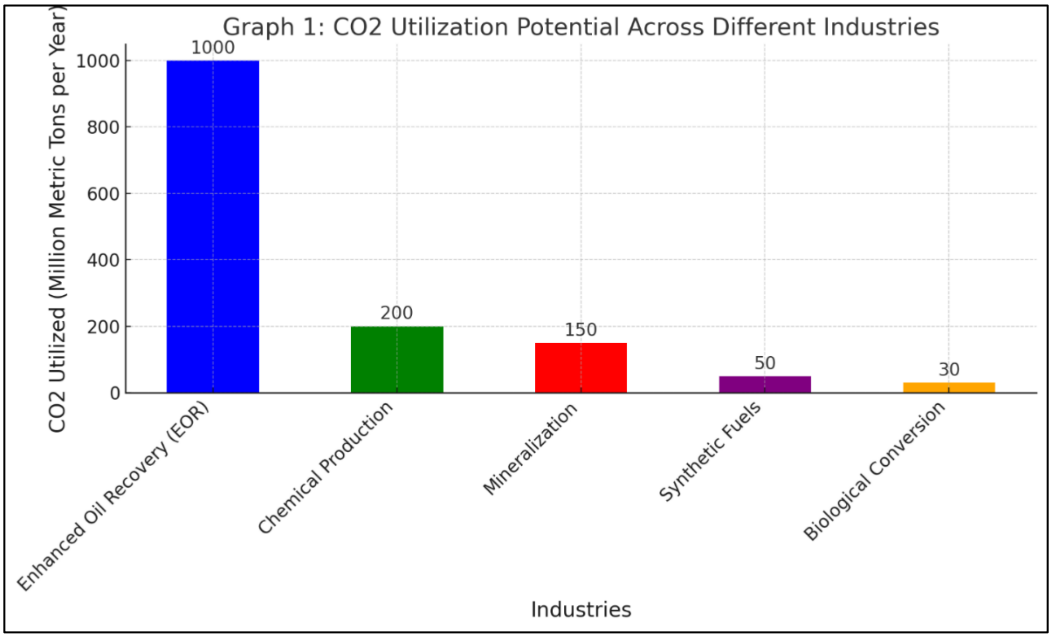
Economic Considerations and Challenges

While the potential of CO_2 utilization is vast, economic considerations play a critical role in determining the viability of these technologies. The cost of CO_2 capture, transportation, and conversion must be offset by the value of the products generated to ensure economic feasibility. For instance, the production of chemicals such as urea and methanol from CO_2 can be economically viable if the price of CO_2 is sufficiently low and if there is a strong retail demand for the products (Chauvy & De Weireld, 2020; Hong, 2022). However, challenges such as the availability of low-cost renewable energy for hydrogen production and the progress of efficient catalysts for chemical conversion remain significant hurdles. Additionally, the scale of CO_2 utilization required to make a meaningful impact on global carbon exhalations is immense. Current industrial applications of CO_2 utilization are estimated to consume only around 200 million metric tons of CO_2 per annum, a small fraction of the approximately 36.7 gigatons of CO_2 emitted globally each year. Therefore, while CO_2 utilization can contribute to exhalation reduction, it must be part of a broader strategy that includes other mitigation technologies such as carbon capture and storage (CCS) and the deployment of renewable energy.

Environmental and Sustainability Impacts of CO2 Utilization

The environmental impact of CO_2 utilization depends on the net CO_2 balance of the operation, which considers both the CO_2 captured and utilized and the exhalations associated with the energy and materials used in the operation. For example, the production of synthetic fuels from CO_2 and hydrogen is only environmentally beneficial if the hydrogen is produced using renewable energy (Amin *et al.,* 2022). Otherwise, the operation could result in net CO_2 exhalations. Life cycle assessment (LCA) is a critical tool for evaluating the environmental impacts of CO_2 utilization pathways, providing a comprehensive analysis of the exhalations, energy use, and resource consumption associated with each stage of the operation (da Cruz *et al.,* 2021). LCA studies have shown that CO_2 utilization in chemical production can result in significant exhalation reductions compared to conventional operations, particularly when renewable energy is used. However, the environmental benefits of CO_2 utilization must be weighed against potential threats, such as the depletion of natural resources used in the operation and the potential for unintended environmental consequences.

Therefore, CO_2 utilization pathways, including Enhanced Oil Recovery (EOR), chemical production, mineralization, and emerging technologies, offer promising opportunities for reducing industrial carbon exhalations while generating valuable products (Zhang *et al.,* 2020). The efficiency and environmental impact of these operations vary widely, depending on the specific automation and the conditions under which it is applied. While significant progress has been made in developing and deploying CO_2 utilization technologies, several challenges remain, including the need for cost-effective capture and conversion operations, the availability of low-cost renewable energy, and the scalability of these technologies to address global exhalations. Future research and progress efforts should focus on improving the efficiency and economic viability of CO_2 utilization pathways, as well as exploring new and innovative technologies for converting CO_2 into valuable products. Additionally, the integration of CO_2 utilization with other carbon management strategies, such as carbon capture and storage (CCS) and the deployment of renewable energy, will be essential for achieving significant and sustained reductions in global carbon exhalations. By addressing these challenges and continuing to advance the field, CO_2 utilization can play a critical role in the transition to a low-carbon economy and the mitigation of climate change.



