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Carbon Capture and Storage for Net Zero Emissions: Current Techniques, Challenges and Future Directions

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ABSTRACT

Carbon Capture and Storage (CCS) is an essential pillar towards achieving net-zero emissions, especially to decarbonise the more than 40% of the global CO_2 emissions associated with industrial and power sectors. Research around CCS technologies is extensive and thorough, but in many cases, they do not bring together a comprehensive quantitative analysis of the full chain of CCS. This review provides a comprehensive and critical synthesis of the state of play regarding technological performance, quantifying capture efficiency, for example, 85-90% for amine scrubbing and 70-90% for direct air capture (DAC) and the costs associated with those technologies ($50-150/tCO2 for point-source capture, over $600/tCO2 for DAC). We also provide insight into geological storage capacity, limits of injectivity, and transport logistics. Importantly, and in addition to a technical assessment, this review assesses future implications of emerging artificial intelligence (AI) and machine learning (ML) capabilities on CCS design, monitoring, and policy. Lastly, we identify critical barriers, including excessive energy penalties (5-10 GJ/tCO_2) and regulatory gaps, and provide a potential research and policy pathway towards improving the viable deployment of CCS as part of climate mitigation goals.

***Keywords*:** CCS Technologies, Net-zero Emissions, Artificial Intelligence, and Machine Learning.

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1. INTRODUCTION

The fact that climate change is spiralling out of control is a strong indicator that there must be a shift to a sustainable society worldwide. In spite of this demand, the emission of greenhouse gases (GHG) has not decreased as the planet continues to rely on fossil fuels to satisfy the increased energy needs [1]. The heat and power generation industries contribute the most to the problem, with more than 42% of the world CO_2 emissions being carried by them [2, 3]. The visual importance of this dependence is emphasised by the fact that the major economies continue to make high emissions (Figure 1).

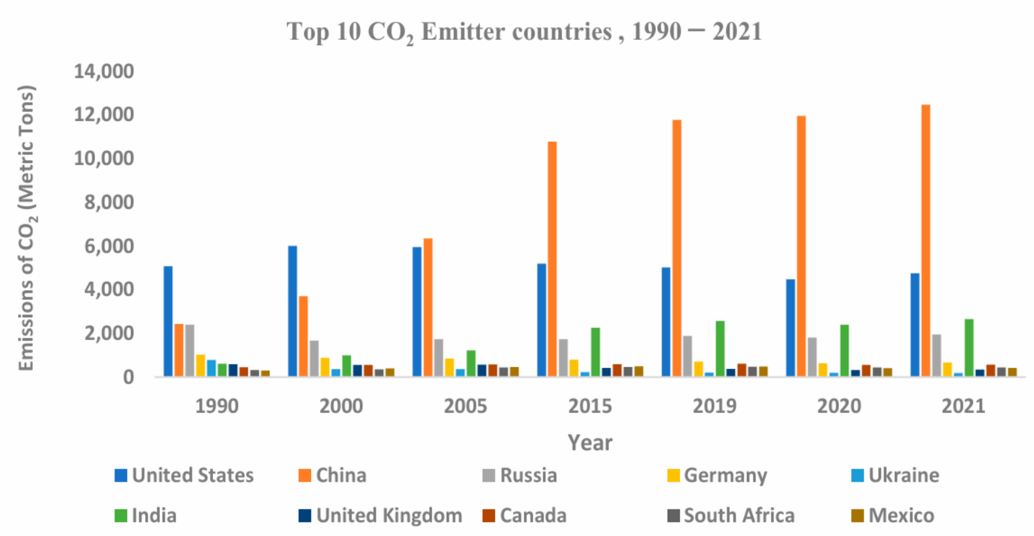


Figure 1. Statistical representation of the top 10 largest CO_2-emitting countries in the world from 1990 to 2021 [4].

The Global Atmospheric Research Database data reveal that the emission of CO2 in the world was 33.4 billion tonnes in 2011, 48 percent more than it was in the 1990s. This increase has taken the atmospheric level of CO2 to an unprecedented high of 400 ppm by May 2013 due to the growth in global surface temperature of about 0.8°C [5,6,7]. The disruption of the COVID-19 pandemic saw the global decrease in CO2 emissions of 5.3% (2.4 billion tonnes) in 2020 versus 2019 [8,9], the greatest of which is transportation [10]. This recession did not last long, though. In 2021, the recovery of emissions was 5.3% to 37.86 Gt CO2, which is almost the same level as before the pandemic [8], as shown in Figures 2 and 3.

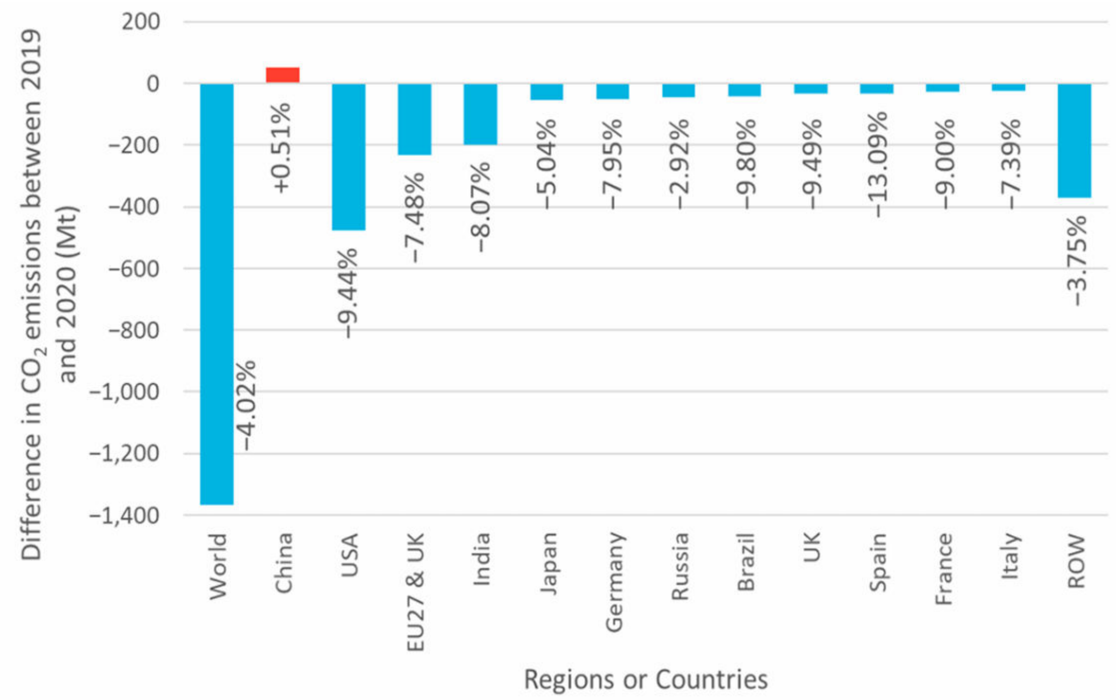


Figure 2. Differences in countries' CO_2 emissions in 2019 and 2020 (ROW = rest of the world) (from [11]).

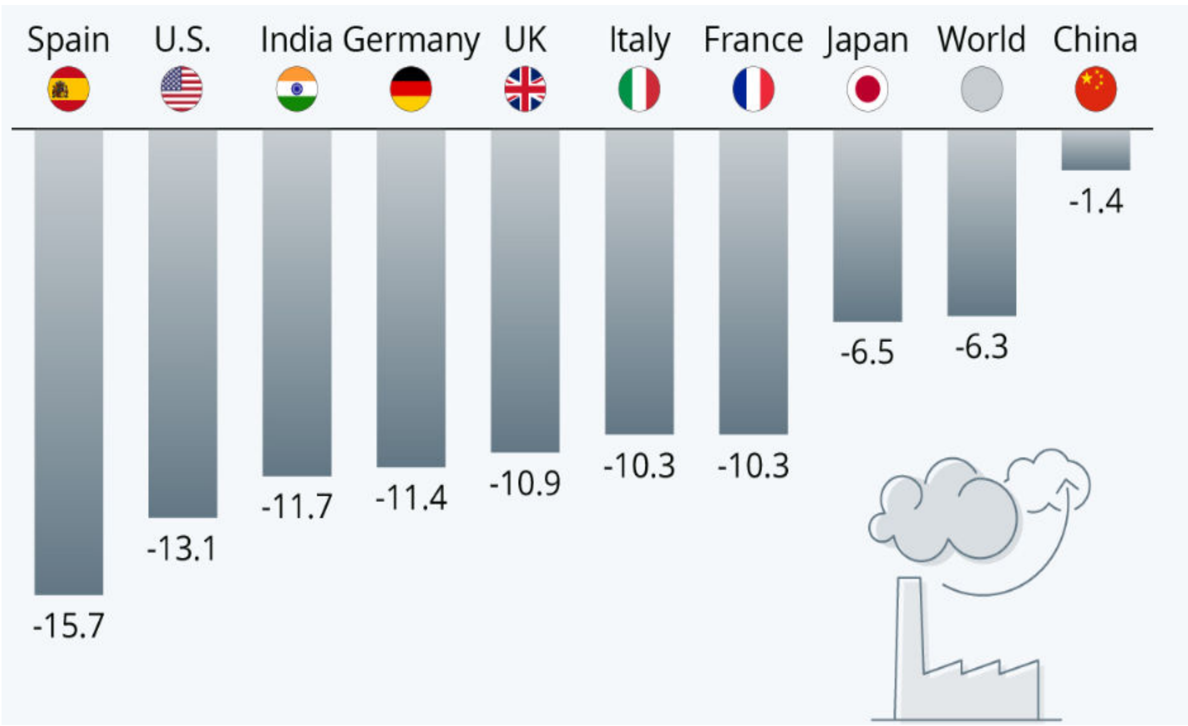


Figure 3. Chart of global emissions fall in 2020 with respect to 2019 (in Gt) (from [12]).