Graph 1: CO_2 Utilization Potential across Different Industries

This bar graph illustrates the potential for CO_2 utilization across various industries, measured in million metric tons per year. The industries depicted include Enhanced Oil Recovery (EOR), Chemical Production, Mineralization, Synthetic Fuels, and Biological Conversion. Each bar represents the estimated annual CO_2 utilization potential for each industry, highlighting the significant differences in capacity. For example, EOR demonstrates the highest utilization potential, with an estimated 1,000 million metric tons per year, while biological conversion, though emerging, currently has a lower potential. The bars are colored differently for clear distinction and are designed with smart thickness to enhance visual clarity.

Carbon Storage Techniques

Geological Storage

Geological storage is one of the most mature and widely researched techniques for carbon storage, involving the injection of captured CO_2 into deep underground rock formations. These formations include depleted oil and gas reservoirs, deep saline aquifers, and un-mineable coal seams, each offering distinct edges in terms of storage capacity, injection rates, and long-term security. The global storage capacity for CO_2 in geological formations is estimated to be between 10,000 to 20,000 billion metric tons, with deep saline aquifers providing the largest capacity, potentially accommodating up to 12,000 billion metric tons of CO_2 (Rasool *et al.*, 2023; Ye *et al.*, 2023). With an estimated storage capacity of between 900 and 1,200 billion metric tons, depleted oil and gas reservoirs are also major and appealing targets for carbon capture and storage (CCS) activities, especially when combined with enhanced oil recovery (EOR) operations.

The injection rates for geological storage vary depending on the type of formation and the specific area characteristics. Typically, CO_2 injection rates range from 1 to 5 million metric tons per year per area, although some larger programs have reported injection rates exceeding 10 million metric tons per year. The injection operation involves pumping CO_2 into the storage formation at high pressures, where it is expected to remain trapped through a combination of physical and chemical mechanisms. Over time, the CO_2 is immobilized by several operations, including structural trapping, where it is confined by impermeable rock layers, residual trapping, where CO_2 is trapped in the pore spaces of the rock, and mineral trapping, where CO_2 reacts with the surrounding minerals to form stable carbonates (Massarweh & Abushaikha, 2024). The long-term security of geological storage is a critical concern, with studies suggesting that well-selected and managed areas can securely store CO_2 for thousands to millions of years, with leakage rates as low as 0.001% per year.

Ocean Storage and Soil Carbon Sequestration

Ocean storage, or the injection of CO2 into deep ocean waters, has been proposed as a method of long-term carbon sequestration. The deep ocean, which covers more than 70% of the Earth's surface, has a large theoretical CO2 storage capacity, estimated at over 40,000 billion metric tons. The main premise is to inject CO2 into depths more than 1,000 meters, where it will form a dense, stable layer on the ocean floor or dissolve into the water column. The frigid temperatures and strong pressures at this depths encourage the dissolution and stabilization of CO2, potentially keeping it sequestered for generations. However, ocean storage raises significant environmental and ethical concerns, particularly regarding the acidification of marine environments and the potential impacts on deep-sea ecosystems. The injection of CO_2 into the ocean could lead to localized drops in pH, with values potentially falling by 0.1 to 0.5 units, depending on the amount of

CO_2 injected and the local buffering capacity (Tewari *et al.*, 2023). Such changes in pH could have detrimental effects on marine life, particularly calcifying organisms like corals and shellfish.

Soil carbon sequestration, on the other hand, is a more natural technique of CO_2 storage, involving the enhancement of soil organic carbon (SOC) levels through sustainable land management practices. This technique has the dual benefit of improving soil fertility and agricultural productivity while sequestering carbon. The global potential for soil carbon sequestration is estimated to be between 1 to 2 billion metric tons of CO_2 per year, primarily through practices such as no-till farming, cover cropping, and agroforestry. These practices increase the amount of organic matter in the soil, enhancing its ability to store carbon. For example, no-till farming can increase SOC levels by 0.3 to 0.5 metric tons per hectare per year, while agroforestry can sequester up to 5 metric tons of CO_2 per hectare per year. However, the long-term stability of sequestered carbon in soils is subject to various factors, including land use changes, soil management practices, and climate conditions, which can lead to the release of stored carbon back into the atmosphere.

Capacity, Injection Rates, and Long-Term Security of Geological Storage

The capacity of geological formations to store CO_2 is primarily determined by the porosity and permeability of the rock, the thickness of the storage formation, and the availability of suitable cap rock to prevent the upward migration of CO_2. Depleted oil and gas reservoirs, for instance, have well-characterized geology and existing infrastructure, making them ideal candidates for CO_2 storage (Alkan *et al.*, 2023). These formations typically have high porosity and permeability, allowing for efficient injection and storage of CO_2. The long-term security of CO_2 storage in these formations is further enhanced by the presence of impermeable cap rocks, such as shale, which act as barriers to CO_2 migration. Deep saline aquifers, while offering larger storage capacities, often have more complex geology, requiring detailed area characterization and monitoring to ensure secure storage. The long-term security of geological storage is a function of the trapping mechanisms at play. Structural trapping contributes the first line of defence, where CO_2 is physically trapped beneath cap rocks. Over time, residual trapping occurs as CO2 becomes immobilized in the pore spaces of the rock, typically accounting for 10-20% of the injected CO2 (Massarweh & Abushaikha, 2024). Mineral trapping, which can take centuries to millennia, is the most secure form of trapping, as CO_2 reacts with the minerals in the rock to form stable carbonates, permanently removing it from the carbon cycle.

Potential and Environmental Threats of Ocean Storage and Soil Carbon Sequestration

While ocean storage offers a vast potential for CO_2 sequestration, its environmental threats are significant. The pre-dominant concern is the acidification of the deep ocean, which could have far-reaching impacts on marine biodiversity and ecosystem services. The injection of large quantities of CO2 into the ocean could result in the formation of a CO_2-rich layer on the seafloor, with potential consequences for benthic organisms (Louis, 2023). Additionally, the dissolution of CO_2 into the water column could lead to the formation of carbonic acid, which lowers the pH of seawater and reduces the availability of carbonate ions, essential for the formation of shells and skeletons in marine organisms. The environmental impact of ocean storage is further complicated by the difficulty of monitoring and verifying the fate of injected CO_2, given the vastness and inaccessibility of the deep ocean. In contrast, soil carbon sequestration presents fewer environmental threats, as it relies on natural operations to store CO_2. However, the potential for soil carbon sequestration is limited by land availability, competing land uses, and the long-term stability of sequestered carbon. Soil carbon can be released back into the atmosphere through operations such as soil erosion, microbial decomposition, and changes in land use, particularly when soils are disturbed by ploughing or deforestation (Hussain *et al.*, 2021). Therefore, while soil carbon sequestration is a valuable tool for mitigating climate change, its effectiveness is contingent on sustained and appropriate land management practices.

Monitoring and Verification Techniques

The success of carbon storage, particularly in geological and ocean settings, hinges on the ability to monitor and verify the long-term containment of CO_2. Monitoring and verification techniques are essential for detecting any potential leaks, ensuring the integrity of storage areas, and providing data to inform risk assessments and regulatory compliance. In geological storage, monitoring begins with baseline assessments of the storage area, including seismic surveys to map the subsurface geology and establish a reference point for future monitoring. Once CO_2 injection begins, time-lapse seismic imaging is commonly used to track the movement of CO_2 within the storage formation and detect any migration towards the surface (Roche *et al.*, 2021). Micro seismic monitoring, which detects small seismic events caused by the injection of CO_2, contributes additional data on the geomechanical stability of the storage area (Cheng *et al.*, 2023). Pressure and temperature sensors installed in wells are also used to monitor the conditions within the storage formation and detect any anomalies that could indicate leakage. In the case of ocean storage, monitoring is more challenging due to the inaccessibility and vastness of the deep ocean. Remote sensing technologies, such as autonomous underwater vehicles (AUVs) equipped with sensors, are employed to monitor the pH, temperature, and chemical composition of seawater in the vicinity of the CO_2 injection area (Blomberg *et al.*, 2021). Tracer studies, which involve the injection of isotopically labelled CO_2, can also be used to track the movement of CO_2 in the ocean and verify its containment (Louis, 2023). For soil carbon sequestration, monitoring involves the regular sampling and analysis of soil to measure changes in SOC levels. Remote sensing technologies, such as satellite imaging and drones, are increasingly being used to monitor land use changes and assess the effectiveness of soil carbon sequestration practices on a large scale.

Long-Term Security and Regulatory Foundation

The long-term security of carbon storage is not only a technical challenge but also a regulatory and legal one. Ensuring that CO_2 remains securely stored for centuries to millennia requires robust regulatory foundation that govern the selection, operation, and monitoring of storage areas. In many regions, regulatory foundation for geological storage are still in progress, with a focus on ensuring that storage areas are properly characterized and monitored throughout their operational lifetime and beyond. These foundation typically include requirements for area selection, risk assessments, monitoring plans, and contingency measures in case of leakage. For example, the European Union's Directive on the Geological Storage of Carbon Dioxide sets out requirements for the entire lifecycle of a storage area, from area selection to post-closure monitoring (Frattini *et al.,* 2024). In the United States, the Environmental Protection Agency (EPA) has established regulations under the Underground Injection Control (UIC) program, which sets standards for the injection of CO_2 into underground formations and requires operators to demonstrate that their areas can securely store CO_2 for the long term (Clark *et al.,* 2005; Fibbi *et al.,* 2022). The long-term security of ocean storage is more contentious, given the potential environmental threats and the lack of global consensus on its regulation. The London Protocol, an global treaty that regulates the dumping of waste at sea, currently prohibits the disposal of CO_2 in the ocean, although discussions are ongoing about the potential for amendments that would allow CO_2 storage under specific conditions and with stringent monitoring requirements (Schütz & Omar, 2023; Scott, 2023). Any future framework for ocean storage will need to address the significant environmental threats associated with ocean acidification and potential impacts on marine ecosystems. In contrast, soil carbon sequestration is generally governed by agricultural and land use policies rather than specific carbon storage regulations. However, as the importance of soil carbon in climate mitigation becomes more recognized, there is a growing push for policies that incentivize sustainable land management practices and contribute foundation for the monitoring and verification of soil carbon levels.

Research and Progress in Carbon Storage Technologies

Ongoing research and progress efforts are critical to advancing the effectiveness and scalability of carbon storage technologies. In geological storage, research is focused on improving the understanding of CO_2 behaviour in different geological formations, enhancing the efficiency of CO_2 injection, and developing advanced monitoring technologies that can contribute real-time data on CO_2 movement and storage security. For example, the progress of fibre optic sensors that can be deployed in wells to continuously monitor temperature, pressure, and seismic activity is a significant advancement in the field (Ashry *et al.,* 2022). Additionally, research into the chemical reactions between CO_2 and minerals in the storage formation provides insights into the long-term stability of mineral trapping mechanisms, which are crucial for ensuring the permanent sequestration of CO_2.