This fast recovery points to the strength of fossil fuel-based systems. China, the US, the EU27, India, Russia, and Japan, which account for 62.4% of the world GDP and two-thirds of fossil fuel consumption, were the top emitters in 2021 [8]. Whereas the emissions of the EU27 were 27.3 percent less than in the 1990s, other countries such as India and Russia experienced high growth of 10.5% and 8.1 percent, respectively [8]. Australia was the only country that reduced emissions by 2.4%, and Brazil had a growth of about 11.0% [8, 13, 14]. International aviation emissions returned to 2/3 of pre-pandemic levels after a two-thirds reduction in 2020, and international shipping emissions rose by about 2.2 percent above the beginning of 2019 [15, 16, 17, 18, 19]. The continued existence of anthropogenic GHG emissions highlights a problematic issue: even though we are all aware of their harmful effects, fossil fuels will continue to be a major energy source in decades to come [20]. This makes it not only suitable but also necessary to come up with innovative strategies to reduce CO2 emission. The most promising ones include the CCS technologies [1, 21, 22, 23, 24]. The ambition of such technologies corresponds to the Paris Agreement aim to curb global warming to levels significantly below 2°C and ideally 1.5°C above the pre-industrial levels [25, 26, 27, 28, 29, 30, 31]. To accomplish it, net-zero carbon emissions have become a focal goal to balance the anthropogenic emissions with the GHG removal during the second half of the century [33, 34, 35]. Carbon capture and storage will become one of the technologies to play a role in this transition [36, 37]. It will collaborate with other policies, including increasing the use of low-carbon fuels, energy efficiency, the use of renewable energy, and geoengineering methods, such as afforestation [38, 39, 40]. Along with these methods, it is important that the existing greenhouse gases in our atmosphere be addressed. The significance of CCS has been explicitly emphasised by reputable organisations such as the Intergovernmental Panel on Climate Change (IPCC) as a key element to attain climate stability [41]. It is particularly so because of the frightening projections that suggest the possible warming of 1.0°C to 3.7°C, which requires all available mitigation instruments [42, 43]. Although there is a rich literature on CCS, this review stands out as a resource offering a holistic and coordinated view of the whole CCS value chain in the critical background of reaching net-zero emissions. Beyond a rare concentration on particular technologies, this work puts into place the most recent developments down the spectrum: on one end, new capture materials and logistics; on the other end, optimisation of geological storage in the subtleties. Moreover, we apply a crucial focus to the non-technical obstacles, such as economic, regulatory, and socio-political, which in most cases present the greatest impediments to mass adoption. This review would not only serve as a state-of-the-art snapshot but also welcome actionable insights and clear future directions to the researchers, industry stakeholders, and policymakers by incorporating recent case studies and the latest research, which would put CCS as an essential component of a range of climate mitigation strategies.

2. CO_2 CAPTURE TECHNOLOGIES

CCS technologies play a crucial role in reducing Scope 1 emissions from major point sources in the energy and industrial sectors when over 40% of total global CO_2 emissions are attributable to energy and industrial processes. This section presents a qualitative and quantitative analysis of three major options for capturing emissions. The subsequent subsections and Table 1 provide further details on the operating principles, recent developments, and specific challenges of each option, with an emphasis on comparative performance metrics that are required for techno-economic assessments and strategic plans to decarbonise industries.

Table 1. Comparative Analysis of Major CO_2 Capture Technologies.

Technology	TRL	Capture Efficiency (%)	Energy Penalty (GJ/tCO_2)	Cost ($\$/tCO_2$)	Key Advantages	Key Challenges
Post-Combustion (Amine Scrubbing)	9	85 - 90 [4, 44]	3.5 - 4.5 [45]	60 - 100 [45]	Retrofit to existing plants; handles low-pressure flue gas.	High energy penalty; solvent degradation.
Post-Combustion (Membrane)	6-7	82 - 88 [46, 47]	2.5 - 4.0 [48]	50 - 90 [48]	Modular; low operational complexity; no chemicals.	Sensitive to flue gas conditions (low pressure/concentration).
Post-Combustion (Cryogenic)	5-6	> 99 [49]	4.5 - 7.0 [49, 50]	70 - 120 [50]	High-purity CO_2; no chemical solvents.	Very high energy intensity; operational complexity (clogging).
Pre-Combustion (IGCC/Solvent)	8-9	85 - 95 [51, 52]	4.0 - 7.0 [45]	50 - 80 [45]	High-pressure, high-concentration stream; high efficiency.	High capital cost; complex integration; limited to new builds.
Direct Air Capture (DAC)	5-6	70 - 90 [54]	7.0 - 12.0 [55]	600 - 1000 (Current) [55, 56]	Location-independent; addresses legacy/diffuse emissions.	Extremely energy-intensive; very high costs; low concentration.

In spite of the potential of these capture technologies, their broad deployment is constrained by significant challenges. High capital costs, high energy expenditures (see energy penalties in Table 1) and regulatory hurdles are a handful of barriers that represent a challenge to large-scale implementation [45, 57, 58]. These challenges must be surmounted to improve the efficiency and commercial feasibility of CO_2 capture technologies. Carbon is able to be captured via capture technology in both pre-combustion and post-combustion processes. The process can be partitioned into chemical absorption and physical absorption stages (Figure 4).

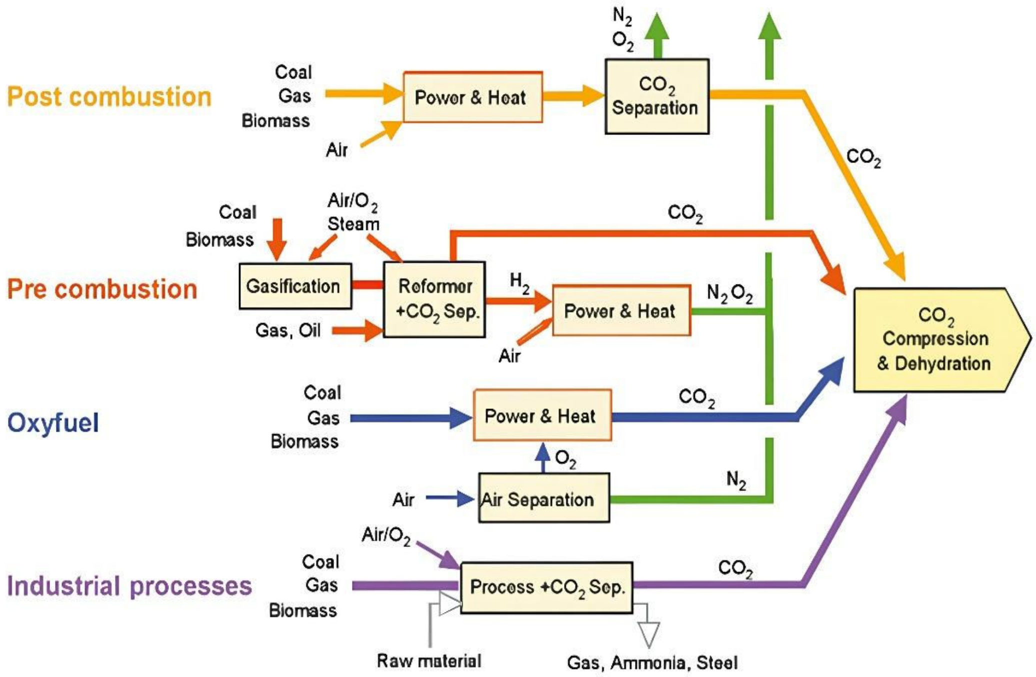


Figure 4. The process of CO_2 capture [59, 60, 61].

2.1. Post-Combustion Capture

Post-combustion capture (PCC) is a critical technology for lowering CO_2 emissions from fossil fuel burning, particularly in industrial processes and generation of power. The three leading methods of PCC are amine scrubbing, membrane separation, and cryogenic distillation.

2.1.1 Amine Scrubbing

The amine scrubbing methodology is recognised as a reliable approach to remove CO_2 from flue gases generated by combustors [63]. According to Ochedi et al. [63], this method utilises chemical absorption, indicated typically via the physical mechanism of flue gases containing CO_2 contacting a liquid mixture of amines (which are organic compounds derived from ammonia). Boakye [64] posits that the amines interact on a chemical level with CO_2 in the form of carbamate intermediates, effectively "trapping" the CO_2 within the liquid. Alivand [65] went on to point out that the CO_2 is then separated from the liquid by heating the solution to allow the amine solution to regenerate and reuse this process. Amine scrubbing uses a solvent such as monoethanolamine (MEA) or diethanolamine (DEA). Because of its commercial application (TRL 9), amine scrubbing is capable of high capture efficiencies (85-90%) but requires significant energy to regenerate the solvent and represents a significant portion of the capture costs (\$60-100/tCO_2) of 3.5-4.5 GJ/tCO_2 (see Table 1; [45, 66]) (Figure 5).

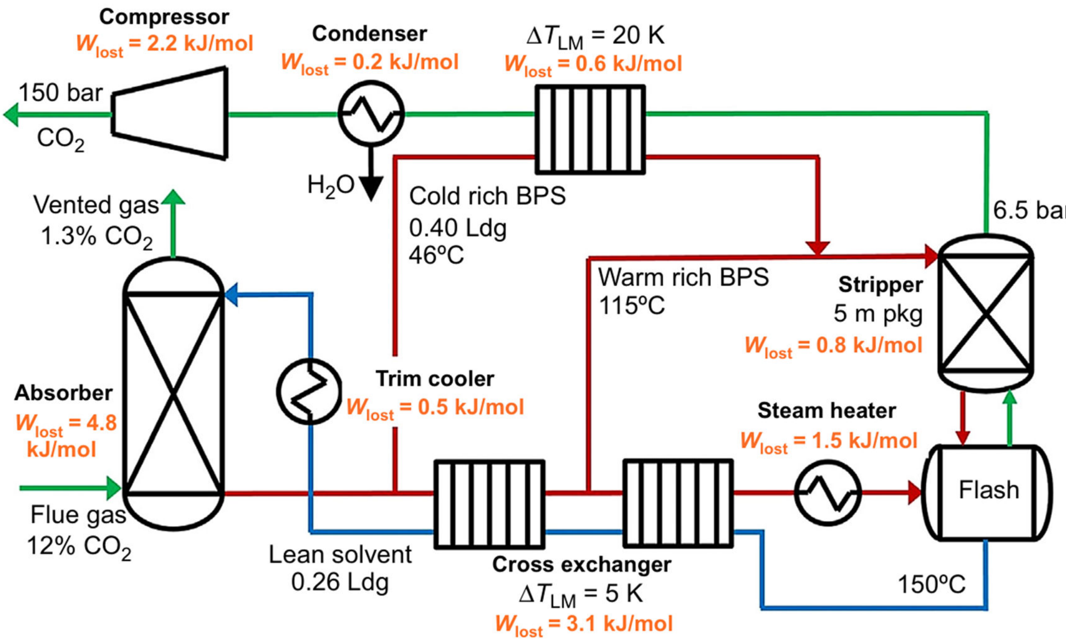


Figure 5. Schematic diagram of conventional amine scrubbing for CO_2 capture [44].

Recent advancements have focused on enhancing the performance of amine-based solvents. Researchers have developed new formulations that reduce solvent degradation and improve CO_2 absorption rates. Innovations such as the chilled ammonia process (CAP) operate at lower temperatures and minimise ammonia slip, thereby enhancing CO_2 capture efficiency while reducing operational costs [4, 44, 61]. In addition, advanced nanomaterials, including nanofluids and nano-emulsions, are being explored to further enhance the absorption capacity of traditional amines, leading to significant improvements in overall capture efficiency [4].

Amines are compounds derived from ammonia, where an organic group takes the place of at least one hydrogen atom. Among the several amine solvents that have been utilised in the natural gas industry over the past few decades are monoethanolamine (MEA), diethanolamine (DEA), and methyldiethanolamine (MDEA), demonstrating their potential for CO_2 capture. Thus, they are attractive candidates for technologies that capture carbon [65, 67, 68].