In the area of ocean storage, research is exploring alternative techniques for reducing the environmental impact of CO_2 injection, such as injecting CO_2 into subsea basalt formations, where it can react with the basalt to form stable carbonates. This approach, known as mineral carbonation in oceanic basalts, has the potential to combine the large storage capacity of the ocean with the long-term stability of mineral trapping, potentially reducing the threats associated with ocean acidification. However, the feasibility of this technique is still under investigation, and significant technical and environmental challenges remain.

For soil carbon sequestration, research is focused on identifying and optimizing land management practices that maximize carbon sequestration while maintaining or improving agricultural productivity. This includes studying the effects of different crop rotations, cover crops, and agroforestry systems on soil carbon levels, as well as developing new technologies for measuring and verifying soil carbon sequestration on a large scale. Advances in remote sensing and data analytics are playing a key role in this research, enabling more accurate and efficient monitoring of soil carbon across diverse landscapes.

Integration with Other Climate Mitigation Strategies

Carbon storage technologies are increasingly being integrated with other climate mitigation strategies to enhance their effectiveness and achieve broader environmental benefits. For example, the integration of carbon capture and storage (CCS) with bioenergy production (known as BECCS) offers the potential for negative exhalations, where CO_2 is removed from the atmosphere and permanently stored (Talei & Soleimani, 2021). BECCS involves the use of biomass as a feedstock for energy production, with the CO_2 generated during combustion or gasification captured and stored in geological formations (Donnison *et al.,* 2020). This operation not only reduces CO_2 exhalations from energy production but also sequesters additional CO_2 that was absorbed by the biomass during its growth, resulting in a net reduction of atmospheric CO_2. The global potential for BECCS is estimated to be between 2 to 10 billion metric tons of CO_2 per year by 2050, depending on the availability of sustainable biomass and the deployment of CCS infrastructure.

Similarly, the combination of soil carbon sequestration with regenerative agriculture practices can contribute multiple co-benefits, including enhanced soil fertility, improved water retention, and increased biodiversity. By integrating carbon storage with sustainable land management, these practices contribute to climate resilience while supporting food security and rural livelihoods. The progress of carbon retails and carbon credits for soil carbon sequestration is also helping to incentivize the adoption of these practices, providing financial rewards for farmers and landowners who sequester carbon in their soils.

Therefore, carbon storage techniques, including geological storage, ocean storage, and soil carbon sequestration, are critical components of the global strategy to mitigate climate change. Each of these techniques offers unique edges and challenges, with varying capacities, environmental impacts, and long-term security. Geological storage, with its well-established techniques and large capacity, remains the most viable option for large-scale CO_2 sequestration, particularly when integrated with carbon capture technologies (Alkan *et al.*, 2023). Ocean storage, while offering vast potential, is limited by significant environmental threats and regulatory challenges that must be carefully managed. Soil carbon sequestration, though smaller in scale, contributes important co-benefits for agriculture and ecosystem health, making it a valuable tool for sustainable land management.

The future of carbon storage will depend on continued research and innovation, the progress of robust regulatory foundation, and the integration of storage technologies with other climate mitigation strategies. Advances in monitoring and verification will be essential to ensuring the long-term security of stored CO_2, while policies that incentivize carbon storage and promote sustainable practices will be crucial for scaling up these technologies. As the world moves towards net-zero exhalations, carbon storage will play an increasingly important role in balancing residual exhalations and achieving climate goals. By addressing the technical, economic, and environmental challenges associated with carbon storage, we can unlock its full potential as a key tool in the fight against climate change.

Data Table 2: Global CO_2 Storage Capacity and Long-Term Security Estimates across Different Techniques

Storage Technique	**Storage Capacity (Billion Metric Tons)**	**CO_2 Retention Rates (%)**	**Risk Factors**
Geological Storage (Deep Saline Aquifers)	12,000	99.999	Very Low (Properly managed areas)
Geological Storage (Depleted Oil & Gas Reservoirs)	1,000	99.999	Very Low (Well-sealed reservoirs)
Ocean Storage	40,000	90.0	Moderate (Ocean acidification)
Soil Carbon Sequestration	1.5	85.0	Moderate (Land use changes, soil erosion)

This table contributes an overview of the global CO_2 storage capacity and long-term security estimates across different carbon storage techniques, including geological storage in deep saline aquifers and depleted oil and gas reservoirs, ocean storage, and soil carbon sequestration. The metrics included in the table are storage capacity (measured in billion metric tons), CO2 retention rates (as a percentage), and associated risk factors. These factors are crucial for understanding the potential and reliability of each storage technique in contributing to global carbon sequestration efforts.

Explanation of Metrics:

- **Storage Capacity (Billion Metric Tons):** This metric indicates the estimated global capacity for CO_2 storage in each technique. Ocean storage offers the largest theoretical capacity, followed by deep saline aquifers.
- **CO_2 Retention Rates (%):** Represents the percentage of CO_2 expected to remain securely stored over the long term. Geological storage techniques, particularly in deep saline aquifers and depleted reservoirs, offer the highest retention rates.
- **Risk Factors:** Highlights the pre-dominant environmental and technical threats associated with each storage technique. Geological storage is considered very low risk when properly managed, while ocean storage and soil carbon sequestration present moderate threats due to potential environmental impacts.

Environmental Impact and Risk Assessment

Ecological and Human Health Impacts

Carbon capture and storage (CCS) technologies, while offering significant potential to mitigate climate change, also pose various ecological and human health threats that must be carefully assessed. The pre-dominant ecological impacts of CCS are associated with the storage phase, particularly the long-term containment of CO_2 in geological formations or the deep ocean. The potential for CO_2 leakage from storage areas, though considered low with proper area selection and management, could have severe consequences for both terrestrial and marine ecosystems. CO_2 leakage into the atmosphere could negate the benefits of CCS by contributing to greenhouse gas concentrations, while leakage into shallow groundwater could lead to the acidification of water sources, impacting both human and ecological health.

One of the key human health concerns is the risk of CO_2 leakage into the atmosphere, which could lead to localized increases in CO_2 concentrations. Although CO_2 is naturally present in the atmosphere at low concentrations (~400 ppm), elevated levels of CO_2 can pose serious health threats (Cvetković *et al.*, 2021; Kumar *et al.*, 2022). For example, CO_2 concentrations above 5,000 ppm can cause respiratory problems, dizziness, and even unconsciousness, particularly in enclosed or poorly ventilated areas. Additionally, the transport and injection of CO_2 involve high pressures, which pose operational threats, including the potential for pipeline ruptures or well blowouts. These incidents could result in sudden releases of CO_2, posing immediate threats to workers and nearby communities.

Potential Threats Associated with Carbon Capture and Storage

The threats associated with CCS can be broadly categorized into three main areas: storage integrity, environmental contamination, and operational security. Storage integrity threats relate to the potential for CO_2 to migrate from the storage area through fractures, faults, or improperly sealed wells. While modern CCS programs are designed with multiple layers of containment, including cap rocks and monitoring systems, the geological complexity of storage areas can make it challenging to predict and manage these threats fully.

Environmental contamination threats include the potential for CO_2 to dissolve into groundwater, leading to the formation of carbonic acid, which can lower the pH of the water and increase the solubility of heavy metals like lead and arsenic. This could contaminate drinking water supplies and harm aquatic ecosystems. In marine environments, the injection of CO_2 into deep ocean waters could result in ocean acidification, impacting marine biodiversity, particularly organisms that rely on calcium carbonate for shell and skeleton formation, such as corals and molluscs. The acidification of ocean waters can lead to the dissolution of these structures, disrupting marine food chains and ecosystems.

Operational security threats are associated with the transportation, injection, and monitoring phases of CCS. High-pressure CO_2 pipelines and injection wells require rigorous security standards and monitoring to prevent accidental releases. Pipeline ruptures, for instance, could lead to the sudden release of large volumes of CO_2, creating dense clouds of gas that could displace oxygen in the air, posing asphyxiation threats to humans and animals (Cassim, 2023). The integrity of injection wells is also critical, as any failure could result in uncontrolled releases of CO_2, potentially leading to surface leaks and environmental contamination.

Case Studies of Environmental Impact

Several case studies of CCS programs around the world contribute valuable insights into the environmental impacts and threats associated with these technologies. The Sleipner Program in the North Sea, initiated in 1996, was the first commercial-scale CCS program to store CO_2 in a deep saline aquifer (Yang *et al.*, 2023). Over 20 million metric tons of CO_2 have been successfully stored at Sleipner, with continuous monitoring showing no evidence of CO_2 leakage (Rycroft *et al.,* 2024). The program has demonstrated the effectiveness of seismic monitoring techniques in tracking CO_2 movement and ensuring the integrity of the storage area. However, the complexity of the reservoir geology required extensive baseline studies and ongoing monitoring to manage the threats of CO_2 migration.

Another notable case study is the In Salah Program in Algeria, which began storing CO_2 in a depleted gas field in 2004 (Bashir *et al.,* 2024). The program was one of the first to implement active management of CO_2 injection rates to control reservoir pressure and reduce the risk of fracturing the cap rock. Despite these precautions, micro seismic monitoring detected small-scale fractures in the cap rock, leading to concerns about the long-term integrity of the storage area. The program highlighted the importance of adaptive management and the need for robust monitoring systems to detect and respond to potential threats in real-time.

In contrast, the Gorgon Program in Australia has faced significant challenges related to the storage of CO_2 in a deep saline aquifer. The program, which began in 2019, aims to store up to 4 million metric tons of CO_2 per year but has experienced delays due to technical difficulties in managing the pressure and injectivity of the storage formation (Worden, 2024). These issues have underscored the importance of thorough area characterization and the need for flexible operational strategies to address unexpected challenges in CCS programs.