The amine-based absorption CO_2 capture process follows specific chemical reactions as shown in Equations (1) and (2), in which R stands for the alkanol group. The amine functions as a weak base in this reaction, neutralising acidic CO_2 to create carbamate (R-NHCOO⁻) via Reaction (1). This carbamate can further convert to bicarbonate, as shown in the reaction when moisture is present (2) [69]:

a) $2R-NH_2 + CO_2 \rightarrow R-NHCOO^- + R-NH_3^+ + heat$ (1)

b) $R-NHCOO^- + H_2O \rightarrow R-NH_2 + HCO_3^-$ (2)

The majority of the absorbed CO_2, according to this mechanism, results in the production of bicarbonate. In the liquid amine capture system, raising the temperature or lowering the solution's pressure can weaken the bond between the absorbent and CO_2. This process facilitates the extraction of CO_2 from the liquid amine solvent and releases it into a stream of water, renewing the solvent for future use [66].

Despite its effectiveness, conventional amine-based solvents face challenges, including reduced absorption rates, slower reactivity rates, and significant energy requirements for solvent regeneration. Nonporous hyper-cross-linked polymeric (HCP) networks have been found to be viable CO_2 absorption rate promoters to overcome these constraints. These networks can significantly enhance CO_2 capture when used in conjunction with N-methyldiethanolamine (MDEA) sorbents [70]. Researchers synthesised two types of HCPs to make a new slurry solvent. These are polystyrene (HCP-S) and benzene (HCP-B) that were made from inexpensive monomers and suspended in MDEA solutions. According to Peu *et al.* [4], the CO_2 absorption rates in MDEA solutions rose by 130% and 253%, respectively, when HCP-B and HCP-S were added.

2.1.2. Membrane Separation

Membrane separation technologies are increasingly acknowledged as a viable substitute for conventional absorption techniques in the capture of CO_2, primarily due to their eco-friendliness and energy efficiency [58]. These technologies use selectively permeable membranes, which let only CO_2 flow through while keeping out other flue gas components to efficiently separate CO_2 from other gases in flue streams (Figure 6). The membrane itself, which is usually made of a composite polymer, is the central element of this procedure. A thicker, non-selective, and reasonably priced layer that offers mechanical support is bonded to a thin selective layer in this composite [71].

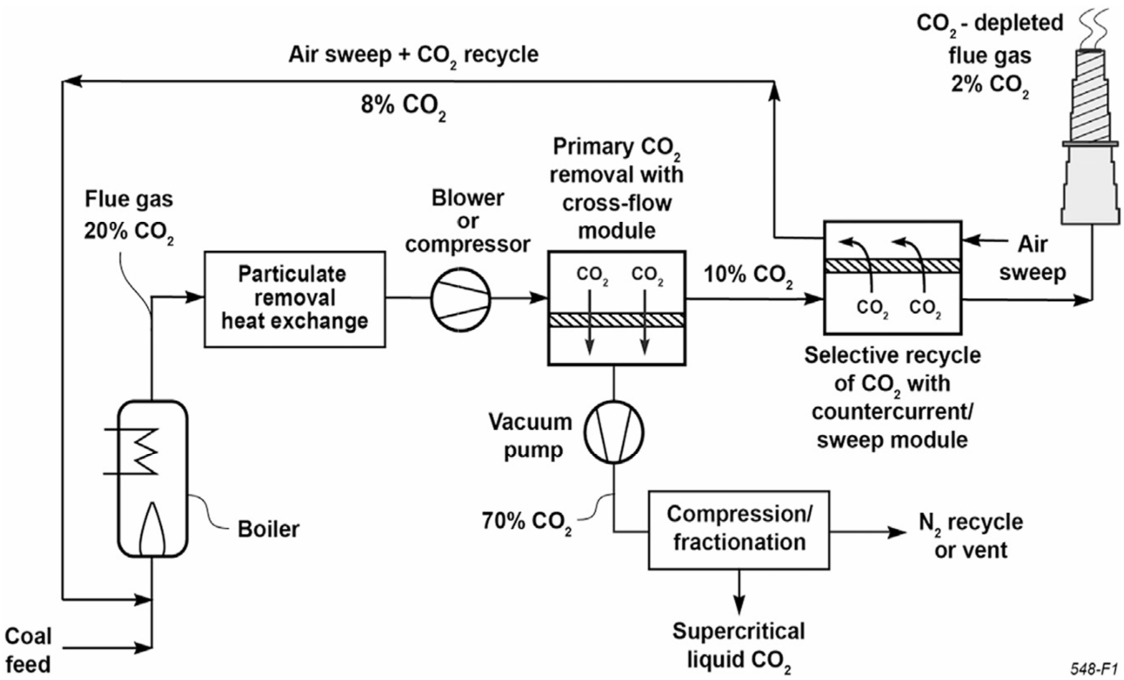


Figure 6. Schematic representation of membrane post-combustion CO_2 capture process with selective CO_2 recycle stream [72, 73].

Membrane separation has also been effectively used to separate other gases, including CO_2 from natural gas and O_2 from N_2. Notably, advancements in membrane technology have led to CO_2 separation efficiencies ranging from 82% to 88% [46, 47]. Various types of membranes, including ceramic, metallic, and polymeric, are being developed to achieve higher efficiency of CO_2 separation in contrast to conventional liquid absorption methods [74, 75].

A thorough analysis of contemporary membrane-based CO_2 separation technologies was presented by Brunetti *et al.* [48], who also contrasted them with alternative techniques like adsorption and cryogenics. They also found out that flue gas conditions, especially low CO_2 concentrations and pressures, have a big impact on membrane system performance and present significant obstacles to the use of this technology. Additionally, Bernardo *et al.* [76] highlighted that despite significant advancements in gas separation membrane systems, there remains a considerable gap in realising their full potential.

Recent studies have been centred on creating mixed-matrix membranes (MMMs), which blend inorganic fillers and polymeric components to enhance CO_2 selectivity and [50, 61]. The integration of these novel membrane materials has demonstrated potential for achieving higher capture efficiencies compared to conventional membranes. Furthermore, ongoing advancements in membrane design and configuration are addressing challenges related to low flue gas pressures and enhancing mechanical stability under operational conditions [58].

2.1.3. Cryogenic Distillation

Cryogenic distillation is an advanced method for post-combustion CO_2 capture that utilises low-temperature physics to achieve effective separation of CO_2 from flue gases [77]. Figure 7 shows that this technique involves cooling flue gases to temperatures below 120 K, which condenses CO_2 into a liquid phase, allowing for its separation from other gas components [78]. A significant advantage of cryogenic distillation is its ability to produce high-purity CO_2 streams, which are crucial for subsequent applications such as enhanced oil recovery and various carbon utilisation processes [49].

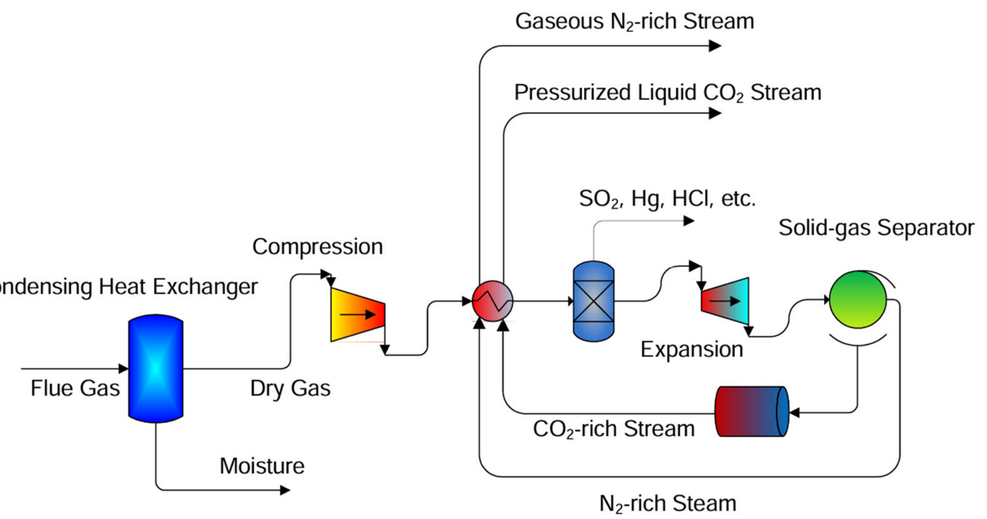


Figure 7. Simple schematic diagram of the cryogenic carbon capture (CCC) process [79].

Nonetheless, cryogenic distillation requires considerable energy, with a substantial energy penalty typically between 4.5 and 7.0 GJ/tCO2, proportionately from the cooling overhead and the high pressure needed to avoid generating solid CO2, which can clog equipment and complicate operations [50, 58], resulting in the technology not being yet widespread on a commercial basis, at an estimated cost of $70-120/tCO2 (see Table 1); hence, many sites are still using traditional technologies such as amine scrubbing.

Recent advancements in cryogenic distillation technology are aimed at enhancing energy efficiency through process optimisation and integration with existing power generation systems [80, 81]. Researchers are investigating hybrid systems that combine cryogenic distillation with other technologies of capturing carbon, like membrane separation and pressure swing adsorption (PSA). These hybrid approaches seek to improve overall performance, lower operating expenses, and lessen the energy requirements related to cryogenic procedures [49, 78, 82, 83].

Moreover, it has been suggested that integrating cryogenic carbon capture with oxy-combustion processes can create an optimal environment for CO_2 purification, as the flue gas produced in such systems is already enriched in CO_2, facilitating more efficient separation [84, 85, 86, 87, 88]. Ongoing research is necessary in addressing energy consumption challenges and operational complexity, thereby optimising the broader adoption of cryogenic distillation in combating climate change [89, 90].

2.2. Pre-Combustion Carbon Capture

Pre-combustion carbon capture (PCC) is a crucial technology that extracts CO_2 from fossil or biomass fuels before combustion, primarily used in processes that gasify these fuels to generate syngas, which contains mostly hydrogen, carbon monoxide, and carbon dioxide [51, 52, 91, 92, 93], as seen in Figure 8. The PCC process typically removes CO_2 from syngas before it is burnt in turbines for electricity generation [51, 94, 95, 96]. This is performed through water-gas shift (WGS) processes, which transform carbon monoxide into additional CO_2, thereby increasing the density of CO_2 and enhancing capture efficiency [52, 97, 98].