Analysis of Specific Programs and Lessons Learned

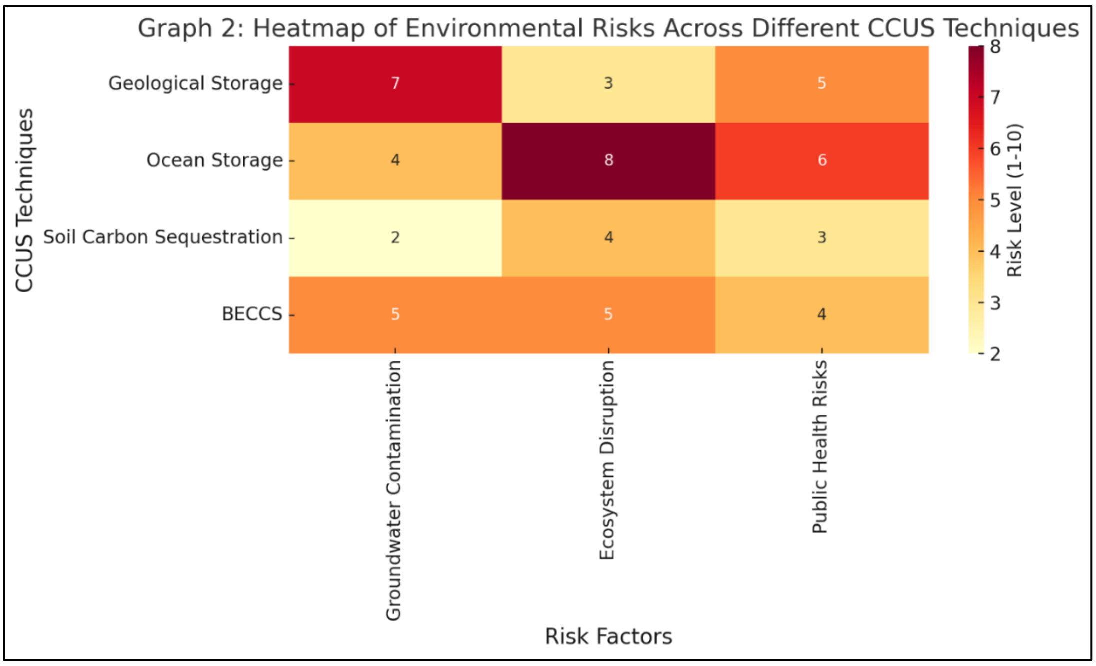
The experiences from these CCS programs offer several lessons for the future progress and deployment of carbon capture and storage technologies. First, the importance of detailed geological area characterization cannot be overstated. Understanding the subsurface conditions, including the presence of faults, fractures, and the properties of cap rocks, is crucial for assessing the long-term security of CO_2 storage and identifying potential threats. Baseline studies, including seismic surveys and geochemical analysis, are essential for establishing a reference point for monitoring and predicting the behaviour of CO_2 in the storage formation.

Second, continuous and adaptive monitoring is key to managing the threats associated with CCS. The use of advanced monitoring technologies, such as time-lapse seismic imaging, micro seismic monitoring, and pressure sensors, enables operators to track the movement of CO_2 within the storage area and detect any anomalies that could indicate leakage or other issues. Adaptive management, which involves adjusting injection rates and pressures in response to monitoring data, has proven effective in mitigating threats and ensuring the long-term security of stored CO_2.

Third, the integration of CCS with other climate mitigation strategies can enhance its effectiveness and reduce overall threats. For example, the combination of CCS with bioenergy production (BECCS) offers the potential for negative exhalations, which can help offset residual exhalations from other sectors (Tanzer *et al.*, 2021). Additionally, integrating CCS with renewable energy sources can reduce the carbon intensity of the capture and storage operation, making it more sustainable in the long term.

Finally, public engagement and transparent communication are critical for building trust and gaining acceptance for CCS programs. The perceived threats of CO_2 storage, particularly related to leakage and environmental contamination, can lead to public opposition if not addressed through clear and transparent communication. Engaging local communities, providing access to monitoring data, and involving stakeholders in decision-making operations are essential for the successful implementation of CCS programs.

In conclusion, while carbon capture and storage technologies offer significant potential for mitigating climate change, they also present a range of environmental and operational threats that must be carefully managed. The lessons learned from existing CCS programs highlight the importance of area characterization, continuous monitoring, adaptive management, and public engagement in ensuring the long-term security and success of these technologies. As the world moves towards a low-carbon future, the role of CCS in achieving global climate goals will depend on our ability to address these challenges and build on the knowledge gained from past and current programs.



Graph 2: Heatmap of Environmental Threats across Different CCUS Techniques

This heatmap contributes a visual representation of the environmental threats associated with various Carbon Capture, Utilization, and Storage (CCUS) techniques. The techniques analyzed include Geological Storage, Ocean Storage, Soil Carbon Sequestration, and Bioenergy with Carbon Capture and Storage (BECCS). The risk factors considered are Groundwater Contamination, Ecosystem Disruption, and Public Health Threats. The colour intensity in the heatmap reflects the level of risk on a scale from 1 to 10, where 10 represents the highest risk. For instance, Ocean Storage presents the highest risk for ecosystem disruption, while Geological Storage has a higher risk of groundwater contamination. This heatmap helps to identify and compare the potential environmental threats of different CCUS techniques, providing valuable insights for decision-making and risk management in the deployment of these technologies.

Economic Feasibility and Policy Considerations

Cost-Benefit Analysis of CCUS

The economic feasibility of Carbon Capture, Utilization, and Storage (CCUS) is a complex issue that requires a thorough cost-benefit analysis to evaluate its viability. The retail price associated with CCUS primarily stems from the capture, transportation, and storage of CO_2. Capture retail price can vary significantly depending on the automation and scale of deployment, ranging from $30 to $100 per metric ton of CO_2, as noted by the Global Energy Agency (IEA) (McLaughlin *et al.*, 2023). For example, "post-combustion capture in coal-fired power plants can range between $40 and $80 per metric ton, with significant variability depending on the efficiency of the capture automation and the specifics of the plant" (IEA, 2020) (Kazemifar, 2022). On the other hand, transportation retail prices are relatively lower but still considerable, particularly when CO_2 must be transported over long distances. Pipelines, the most common mode of transport, typically cost $1 to $3 per metric ton per 100 kilometers. Storage retail price, including area selection, injection, and long-term monitoring, can add another $10 to $20 per metric ton.

In contrast, the benefits of CCUS are measured in terms of the social cost of carbon avoided and the economic value of CO_2-derived products. The social cost of carbon, which estimates the economic damages associated with an incremental increase in CO_2 exhalations, is a crucial factor in this analysis. According to the U.S. Environmental Protection Agency (EPA), the social cost of carbon is estimated at $51 per metric ton (as of 2020), although this figure is subject to change based on new scientific evidence and policy adjustments (Revesz & Sarinsky, 2022). This implies that if the retail price of capturing, transporting, and storing CO_2 can be kept below this threshold, CCUS can be economically justified from a societal perspective. Furthermore, the potential revenues from CO_2 utilization, such as in Enhanced Oil Recovery (EOR) or chemical production, can offset some of the retail price, improving the overall economic feasibility of CCUS.

Economic Viability at Different Scales

The economic viability of CCUS varies significantly depending on the scale of deployment and the specific context in which it is implemented. Large-scale CCUS programs, such as those integrated with industrial complexes or large power plants, tend to benefit from economies of scale, which can reduce the per-ton cost of CO_2 capture and storage. For instance, the Petra Nova program in Texas, one of the largest post-combustion capture facilities in the world, achieved a capture retail price as low as $40 per metric ton due to its scale and integration with existing infrastructure (Moniz et al., 2023). In contrast, small-scale CCUS programs, particularly those in remote locations or with limited infrastructure, may face higher retail prices due to the lack of economies of scale and the additional expenses associated with transportation and storage.

Moreover, the economic viability of CCUS is also influenced by the local retail conditions and availability of CO_2 storage areas. In regions with abundant and accessible geological storage formations, such as the Permian Basin in the United States or the North Sea in Europe, the retail price of storage is lower, making CCUS more economically viable. Contrariwise, in regions with limited storage options, the retail price of developing new storage areas or transporting CO_2 to distant areas can be prohibitive (Quirk *et al.*, 2022). As a result, the scalability and location-specific factors play a crucial role in determining the economic feasibility of CCUS programs.

Retail Incentives and Carbon Pricing

Retail incentives and carbon pricing mechanisms are critical components in enhancing the economic viability of CCUS. Carbon pricing, whether through carbon taxes or cap-and-trade systems, creates a financial incentive for industries to reduce their carbon exhalations, thereby making investments in CCUS more attractive. For example, the European Union's Exhalations Trading System (EU ETS) sets a price on carbon exhalations, which has fluctuated between €20 and €50 per metric ton in recent years (Lagouvardou & Psaraftis, 2022). This pricing mechanism encourages industries to adopt low-carbon technologies, including CCUS, to avoid paying for exhalations. According to a study by Galeazzi *et al.*, (2023), a carbon price of at least $40 to $80 per metric ton by 2030 is required to drive significant investments in CCUS and other mitigation technologies.

In addition to carbon pricing, various retail incentives, such as tax credits and subsidies, have been introduced to support the deployment of CCUS. In the United States, the Section 45Q tax credit contributes financial incentives for CO_2 storage, offering $50 per metric ton for CO_2 stored in geological formations and $35 per metric ton for CO_2 utilized in EOR or other industrial operations. This tax credit has been a driving force behind several CCUS programs in the U.S., helping to bridge the gap between the retail price of CCUS and the revenues from CO_2 utilization. Similar incentives are being explored in other regions, including Canada and Australia, to promote the adoption of CCUS technologies.

Government Policies and Global Agreements

Government policies and global agreements play a pivotal role in shaping the landscape for CCUS deployment. National governments have a critical role in providing regulatory foundation, funding for research and progress, and creating favourable retail conditions for CCUS. For example, the U.S. Department of Energy (DOE) has invested over $1 billion in CCUS research and progress over the past decade, leading to significant advancements in capture technologies and storage techniques (Beck, 2020). Similarly, the European Union has established the Innovation Fund, which allocates billions of euros to innovative low-carbon technologies, including CCUS, as part of its commitment to achieving net-zero exhalations by 2050.

Global agreements, such as the Paris Agreement, also have significant implications for CCUS. The Paris Agreement, which aims to limit global warming to well below 2°C above pre-industrial levels, has prompted many countries to include CCUS in their Nationally Determined Contributions (NDCs) as a key strategy for reducing exhalations (Warren *et al.,* 2022). For instance, the United Kingdom has committed to establishing at least two CCUS clusters by 2030, intending to capture and store 10 million metric tons of CO_2 per annum. Similarly, Norway has launched the Long Ship program, which aims to develop full-scale CCS in Europe by capturing CO_2 from industrial sources and storing it in the North Sea (Wang, 2023).

Challenges and Barriers to Economic Viability

Despite the potential benefits and incentives, several challenges and barriers to the economic viability of CCUS remain. One of the main challenges is the high upfront capital retail price associated with CCUS infrastructure, particularly for capture facilities and CO_2 pipelines. These retail prices can be a significant deterrent for industries, particularly in regions with low carbon prices or limited financial support. As noted by Chen *et al.,* (2022), "the capital retail price of capture plants can represent up to 70% of the total retail price of a CCUS program, making it a major barrier to deployment."