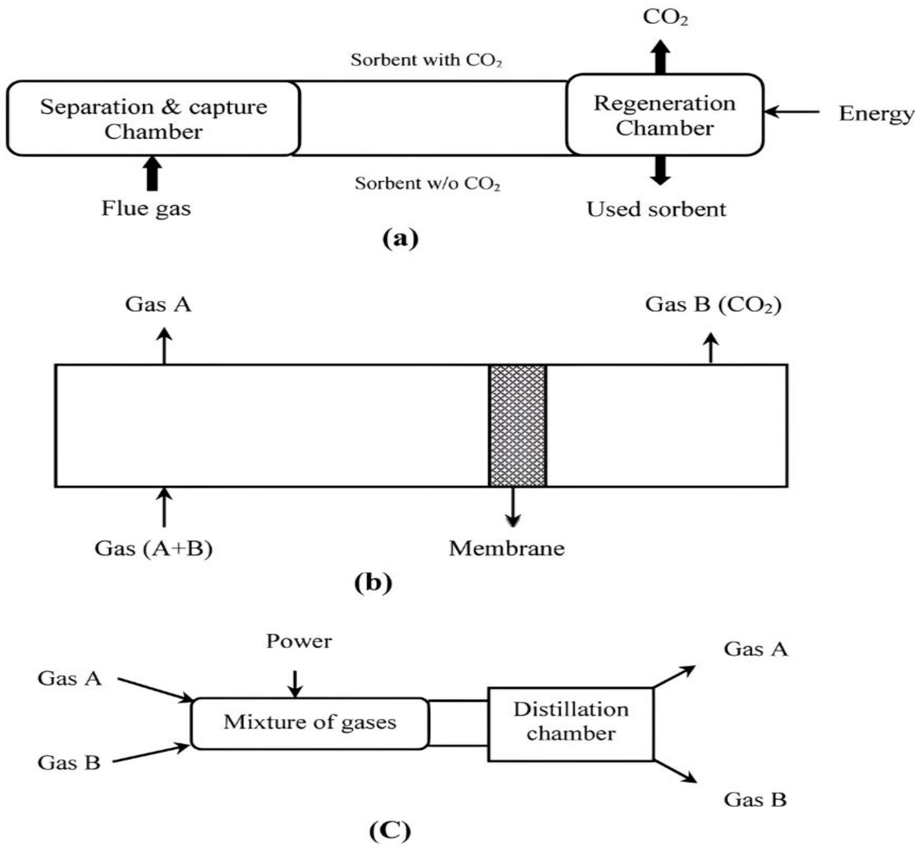


Figure 8. (a) Using a sorbent or solvent to separate carbon dioxide (CO_2). (b) The separation of membranes. (c) Cryogenic/refrigerated separation [99].

PCC can be categorised into four main areas of post-combustion capture: solvent-based, sorbent-based, membrane-based, and innovative approaches [52]. In solvent and sorbent capture processes, CO_2 is extracted from flue gas using either liquid or solid sorbents. After that, the sorbent is heated to regenerate it, allowing the trapped CO_2 to be transported and stored [100]. Various regeneration techniques are employed, such as pressure swing adsorption (PSA), temperature swing adsorption (TSA), and even vacuum swing adsorption (VSA) [101].

Commercially available sorbents include liquid sorbents, solid regenerable sorbents, and both physical and chemical adsorbents [74, 102]. The integration of these CO_2 separation processes with advanced technologies, such as Integrated Gasification Combined Cycle (IGCC) systems, is pivotal for reducing CO_2 emissions in energy generation. This integration enhances the overall efficiency and effectiveness of carbon capture strategies in the fight against climate change.

2.2.1. Integrated Gasification Combined Cycle (IGCC)

An important development in coal-based power production is the Integrated Gasification Combined Cycle (IGCC) method. It effectively combines gasification and combined cycle technologies to enhance efficiency and reduce environmental impacts [103, 104]. In this system, coal is converted into syngas through a gasification process involving reactions using steam and oxygen at high temperatures.

The resultant syngas, which is mostly made up of carbon monoxide and hydrogen, is cleaned and utilised to generate electricity in a gas turbine [105, 106, 107]. Steam is then created by recovering the gas turbine's waste heat. This created steam, then drives a steam turbine while maximising energy extraction from the fuel [108, 109, 110], as seen in Figure 9.

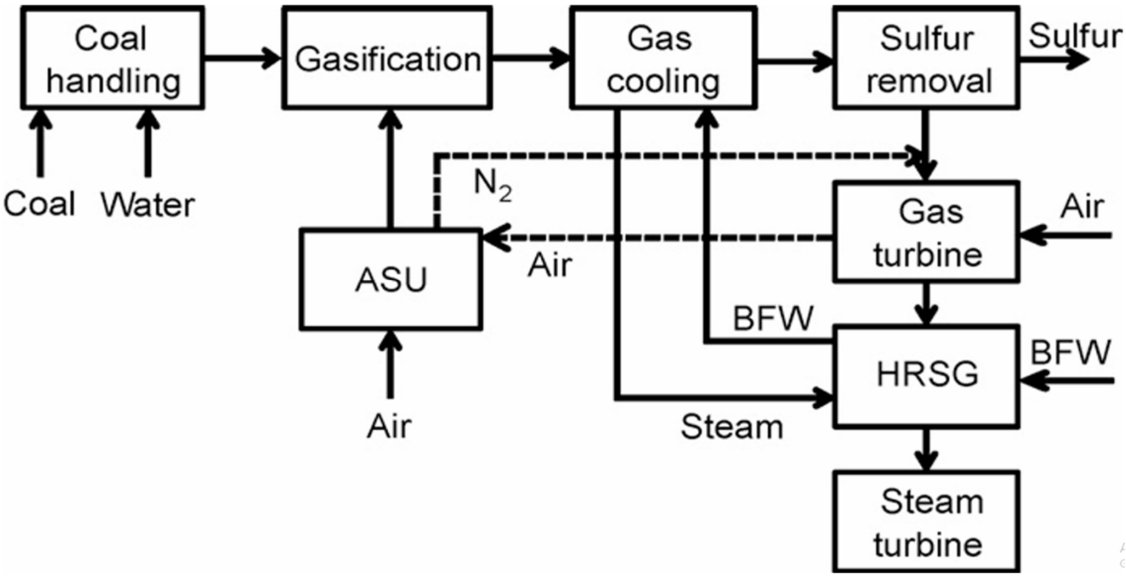


Figure 9. Simplified diagram for IGCC [110, 111, 112].

One of the primary benefits of the Integrated Gasification Combined Cycle (IGCC) process is that it can achieve thermal efficiencies of up to 45%, thus enhancing utilisation of coal resources and reducing GHG emissions [106, 113, 114]. Pre-combustion capture is possible due to the high concentration and pressure of CO_2 in the syngas stream, with capture efficiencies expected between 85% and 95%. The IGCC process has a significant energy penalty to address, with some estimates of 4.0-7.0 GJ/tCO_2, and costs are estimated between approximately $50-80/t$CO_2$ (see Table 1; [45]). This IGCC process also integrates components, such as units of air separation units (ASUs), gas cleaning systems, etc., for the general performance of the IGCC plant, which makes it a stronger design. Using pinch analysis to identify opportunities for heat integration into the process or capture can improve energy recovery and reduce costs associated with operational performance [115, 116, 117].

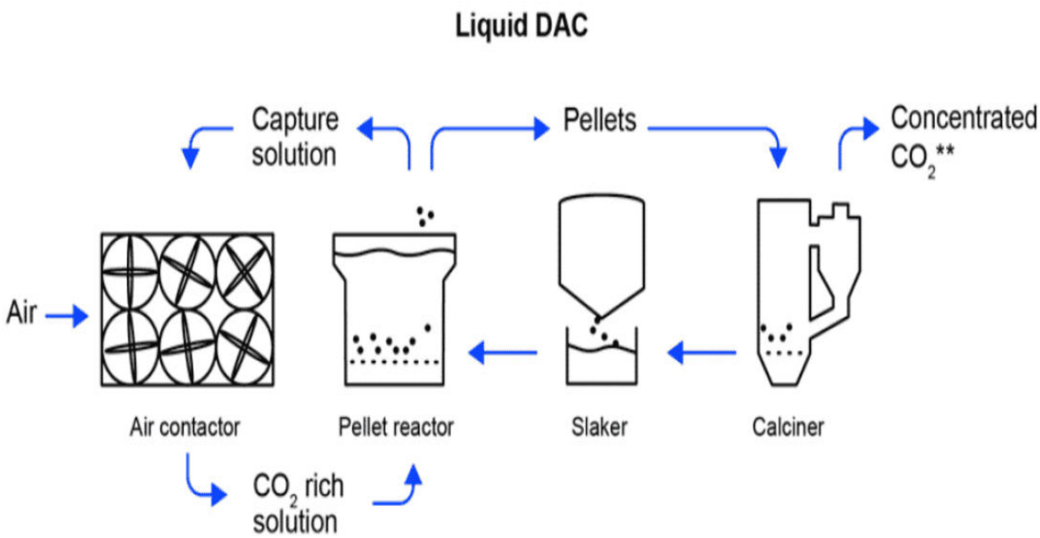
The IGCC process also addresses coal power generation environmental concerns, with the capability to capture and reduce emissions of CO_2 and SO_x. Studies indicate emission levels of 698 kg/MWh for CO_2 and 0.15 kg/MWh for SO_x, demonstrating compliance with stringent environmental regulations [118, 119, 120, 121]. With the growth in the demand for cleaner energy sources, IGCC presents a viable solution for sustainable coal utilisation, balancing lower emissions with economic competitiveness in the energy market [10, 106, 112].

Emerging technologies are also being explored to enhance pre-combustion capture, including advanced membrane technologies and novel absorbents for CO_2 separation during the water-gas shift reaction. Membrane separation offers potential for lower energy requirements and improved efficiency in capturing CO_2 from high-pressure gas mixtures [48, 123, 124, 125]. Research continues to optimise these membranes for better selectivity and permeability, potentially reducing carbon capture costs.

Additionally, oxy-fuel combustion technologies, which use nearly pure oxygen in place of air, simplify the capture process by producing flue gases primarily composed of water vapour and CO_2 [126, 127, 128]. Supercritical CO_2 cycles are attracting interest due to their potential to outperform traditional systems in terms of efficiency and emissions [72, 129, 130]. Notably, projects like NET Power's Allam cycle aim to leverage these advancements to create zero-emissions power generation solutions using natural gas [131, 132].

2.3. Direct Air Capture: Feasibility and Scalability for Ambient Air CO_2 Removal

DAC technology is designed to remove CO_2 straight from the surrounding air using two primary methods: systems based on liquid solvents and systems based on solid sorbents [133]. In sorbent-based systems, air is passed over a solid material coated with chemicals that selectively bind to CO_2 (Figure 10). To liberate the trapped CO_2, the sorbent is heated when it reaches saturation, allowing the material to be reused. In liquid solvent-based systems, air is bubbled through a liquid solvent that absorbs CO_2. Advanced DAC systems are also exploring innovative techniques such as electrochemical separation and high-capacity sorbents to enhance capture efficiency and lower costs [134].



- The capture solution reacts with the CO in the air to form a carbonate salt.
- The salt is separated into small pellets that are then heated in a calciner to release the CO in pure gas form.
- Processed pellets are hydrated in a slaker and recycled back into the capture solution.
  May include CO, captured from the energy used in the process as well as from the air.

Figure 10. Schematic Illustration of the Mode of Operation of Direct Air Capture [135].

This section evaluates the feasibility and scalability of DAC methods for airborne CO_2 removal, focusing on their operational characteristics, economic implications, and challenges. According to Erans *et al*. [55] and Bhatnagar [89]. DAC is inherently more energy-intensive than capturing CO_2 from concentrated sources like electricity plants because of the atmosphere's low CO_2 content (around 400 parts per million). This low concentration presents significant challenges for efficient capture.

Current DAC technologies include systems based on solid sorbents, systems based on liquid solvents, and emerging methods like electrochemical DAC and membrane technologies. Each approach has varying degrees of capture efficiency and operational requirements. For example, while liquid solvent systems usually reach 85-90% capture efficiency, solid sorbent systems can reach 70-90% [53, 54, 136, 137, 138, 139, 140, 141, 142]. However, the immense energy required to move large volumes of air results in a prohibitive energy penalty of 7-12 GJ/tCO_2, which is the primary driver behind current costs of $600-1000/t$CO_2$ (see Table 1; [55,56]).

Scaling DAC technologies from pilot projects to widespread deployment faces several hurdles. High operational costs are a significant barrier, with estimates suggesting that capturing CO_2 could eventually fall below $100 per tonne with ongoing advancements [56]. However, current costs often exceed this benchmark, necessitating substantial investments in R and D in order to increase productivity and cut costs. The modular design of DAC systems allows for adaptability in size and capacity, enabling tailored solutions that can be mass-manufactured to meet varying demand levels. This scalability is crucial for integrating DAC into broader carbon management strategies [56, 143, 144].

The energy demands of DAC are considerable, making the choice of energy source vital for its sustainability. By using renewable energy sources like solar or wind, DAC systems can function in a way that is carbon-neutral or even carbon-negative [56]. However, the current dependence on fuels of fossil origin for energy in many DAC configurations raises concerns about their overall environmental impact. Innovations in energy management and integration of energy sources associated with low carbon are essential for enhancing the sustainability of DAC technologies.

Notwithstanding its promise, DAC technology has a number of issues that need to be resolved in order to reach its maximum potential:

a) High Operational Costs: The economic viability of DAC is hindered by high capital and operational costs, which need to be reduced through technological advancements and economies of scale.

b) Energy Intensity: The amount of energy needed to extract CO_2 from the surrounding air is significantly higher than that needed for point-source capture, necessitating improvements in energy efficiency.

c) Material Limitations: The effectiveness of different capture materials varies significantly under low CO_2 concentration conditions, requiring ongoing research into new materials that can enhance capture performance.

While direct air capture presents a viable way to remove CO_2 from ambient air, its feasibility and scalability depend on overcoming substantial technical and economic challenges. Continued innovation in technology and supportive policy frameworks will be critical to advancing DAC as a cornerstone of global climate strategies aimed at achieving net-zero emissions. Additionally, integrating DAC into existing infrastructure, such as traditional HVAC systems, may provide a pathway to enhance its deployment and effectiveness in urban environments [56].

3. TRANSPORT OF CAPTURED CO_2

The transport of carbon dioxide (CO_2) is an essential link in the CCS chain, connecting capture facilities to geological storage sites [145, 146]. As global CCS deployment scales, optimising this infrastructure becomes paramount. This section critically reviews the two primary large-scale transport methods: pipelines and ships. These methods are chosen for their economic advantage over alternatives like trucks, especially for volumes exceeding several million tonnes per year. The choice between them hinges on distance, volume, and geography, with pipelines typically favoured for continental-scale, high-volume transport and ships providing flexibility for intercontinental or regional "milk-run" logistics [147].

3.1. Pipeline transport

According to Adu et al. [148], the transport of a large volume of CO_2 using a pipeline is the most widespread approach, particularly in the context of enhanced oil recovery (EOR). For optimal transport, CO_2 is usually consolidated into the dense-phase or supercritical form (the critical point of CO_2 is 31°C and 73.8 bar), with CO_2 in the supercritical form displaying properties of both liquid and gas, resulting in a high density and a low viscosity that provides an efficient transport mechanism over a sufficiently long distance. Operating pressures are generally kept between 80 and 150 bar for maintaining CO_2 in dense phase while providing relatively low pumping/compression costs and, most importantly, lower corrosion risks than transporting CO_2 as a gas [149].

3.1.1. Transport Methods and Mechanisms

The transport of CO_2 can take place in a gaseous form, a dense phase liquid, or as a supercritical fluid. The supercritical form has been utilised in existing infrastructure, such as the Canyon Reef Carriers pipeline in the USA, which transports CO_2 over 800 km, because it has a relatively high density (~600-800 kg/m³), which minimises volumetric transport requirements, and a low viscosity, which helps to improve flow rates [150]. Some key considerations for engineering, as posited by Venter and van Eldik [151] and Skaugen et al. [152] include:

- Pressure Drop and Booster Stations: The frictional losses due to pressure along the pipeline should be modelled appropriately. When transporting CO_2 over long distances (>250 km), booster stations are often required at intermediate locations to help re-pressurise the CO_2; this additional pressure drop adds to both capital and operational costs. The loss of pressure will be influenced by the diameter of the pipeline, the flow rate of CO_2, topography, and the properties of the fluid itself.
- Temperature Maintenance: The temperature of the transport fluid (CO_2) must be maintained during transport to avoid phase change. To limit heat gain from the environment and to accommodate unwanted thermal expansion, pipelines will often be buried, insulated, and/or chilled inline to ensure stability and meet equipment specifications. Failure to manage your temperature will cause unwanted pressure spikes.
- Impurities: Impurities such as H_2S, SO_x, NO_x, water, and O_2 in the captured CO_2 stream can greatly influence the phase behaviour of the fluid, decrease the critical point, increase compression power, and facilitate corrosion, which will require more expensive materials (e.g., stainless steel cladding, etc.) and require purification before transport [149].

On the contrary, transport with sub-cooled liquid (below -20 degrees Celsius and 15-20bar) has begun to emerge as a possible alternative, particularly in colder weather and/or with high-quality insulation. It is able to offer energy savings of 10-20% for very long distances by decreasing the temperature, k. This option does require high-quality insulation and cooling capacity (see Figure 11).

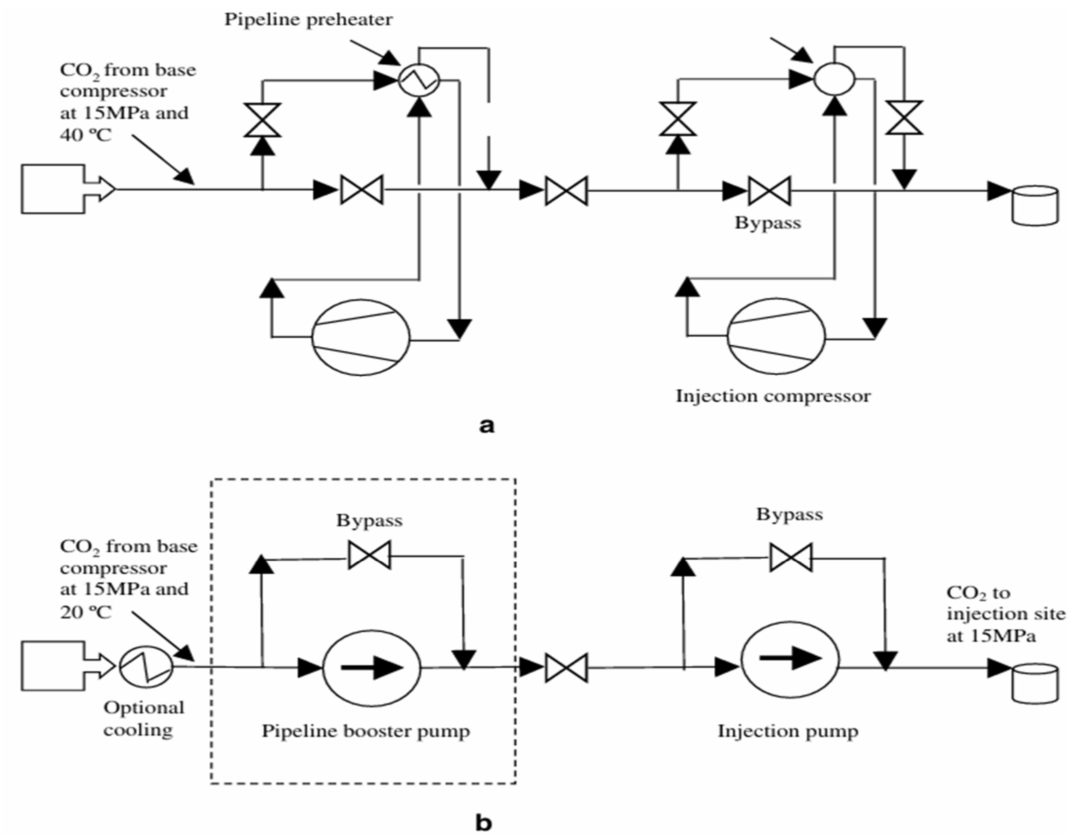


Figure 11. CO_2 transport schemes include (a) supercritical CO_2 transport using compressors and (b) liquid CO_2 transport with pumps [149].

3.1.2. Economic Considerations and System Optimization

The economic assessment of transporting CO_2 via pipeline is dependent on scale and distance. The primary driver is capital costs, which range from $0.5 to 2.5 million per km and vary significantly due to terrain, population density, and right-of-way-associated costs [153]. Operational costs, which include the cost of compressing the CO_2 energy use, monitoring, and other logistics, can range from $1 to $5 per tonne when the CO_2 is transported at a distance of 250 km. Since there is limited real-world data around operational costs for transporting the CO_2, some studies suggest that improving operating parameters such as temperature, pressure, and flow could improve overall system efficiency between 10 and 15% [154, 155]. However, standardised methodologies for collecting and analysing data around quantitative analysis need to be developed due to the variations in climate and transport whims associated with the sequestration [149].

3.1.3. Regulatory Framework and Safety Standards

CO_2 pipelines are constructed and operated within stringent regulatory requirements such as the ASME B31.4/31.8 in the United States of America and the European CO_2 Pipeline Directive, which categorise CO_2 pipelines according to the population density near the route. These regulations impose certain safety requirements to reduce the risk from hazards, primarily asphyxiation, in the case of a large-scale uncontrolled release through a rupture due to the colourless and odourless properties of the gas [156, 157]. It is important to comply with the governing regulations, including the selection of high-quality materials, the installation of leak detection systems such as mass-balance or acoustic sensing capabilities, and emergency response planning to ensure public safety and social licence to operate [149].

3.1.4. Future Prospects and Research Needs

Research going forward should develop advanced dynamic simulation models for accurately predicting transient flow behaviour and developing the optimal system. Additionally, low-cost, corrosion-resistant materials or possible new insulation could significantly improve the CO_2 transport efficiency and safety. Participation from academia, the industry, and the regulatory side will be critical to standardising practices and derisking the development of large-scale, integrated CO_2 transport infrastructure [149, 158].

3.2. Ship Transportation of Captured CO_2 for Sequestration

The option of shipping, when viewed for regions without pipeline infrastructure or where the distances to storage are transoceanic, provides a flexible and scalable option [158, 159]. In particular, shipping plays a key role when collecting CO_2 from many smaller emitters together for a "milk run" or "hub and spoke" approach, which allows the early days of CCS deployment without the capital cost of a pipeline network [147, 160].