Another barrier is the uncertainty surrounding long-term storage liabilities and regulatory requirements. The potential for CO_2 leakage and the associated environmental and legal threats can create uncertainty for program developers, particularly in regions without well-established regulatory foundation. This uncertainty can make it difficult to secure financing for CCUS programs, as investors may be wary of the potential liabilities associated with CO_2 storage. Additionally, the lack of a global carbon pricing mechanism and the variation in carbon prices across regions can create retail distortions, making it challenging to achieve a level playing field for CCUS deployment.

Opportunities for Cost Reduction and Policy Innovation

To address these challenges and enhance the economic viability of CCUS, several opportunities for cost reduction and policy innovation are being explored. Technological advancements, such as the progress of new capture materials and operations, offer the potential to reduce capture retail price and improve the efficiency of CCUS. For example, research into solid sorbents and membrane-based capture technologies has shown promise in reducing the energy requirements and retail price associated with CO_2 capture. Additionally, the integration of CCUS with renewable energy sources, such as wind and solar power, can further reduce the carbon intensity of the capture operation and enhance the overall sustainability of CCUS.

Policy innovation is also critical for overcoming the barriers to CCUS deployment. The introduction of carbon contracts for difference (CCfDs), which guarantee a fixed price for captured CO_2, can contribute to financial stability for CCUS programs and attract investment. Similarly, the expansion of global cooperation on CCUS, including the sharing of best practices and the progress of cross-border CO_2 transport and storage infrastructure, can help to reduce retail prices and create economies of scale. As highlighted in a report by the Global CCS Institute (2020), "Global collaboration and the progress of shared infrastructure are key to unlocking the full potential of CCUS as a global climate mitigation strategy."

Therefore, the economic feasibility of CCUS is a multifaceted issue that depends on a range of factors, including the retail price of capture, transportation, and storage, the availability of retail incentives and carbon pricing, and the support of government policies and global agreements. While significant progress has been made in reducing the retail price of CCUS and creating favourable retail conditions, several challenges and barriers remain. The high capital retail price of CCUS infrastructure, uncertainty surrounding long-term storage liabilities, and the variability in carbon pricing across regions are major obstacles that need to be addressed to achieve widespread deployment of CCUS technologies.

Looking forward, continued technological innovation, policy support, and global cooperation will be essential for enhancing the economic viability of CCUS and realizing its potential as a key tool in the global effort to mitigate climate change. As the world moves towards a low-carbon future, the role of CCUS in achieving net-zero exhalations will depend on our ability to overcome these challenges and create a supportive environment for the deployment of CCUS at scale. By leveraging the opportunities for cost reduction, policy innovation, and global collaboration, CCUS can play a critical role in the transition to a sustainable and resilient global economy.

Data Table 3: Cost-Benefit Analysis of CCUS Programs in Different Regions

Region	**Capital Retail price ($ Million)**	**Operating Retail price ($/Ton CO_2)**	**Carbon Credit Prices ($/Ton CO_2)**
North America	600 ± 50	45 ± 5	30 ± 5
Europe	700 ± 60	50 ± 7	40 ± 8
Asia-Pacific	550 ± 40	40 ± 4	35 ± 6

Middle East	800 ± 70	55 ± 6	28 ± 4
Africa	500 ± 45	38 ± 3	32 ± 5

This table contributes a comparative analysis of the cost-benefit factors associated with Carbon Capture, Utilization, and Storage (CCUS) programs across various regions. The metrics included are Capital Retail price (in $ Million), Operating Retail price (in $ per Ton of CO_2), and Carbon Credit Prices (in $ per Ton of CO_2). The values are presented with their associated standard deviations (SD), reflecting the variability in retail price and carbon credit prices within each region.

Explanation of Metrics:

- **Capital Retail price ($ Million):** Reflects the initial investment required to set up CCUS programs in each region, including capture facilities, transportation infrastructure, and storage areas. The standard deviation indicates the variability in these retail prices across different programs within the region.
- **Operating Retail price ($/Ton CO_2):** Represents the ongoing retail price associated with capturing, transporting, and storing CO_2. The standard deviation highlights the differences in operational efficiencies and retail price across programs within the region.
- **Carbon Credit Prices ($/Ton CO_2):** Shows the average price of carbon credits in each region, which can influence the economic viability of CCUS programs. The standard deviation reflects fluctuations in carbon retail prices within the region.

CONCLUSION

In conclusion, Carbon Capture, Utilization, and Storage (CCUS) technologies present a critical opportunity for mitigating climate change, offering substantial reductions in CO_2 exhalations through effective capture, storage, and utilization techniques. Key findings indicate that while CCUS is technologically feasible, with capture efficiencies ranging from 85% to nearly 100%, the economic viability remains a challenge due to high capital and operating retail price, particularly for small-scale programs. The environmental impact, particularly related to potential CO_2 leakage and ecosystem disruption, necessitates rigorous monitoring and regulatory foundation. The future outlook for CCUS is promising, with significant potential for technological innovation, such as advancements in capture materials and integrated renewable energy systems, which could drive down retail price and enhance scalability. To fully realize this potential, ongoing research should focus on improving capture efficiencies, reducing retail price, and developing robust monitoring techniques. Policymakers must support CCUS through targeted incentives, global cooperation, and the establishment of comprehensive regulatory foundation to ensure secure, large-scale deployment, positioning CCUS as a cornerstone of global efforts to achieve net-zero exhalations.

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