Current developments have improved the viability of shipping liquid CO_2 (LCO_2). Pressurised, refrigerated vessels that operate with similar principles and conditions as the gas liquefaction ships (LPG) are already operational. These specialised vessels transport LCO_2 in the range of ~5-18 bar and temperatures between -28°C and -50°C. The Northern Lights project in Norway has contracted the construction of specialised vessels for LCO_2 with capacities around ~7500 m^3. Existing LPG vessels can be modified to transport LCO2, which is also a lower-cost, quicker step related to scaling up the transport industry [147]. It is important to highlight that shipping provides flexibility; however, there are costs and logistical issues with ship transportation. The capital costs of the specialised ship vessels are notably high (>$50 million per ship), and the liquefaction process is energy intensive (approximately ~100-200 kWh/t CO_2). When regional volumes are low, shipping can be significantly more expensive per tonne than transport via pipeline over shorter distances. Shipping costs can vary significantly, but estimates are that shipping will cost between ~$30 and $80 per tonne depending on distance, volume, and liquidification [147] and port logistics make the process of marine transport more complicated.

Safety procedures for transporting dangerous goods via ships are established by the LPG industry. Risks to safety consist of fast release (liquid-gas) and/or risk of asphyxiation while loading or unloading the ship. Utilising double-hulled ships and robust containment systems, alongside advanced monitoring systems and procedures developed by the International Maritime Organization (IMO) codes, minimises risks [161].

Developing low-pressure transportation and practical applications is a new field of research. To carry out lower pressures (<7bar) and lower-temperature transportation, design large ships that can operate safely while achieving major economies of scale ranging between 15 and 30% of transportation cost reductions. There is a global shift in commitment to the development of marine CO_2 logistics, as evidenced in Denmark's Project Greensand and associated research partnerships from Singapore to Australia and development alliances in other nations [147]. Thus, challenges exist, but ship transportation will continue to emerge as an enabling process of a future global CO_2 transport network via the ship to source and optimal storage locations across the globe.

4. CARBON SEQUESTRATION IN GEOLOGIC FORMATIONS

Alongside considerations of transport, options for geological storage are also vital to ensure that captured emissions can be sequestered for the long term [162, 163, 164, 165, 166, 167]. After capture and transport, CO_2 will need to be housed in geological formations so it does not return to the atmosphere [168, 169, 170]. The main geological storage options are deep saline aquifers, unmineable coal seams, basalt formations, depleted oil and gas reservoirs, and organic-rich shales [146, 171, 172, 173, 174, 175]). Each option has unique advantages and drawbacks regarding capacity, safety, and environmental impact. Key attributes of these formations are summarised in Table 2 to provide a concise comparative summary.

Table 2. Comparative Analysis of Primary Geological CO_2 Storage Formations.

Storage Formation	Global Storage Potential (Gt CO_2)	Key Trapping Mechanisms	TRL	Advantages	Key Challenges and Risks
Deep Saline Aquifers	1,000 - 10,000+ [59, 176]	Structural, Residual, Solubility, Mineral	7-9	Largest capacity; widespread.	Less characterised; potential for pressure buildup.
Depleted Oil and Gas Reservoirs	675 - 900 [177]	Structural, Residual	9	Proven seal; existing infrastructure.	Limited capacity; integrity of old wells.
Unmineable Coal Seams	3 - 200 [170]	Adsorption	5-6	Enhanced Coalbed Methane (ECBM) revenue.	Low injectivity; coal swelling.
Basalt Formations	953 – 2,470 [178]	Mineral Trapping (Fast)	4-5	Permanent mineralisation.	Limited site availability.
Deep Ocean Storage	~10,000 [59]	Solubility, Hydrate Formation	3-4	Immense theoretical capacity.	Major ecological risks; international moratoria.
Ignimbrites	Under Evaluation	Mineral Trapping	3-4	High reactivity; potential for rapid carbonation.	Poorly understood; limited exploration.

The effective implementation of CO_2 sequestration is dependent on a mechanism for trapping carbon dioxide that occurs over various timescales. In the first few weeks to months, structural and stratigraphic trapping contain the CO_2 plume beneath a sealing caprock; afterwards, within the first weeks to years, capillary forces can trap residual CO_2 in pore spaces (residual trapping), and CO_2 can dissolve into the formation brine (solubility trapping); over centuries, the CO_2 can react with the rock to produce stable carbonate minerals (mineral trapping), providing the greatest degree of permanent containment.

4.1. Geologic Formations

4.1.1. Saline Aquifers

Saline aquifers refer to porous geological structures filled with brine and are regarded as one of the most desirable options for CO_2 storage due to their high capacity, with theoretical estimates suggesting they might hold between 150 and 1,500 gigatons (Gt) of CO_2 in Western Europe alone [179]. They are an attractive option for large sources of CO_2, as they are more likely to exist in landlocked, onshore, or offshore regions while also possessing the highest potential for sequestration of CO_2 in terms of volume and permanence [162, 163, 164, 165]. The effectiveness of saline aquifers relies on many factors, including porosity (generally 5-30%), permeability (generally 10-1000 millidarcies), and the integrity of the caprock seals. One technical issue is that if the pressure buildup is not properly managed, the increased pore pressure can easily induce caprock failure due to fracturing. The technology to inject CO_2 into deep saline aquifers already exists and will be the simplest to implement [180, 181, 182, 183].

In addition, the potential for unintended CO_2 leakage, or undesired almost-accidental expulsion to the atmosphere, from saline aquifers is typically low when geological assessment is adequately considered. Studies have indicated that many saline aquifers have strong caprock formations that can seal CO_2 over long periods [184]. For example, a study of saline aquifers in Nigeria showed strong lateral continuity and thickness, indicating a significant capacity for CO_2 storage and very low leakage potential due to trustworthy sealing layers [184, 185, 186]. However, it is complicated by several uncertainties surrounding the actual capacity due to variability in geological properties and lack of data at sites, which has inherent risks. Therefore, it is important that organisations seeking to store CO_2 in saline aquifers make efforts to characterise the saline aquifers. The more one can characterise, the more confident one is in knowing the formation can hold CO_2 in the long term.

4.1.2. Depleted Oil and Gas Reservoirs

Depleted oil and gas formations are likely the most feasible asset for carbon dioxide (CO_2) storage due to their existing infrastructure and demonstrated storage potential. These rock formations are capable of maintaining hydrocarbons over geological periods and are therefore ideal candidates for the long-term sequestration of CO_2. The benefit of using depleted reservoirs for CO_2 is that, with primary recovery, the reservoir may be re-pressurised by injecting CO_2, while the original gas removed from the reservoir is upwards of 95%. When CO_2 is injected into these reservoirs, enhanced oil recovery (EOR) may be possible, thus not only storing CO_2 but also capturing this CO_2 and increasing oil recovery. Existing infrastructure from oil and gas production may facilitate the use of the depleted oil and gas formations for CO_2 injection, rendering this an economically feasible option [180, 181, 187, 188].

Utilising CO_2 during EOR processes enables carbon sequestration and improved oil recovery efficiency. CO_2 behaves as a solvent, driven by its low surface tension, which lowers oil viscosity and interfacial tension, which could help displace oil remaining in place in the reservoir [189, 190, 191, 192, 193]. The pressure builds due to CO_2 injection, raising concern regarding the integrity of the seals, which could lead to leakage, which requires an effective monitoring and risk framework. While depleted reservoirs present a good storage option, they have some challenges associated with seal integrity. The injection of CO_2 can change the pressures in the reservoir, bringing into question the integrity of the existing seals and potentially creating pathways for reservoir leakage [173]. Therefore, effective monitoring strategies and risk assessments are necessary to ensure the CO_2 is safely contained in these formations [187].

4.1.3. Deep Ocean Storage

Deep ocean storage entails the pumping of captured CO_2 into the deep oceans, typically more than 1,000 metres below sea level. Due to the pressure at these depths being far greater than norms, CO_2 can exist as a liquid or supercritical substance, which reduces the volume and increases the solubility of CO_2 in saltwater. This method takes advantage of the inherent ability of oceans to take on CO_2 and can store large quantities of carbon while reducing the emissions to the atmosphere. Additionally, the capacity of the ocean is vast, and estimates suggest oceans could contain several thousand gigatons of CO_2 [173, 194]. Importantly, the thermal and pressure environments found in the deep ocean create a natural containment barrier for injected CO_2, reducing the risk of release [195, 196].

Nevertheless, deep ocean storage does have challenges and concerns that need to be addressed. The environmental consequences of increasing concentrations of CO_2 in oceans are uncertain, and impacts could include ocean acidification and harm to marine organisms [173, 194]. Additionally, demonstrating that injected CO_2 will remain stored is a challenge that requires comprehensive monitoring to detect leaks or changes to the environment [194,195].

4.1.4. In Situ Carbonation

In situ carbonation is a process that enhances natural weathering reactions to permanently sequester CO_2 by converting it into stable solid carbonate minerals, such as calcite ($CaCO_3$) and magnesite ($MgCO_3$) [197, 198]. This approach provides long-term security for stored carbon with minimal risk of re-release to the atmosphere, as the CO_2 is bound in a chemically stable mineral form.

The process is most effective in mafic and ultramafic rocks, which are rich in calcium and magnesium silicates (e.g., olivine and pyroxene) that readily react with CO_2. By injecting carbon dioxide into these geological formations, the inherent minerals react to form carbonates, effectively locking the carbon away. This enhanced natural process offers a significant alternative to ex-situ mineral carbonation [198].

Several rock types show promise for this technology:

- Basalt formations have demonstrated successful CO_2 mineralisation in pilot projects, offering vast storage potential in stable mineral forms.
- Peridotite, the mantle-derived rock that is the source of olivine, undergoes natural carbonation and is a prime target for enhanced in situ methods.
- Ignimbrites (volcanic rocks from pyroclastic flows) are also being evaluated for their high reactivity, though research is still in early stages [199].

A significant advantage of in-situ carbonation is the potential to utilise silicate-rich industrial byproducts or waste materials, thereby contributing to both carbon capture and waste management [200, 201]. Despite its promise, the technology faces hurdles. The natural carbonation process can be slow, requiring substantial time to mineralise even modest amounts of CO_2 without enhancement [203, 204]. Furthermore, the necessity of locating and assessing suitable geological formations with the right chemical composition and permeability narrows its widespread applicability [204, 205]. Consequently, while each rock type presents a unique set of benefits, significant research and development are needed to fully realise the potential of in-situ carbonation as a major tool in climate change mitigation.

4.2. Ensuring Optimum Geological Formation Storage of CO_2

A number of key factors must be considered and optimised at the planning, implementation, and monitoring stages to achieve safe and efficient geological storage of CO_2. A comprehensive site characterisation is important and begins with robust geological characterisation to assess the characteristics of potential storage sites. This site characterisation includes the lithology, stratigraphy, and structural geology to identify formations associated with low permeability and high porosity, both of which are necessary for effective CO_2 trapping [206, 207]. Hydrogeological studies should also be undertaken to understand the hydrodynamic regime of the formation waters, including pressure, temperature, and fluid flow, to help in predicting how the CO_2 is likely to behave after injection and whether it will remain contained [208]. Geochemical considerations are also important, as they will help evaluate mineralisation potential and reactivity of CO_2 with surrounding rock. This consideration will guide our predictions about the stability of long-term storage and the possibility of leakage [209].

Choosing appropriate geological formations is another important item to achieve optimum storage of CO_2. Selecting mature sedimentary basins with hydrocarbon production are better geological formations to store CO_2 because these basins already have existing structures for CO_2 injection [210, 211]. Sedimentary basins contain cap rocks (or seals), which are suitable for CO_2 storage. Specific areas within geological formations where cap rocks cannot be influenced geologically preferentially have lower cap rock sealing. Another consideration is to ensure the geological formations or captured CO_2 are not located in tectonically active areas; geologically stable formations can be contacted to minimise the risk of unintentional escaped CO_2 based on geological dynamics [174, 212]. Improving the injection technique is also central to CO_2 storage success. Injecting CO_2 at controlled and equitable rates helps reduce pressure forces acting on the formation of cap rock fracturing failure of sealing CO_2 into the geological storage site. Targeting zones of sufficient energy of permeability increases the efficiency of storage by the CO_2 graphing less momentum of storage within the formation. Pressure events still happen within high levels of energy, while limiting storage of CO_2 into areas of low-pressure-related events as soon as possible [213, 214, 215].

The monitoring and verification component is key for assuring the geologic integrity of CO_2 storage. In addition, monitoring systems also must be set up to track how the stored CO_2 behaves in the geologic formation. The monitoring must consist of multiple monitoring techniques such as seismic surveys, pressure sensing, and geochemistry sampling to observe potential changes in the geologic formation indicative of leakage and CO_2 migration [35, 216, 217]. Once the CO_2 is stored deep underground, it is extremely important to establish long-term monitoring protocols for the monitoring of the geologic formation's intactness over the long-term storage period. In addition, the periodic monitoring of the stored CO_2 as well as the geologic formations and surrounding environments, must be performed to demonstrate that it remains securely contained.

Risk assessment of CO_2 storage is necessary to recognise any hazards the operation presents regarding CO_2 leakage, pressure buildups, and environmental effects. Risk assessment information is also very useful in developing the mitigation strategies for the aforementioned hazards. Additionally, contingency plans should also be developed to address unanticipated CO_2 leakage or other unforeseen issues. The contingency plan must establish a protocol for prompt response for all identified CO_2 leak scenarios and remediation to minimise environmental complications and public safety [218, 219, 220, 221, 222, 223].

The compliance with regulations and engaging with the community are therefore significant factors for success in CO_2 storage practices. The process of securing any necessary permits and undertaking an environmental impact assessment is critical for adherence to local, national, and international regulations regarding CO_2 storage. Involving a stakeholder input and having open communication with local communities facilitates trust and addresses CO_2 storage concerns. Public participation, along with stakeholder involvement, increases accountability and support for CO_2 sequestration initiatives [224, 225, 226]). Collectively set forth, these practices will allow the operator to maximise the geological storage of CO_2 and achieve long-term storage while limiting the effects of nature on that storage. Through a systematic approach involving detailed site characterisation, appropriate site selection, effective injection techniques, monitoring, and community engagement to improve safety and efficacy, it can create a holistic approach to adopting CO_2 sequestration efforts. This system is essential for promoting geological storage as a climate change mitigation measure and achieving sustainability aspirations.

5. ARTIFICIAL INTELLIGENCE AND MACHINE LEARNING IN CCS

Khalil et al. [227] noted that the global CCS enterprise is a complicated and large undertaking that requires sophisticated tools for optimising, predicting, and integrating. AI and ML are increasingly being considered breakthrough technologies across the entire CCS value chain [228, 229]. Here we review the growing use of AI/ML to improve the efficiency, safety, and speed of deploying CCS technologies.

5.1. Process Optimization in Capture

Aigbedion et al. [230] posit that the CO_2 capture process is one of the most energy-demanding operations, and as such, it is an excellent opportunity for AI and models to assist in optimisation. For example, ML models or algorithms such as Extreme Learning Machine (ELM) and Gradient Tree Boosting (GTB) can be trained on large operational datasets obtained from CO_2 capture pilot and commercial plants to learn optimal controllable parameters in order to minimise energy usage (on the energy intensity of CO_2 removal) while maximising CO_2 capture [231, 232, 228]. One example would be for reinforcement learning algorithms, where the model learns to generate real-time control recommendations to control amine scrubbing units based on changing flue gas chemistry and emissions [223]. The model could then adjust controllable parameters such as solvent flow rate, stripper temperature, or stripping time, amongst other parameters, to develop control algorithms as the flue gas conditions change to reduce the process energy penalty by 10-20% [234, 235]. This approach could also reduce the time and laboratory effort in R&D of new capture materials. For example, ML models can also be trained on experimental data to predict a new solvent molecule's CO_2 absorption capacity, degradation rates, and other desirable properties or an advanced membrane's selectivities and permeabilities to develop great candidate materials to screen in the lab, effectively reducing years of R and D down to months [236]. An approach reliant on data to discover new materials would represent an important step to moving beyond trial-and-error-based approaches typical of materials science.

5.2. Site Selection, Monitoring, and Risk Management in Geological Storage

According to Li et al. [237], the safe geological storage of CO_2 requires solid site characterisation and monitoring for the long term, which is where AI can make a difference. ML algorithms have the capacity to combine diverse datasets, including seismic attributes, well logs, core samples, or geological maps, into high-resolution three-dimensional models of target storage formations [238]. These models also have the ability to forecast desirable properties such as porosity and permeability throughout the entire reservoir model to find the key injection "sweet spots" more quickly and accurately than conventional means [239,240].

As posited by Islam [241], once injection is complete, AI is now being employed to transform Monitoring, Verification, and Accounting (MVA). Ahmad [242] has also stated that deep learning models, and in particular convolutional neural networks (CNNs), can automatically analyse and interpret time-lapse (4D) seismic data as accurately as ever to observe and track where the CO_2 plume is going. These models are capable of identifying the plume's signature despite the background noise of the other time-lapse seismic data and can even predict where the plume will go [243]. AI can also aid risk assessment by generating hundreds or thousands of simulated scenarios that forecast leakage pathways through faults or abandoned wells. In this way, the reliability of predictions that rely on the ability to forecast long-term security of storage will improve.

5.3. Supply Chain Logistics and Policy Acceleration

Designing a robust CCS (carbon capture and storage) infrastructure requires logistical planning for the transport of CO_2 that involves complex considerations, creating various layers of logistical planning which can involve different levels of CO_2 transport [244]. Supply chain optimisation tools, utilising AI for this task, can comparatively model economical, low-emission pipeline and ship transport networks [245]. These models can develop the optimum pipeline routes and ship schedules and can also model hub locations, which all work to trade off capital costs and operating costs while providing reliable transport of CO_2 to various storage locations from various sources [246].

Infrastructure planning is not the only space that can benefit from AI, specifically through the lens of AI tools called Large Language Models (LLMs), in the current policy and regulatory landscape. Törnberg [274] posits that LLMs can be trained on massive corpora of legal documentation, scientific literature, and social sentiments on social media and the news. Thus, LLMs could facilitate the following support for policymakers:

a) Speeding the Regulatory Framework: Learning international standards for CCS policies to determine best practices and regulatory gaps.
b) Public Engagement: Engaging analysis of public concerns and perceptions can aid in informal communication strategies to improve social licence.
c) Permit Streamlining: Automating initial assessments of environmental impact assessments and permit applications can help decrease administrative delays.

AI and ML's contribution is therefore not just an upgrade but a revolution for CCS. Through improvements in operational efficiency, storage risk reduction, and logistics and policy optimisation across the system, AI acts as a strong accelerant needed to scale CCS sufficiently to meet global net-zero targets.

6. CHALLENGES AND OPPORTUNITIES

The results of numerous studies highlight how important CCS technologies are to solving the urgent problems caused by climate change. The Sleipner project in Norway, the Petra Nova project in Texas, the Snohvit fields in Norway, the Quest project in Alberta, Canada, and the Boundary Dam project in Canada, which was dubbed the world's first commercial post-combustion carbon capture system, are a few examples of CCS projects that have been successfully implemented. The best practices in site selection, risk assessment, monitoring methods, and sociopolitical support are highlighted in these projects. The viability of long-term geological storage has been demonstrated by the Sleipner project, the longest-running commercial CO_2 sequestration project, which has been in operation since 1996 and has stored over 1 million tonnes of CO2 yearly in a salty aquifer [248, 249]. In a similar vein, Pradoo *et al.* [250] assert that the Boundary Dam project, which combines CCS with coal-fired power generation, has not only decreased emissions but also offered important information about the CCS technologies' economic feasibility. These case studies illustrate that with proper planning and execution, CCS can greatly contribute to the reduction in the emissions of greenhouse gases.
However, to scale CCS from megatonnes to gigatonnes per year, which is the level required for climate mitigation, a complex array of technological, economic, and socio-political hurdles must be systematically addressed.

6.1. Technological Problems

Mitigating climate change requires the development of CCS technologies; however, a number of technological obstacles need to be overcome in order to increase their effectiveness, lower their prices, and use less energy. Current capture technologies, including DAC, absorption, adsorption, and membrane separation methods, face key limitations that hinder their widespread adoption.

One significant challenge is the efficiency of current capture technologies in CO_2 removal. Direct air capture systems often exhibit an efficiency of around 10% for many existing technologies, necessitating substantial improvements to make these systems economically viable at scale. In contrast, absorption technologies typically achieve capture efficiencies between 70% and 90%, although these efficiency values can vary significantly based on specific design and operational conditions [251]. The optimisation of systems that help to achieve higher efficiencies without incurring prohibitive costs remains a critical focus area.

Energy consumption is another critical factor influencing the viability of CCS technologies. The energy required to operate capture systems can lead to increased overall emissions if sourced from fossil fuels. For instance, some absorption processes have been reported to impose an energy penalty of CO_2 captured to the tune of approximately 5.75 GJ per tonne [252]. This energy demand not only raises operational costs but also diminishes the net climate benefit of capturing CO_2 from energy that is not from renewable sources. Therefore, enhancing the energy efficiency of capture technologies is essential for reducing their carbon footprint and improving their economic feasibility [253].

6.2. Economic viability

One of the foremost economic challenges that CCS is facing is the substantial initial investment required for capture technologies, transport infrastructure, and storage facilities. Current cost estimates indicate that capturing CO_2 can cost between $50 and $150 per tonne for processes dealing with gas streams that are diluted, such as those from power plants that are coal-fired [254]. Direct air capture technologies are even higher, ranging from $600 to $1,000 per tonne, with projections suggesting future costs may decrease to a range of $230 to $540 as technologies mature [255]. These costs are often prohibitive for many potential investors, particularly in sectors where profit margins are already tight. Furthermore, the ongoing operational costs associated with maintaining CCS systems can deter investment, especially when competing against other low-carbon technologies that may require less financial commitment.

Another significant barrier is the lack of reliable revenue streams for captured CO_2. While some facilities utilise CO_2 for enhanced oil recovery (EOR), which provides a short-term financial incentive, this approach is not universally applicable. Many potential CCS projects lack a clear business model that ensures profitability over time [256]. The uncertainty surrounding carbon pricing mechanisms further complicates investment decisions; fluctuations in carbon prices can create financial risks that dissuade stakeholders from committing resources to CCS initiatives [257, 258].

To overcome economic barriers, strong policy incentives are necessary. Governments worldwide are increasingly recognising the importance of supportive frameworks to promote private sector investment in CCS infrastructure. For example, Canada's Investment Tax Credit (CCUS-ITC) offers a 50% credit on capital costs for CO_2 capture projects, with even higher rates for direct air capture initiatives [259, 260, 261]. The Inflation Reduction Act in the United States has introduced significant changes to tax credits for carbon capture under Section 45Q, offering guaranteed incentives over ten years to encourage investment in large-scale CCS projects [260, 262, 263]. Such incentives provide long-term certainty regarding the financial viability of CCS projects, making them more appealing to investors.

6.3. Insufficient and Inconsistent Policy Hurdles

Even though the aforementioned projects have recorded massive success, carbon capture and storage technology implementation continues to face a complex interplay of economic and socio-political factors that significantly affects its effectiveness and acceptance [264, 265, 266]. One of the primary challenges is public perception. Misconceptions about the safety and efficacy of CCS continue to lead to resistance against projects. These are often fuelled by a lack of knowledge about the advantages of the technology [65, 267, 268]. According to Leiss and Larkin [269], engaging the public through transparent communication and educational initiatives is essential to foster trust and acceptance. Community involvement in the planning and monitoring processes can also enhance public support and address concerns related to environmental impacts.

Alizadeh *et al.* [270] and Nooraiepour [271] noted that the environment for the implementation of CCS is greatly influenced by legislative frameworks, and the lack of thorough and precise laws can create uncertainty for investors and stakeholders, thus hindering progress. Policymakers must therefore establish robust regulatory environments that not only incentivise investment but also ensure environmental protection and public safety.

Streamlining the permitting process and providing clear guidelines for CCS projects can facilitate faster deployment and reduce barriers to entry for new technologies. A major example of successfully implemented CCS regulatory frameworks that can be emulated is that of Australia, as captured in Dixon *et al.* [272].

The effective implementation of CCS technology is largely dependent on strong legislative and regulatory frameworks that offer crucial assistance and incentives for investment and innovation [272, 273]. International agreements and national policies are crucial in shaping the landscape for CCS development, guiding countries toward effective implementation strategies that align with their climate goals [84, 214, 272]. Understanding these frameworks is vital for evaluating how they can create an environment that is conducive for CCS adoption and address the challenges that lie ahead.

International agreements are essential to the creation and implementation of CCS technologies. The Paris Agreement emphasises the need for countries to implement measures that can prevent global warming from rising above 2°C, including using CCS as a practical way to cut greenhouse gas emissions [274, 275, 276, 277]. The agreement encourages nations to enhance their climate action plans, often incorporating CCS as a key component of their strategies to attain net-zero emissions by the middle of the century [268, 278, 279]. Additionally, frameworks like the Kyoto Protocol's Clean Development Mechanism (CDM) have historically facilitated investments in CCS projects by permitting wealthy countries to fund initiatives in developing ones to reduce emissions, fostering international collaborations and inclusivity [279, 280].

Financial incentives also play a crucial role in encouraging investment in CCS technologies. Subsidies, grants, and tax credits can greatly lessen the financial strain brought on by the high upfront costs of CCS projects. Incentives are sometimes driven by policies; for example, the U.S. offers tax incentives under Section 45Q for carbon capture and storage that can help offset operational costs for companies investing in these technologies [273, 279]. However, the effectiveness of such incentives varies widely based on local economic conditions and political will.

Notwithstanding the impact of these efforts, challenges persist in ensuring that national policies effectively support CCS deployment. Issues such as public perception, technical barriers, and economic constraints continue to hinder progress. Governments must establish stronger regulatory frameworks to address public concerns about the safety and environmental effects of CCS technologies while simultaneously encouraging investment in order to overcome these obstacles [273, 281].

Despite these frameworks, challenges remain regarding the implementation and effectiveness of international agreements. Many countries still lack comprehensive legal frameworks that explicitly support CCS deployment, leading to inconsistent regulatory environments that can hinder investment and technological advancement [194, 280]. The UK's ambitious carbon capture ambitions, which seek to collect 20-30 million tonnes of CO_2 annually by 2030, demonstrate the importance of national policies and incentives in promoting the expansion of CCS projects. This ambition is backed by substantial government funding [282, 283, 284]. In contrast, countries like Nigeria face significant hurdles due to inadequate policy frameworks, illustrating how national policies can either catalyse or hinder CCS development when they are insufficient or poorly designed [119, 275, 280, 285].

6.4. The Transformative Role of Artificial Intelligence and Machine Learning

A significant emerging opportunity to address these challenges lies in the application of AI and ML. AI is poised to be a game-changer across the CCS value chain:

- ML algorithms can optimise capture processes in real-time, potentially reducing energy penalties by 10-20% [286].
- AI can enhance geological storage site selection accuracy and enables automated, high-resolution monitoring of CO_2 plumes, improving forecasting and risk management [237, 287].
- AI can optimise complex CO_2 transport networks and, through Large Language Models (LLMs), accelerate the analysis of regulatory frameworks and public sentiment, streamlining deployment [110, 246].

6.5. Integrated Opportunities and Future Pathways

Despite these challenges and the global effort to improve on standards, there are still substantial opportunities for advancing CCS technologies [288]. Combining CCS with renewable energy sources offers a strong way to optimise its effects. We can build a more robust and sustainable energy system by integrating CCS with solar, wind, and other renewable technologies [72, 247, 289, 290, 291]. Additionally, global cooperation in best practices, knowledge transfer, and research might hasten the global adoption of CCS technologies, ensuring that countries share knowledge and resources to develop a robust global CCS network.

Therefore, addressing the socio-political and economic factors influencing CCS deployment is essential for unlocking its full potential as a viable climate mitigation strategy [292]. By fostering public acceptance, establishing supportive regulatory frameworks, and implementing innovative funding mechanisms, a favorable environment for the effective implementation of CCS technologies can be established by stakeholders [293]. The optimisation of capture technology, enhancement of monitoring techniques, and exploration of innovative financing models to facilitate the scaling up of CCS projects should be the main emphasis of future studies. By learning from successful case studies and addressing existing challenges, stakeholders and policymakers can make a substantial contribution to the global climate goals.

7. FUTURE DIRECTIONS

The critical analysis presented in this review affirms that carbon capture and storage is an indispensable, yet maturing, pillar of the global net-zero strategy. The path forward must therefore transition from foundational research to targeted innovation and strategic deployment, addressing the key challenges of cost, efficiency, and integration. The future trajectory of CCS will be defined by advancements in next-generation capture materials and processes, which are essential to drastically reduce the energy penalty and economic burden of CO_2 separation. This entails a focused pursuit of novel solvents, sorbents, and membranes with higher selectivity and lower regeneration demands, moving beyond conventional amine-based systems to explore metal-organic frameworks, biomimetic designs, and electrochemical pathways [73, 284]. Concurrently, the integration of artificial intelligence and machine learning will revolutionise the entire CCS value chain, enabling real-time optimisation of capture plants, enhancing the precision of geological site selection, and providing powerful predictive capabilities for monitoring plume behaviour and ensuring long-term storage integrity [237, 287].

Beyond standalone technological progress, the full potential of CCS will be unlocked through its synergistic integration with the broader clean energy ecosystem. The coupling of CCS with renewable energy sources, such as using low-cost solar or wind power to operate capture units, particularly for Direct Air Capture, creates a mutually reinforcing system that minimises the carbon footprint of the mitigation process itself [294, 295]. Furthermore, CCS is a critical enabler for a low-carbon hydrogen economy, providing the means to produce clean "blue" hydrogen from natural gas as a bridge fuel, while also finding a role in hard-to-abate industrial sectors like cement and steel [296]. Exploring viable pathways for Carbon Capture and Utilisation (CCU), transforming CO_2 into building materials, polymers, or sustainable fuels, can also create early market opportunities, though such utilisation must be carefully assessed for its scale and permanence relative to geological storage [66].

However, technological and synergistic advances alone are insufficient without a robust and supportive socio-economic framework. The establishment of stable, long-term policy signals, such as effective carbon pricing and technology-neutral tax credits modelled on successful frameworks like the U.S. Section 45Q, is fundamental to de-risking investment and attracting the private capital necessary for large-scale projects [284]. This establishment of stable, long-term policy signals must be coupled with a multidisciplinary approach that proactively engages social sciences to foster public understanding and acceptance, addressing misconceptions through transparent communication and community involvement in project planning and monitoring [225]. Ultimately, realising the promise of CCS demands unprecedented collaboration across academia, industry, and government to not only drive down costs through innovation but also to build the necessary infrastructure, create new job opportunities, and ensure that CCS evolves from a technological prospect into a deployed and accepted cornerstone of a sustainable and climate-secure future [73].

8. CONCLUSION AND RECOMMENDATION

Reaching net-zero emissions is an urgent global imperative, and this review has substantiated CCS as a critical technological pillar for decarbonising the power and industrial sectors. Our analysis demonstrates that while the core technologies spanning across the entire capture, transport, and storage chain are technically viable, their widespread deployment is impeded by a confluence of technical, economic, and socio-political barriers. The path forward requires a targeted and synergistic strategy that leverages the quantitative insights and emerging opportunities identified herein.

Technological innovation must remain a primary focus, with R&D prioritising next-generation capture materials such as advanced solvents and metal-organic frameworks – to reduce the prohibitive energy penalties, which currently range from 3.5 to 4.5 GJ/tCO_2 for amine scrubbing to over 7 GJ/tCO_2 for direct air capture (DAC). Concurrently, the integration of AI and machine learning presents a transformative opportunity to optimise processes, enhance predictive maintenance, and improve the monitoring and verification of stored CO_2, thereby increasing efficiency and building confidence in storage security. The safety and efficacy of geological storage, particularly in saline aquifers with capacities of 150-1,500 GtCO_2 in Europe alone, must be underpinned by these advanced monitoring technologies to ensure public trust and regulatory compliance.

Overcoming the significant economic hurdles, with capture costs ranging from \$50 to \$150/tCO_2 for point sources to over \$600/tCO_2 for DAC, demands robust and predictable policy frameworks. Financial mechanisms such as enhanced tax credits, grants, and carbon pricing are exemplified by the U.S. 45Q tax credit and Canada's CCUS-ITC and are essential to de-risk investment and stimulate private sector participation.

Streamlining the regulatory permitting process is equally critical to accelerate project timelines. Furthermore, proactive public engagement and transparent communication are not ancillary activities but foundational requirements for earning the social licence to operate; involving local communities in planning and monitoring can directly address safety concerns and dispel misconceptions.

Finally, the full potential of CCS will be realised through strategic system integration. Coupling CCS with renewable energy can power capture processes sustainably, while its application in low-carbon hydrogen production and hard-to-abate industrial sectors creates synergistic pathways to deep decarbonisation. International collaboration is paramount to facilitate knowledge transfer, especially to developing nations, and to foster a global carbon market. By concentrating on these actionable pillars, such as targeted R&D, smart policies, genuine public engagement, and systemic integration, stakeholders can catalyse the deployment of CCS technologies. This concerted effort will not only facilitate significant reductions in global carbon emissions but also stimulate the creation of new industries and job opportunities, ultimately underpinning a sustainable and climate-secure future.

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