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Carbon Capture and Storage Technologies: Advances in Capture Methods, Transportation, Geological Storage, and Future Prospects

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Abstract

Carbon capture and storage (CCS) is an important technology for reducing carbon dioxide (CO_2) emissions from energy generation and industrial processes, particularly in hard-to-abate sectors. This review examines conventional and emerging CCS technologies, their operating principles, performance evaluation, applications, limitations, and contributions to global decarbonization. Conventional capture approaches, including pre-combustion, post-combustion, and oxy-fuel combustion, are discussed alongside emerging technologies such as cryogenic separation, chemical looping, direct air capture (DAC), graphene-based membranes, and metal–organic frameworks (MOFs). Other carbon removal approaches, including bioenergy with carbon capture and storage (BECCS), biochar, and enhanced rock weathering, are also considered. CO_2 transportation by pipeline and ship is reviewed in terms of infrastructure requirements, material compatibility, safety, and economic feasibility. Geological storage options, including deep saline formations, depleted hydrocarbon reservoirs, and suitable basalt formations, are examined with respect to trapping mechanisms, monitoring, containment, and long-term stability. Industrial case studies, including Sleipner, Gorgon, and Boundary Dam, provide insights into practical experience and operational challenges. The review also evaluates economic, environmental, and regulatory barriers to CCS deployment, including capital costs, energy penalties, public acceptance, and lifecycle emissions. Future progress will require affordable and durable capture materials, effective integration with industrial processes, reliable transportation and storage infrastructure, appropriate regulatory frameworks, and supportive financial incentives. Overall, CCS can contribute significantly to industrial decarbonization when implemented alongside other emissions-reduction strategies and supported by robust environmental assessments, effective monitoring, and long-term infrastructure planning.

Keywords: Carbon Capture and Storage; CO_2 Capture Technologies; Geological Storage; Direct Air Capture; Advanced Separation Materials; Techno-Economic Assessment; Lifecycle Assessment; Industrial Decarbonization

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Introduction

Human activity in the industrial era has irreversibly increased the concentration of atmospheric carbon dioxide (CO_2) and has caused man-made climate change. Emissions estimates depend on sources, and even accounting boundaries differ, so if you are citing an emissions number, include the year of reporting and the source [1]. This presents challenges for decarbonizing different sectors: in addition to combustion emissions from fuels, process emissions effluent from the cement, iron, steel, and chemical industries are significant [2]. Alternatives such as renewable energy, electrification, and energy efficiency should be complemented by other solutions, and process redesign, material substitution, and demand-side measures when residual emissions are significant. Carbon capture

and storage (CCS) [3] are possible options for some industrial process with residual emissions.

The Paris Agreement includes the goal of limiting the increase in the global mean temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the increase to 1.5°C [4]. The Intergovernmental Panel on Climate Change (IPCC) in 2018 presented modelled pathways limiting global net anthropogenic CO_2 emissions to under 2°C by 2030 and to net zero mid-century [5]. These pathways emphasize the importance of rapid and sustained reductions in emissions in the energy system, industry, land use, and infrastructure. However, the necessary measures vary between countries and sectors and are conditioned by technological, economic and emissions profiles.

Carbon capture and storage (CCS) involve capturing CO_2 at an emission source, conditioning and transporting it, and injecting it into suitable geological formations for permanent storage [6]. Carbon capture, utilization and storage (CCUS) ideas of utilizing the captured CO_2 in industrial processes and products. Environmental benefits of utilization depend on the energy and materials used for utilization, the benefit to displaced products, and the length of time carbon is sequestered. Capture configurations include post-combustion capture, precombustion separation, and oxy-fuel combustion. Their suitability as a function of the gas composition, operating pressure, plant configuration and plans for retrofitting, use of energy sources, as well as transport and storage infrastructure, vary [7].

Recent efforts have extended the range of technologies considered to include advanced solvents, solid adsorbents, membrane separation, cryogenic capture, chemical looping, and hybrid systems [8]. Direct air capture (DAC) involves capturing CO_2 from ambient air, but the low concentration in air poses a major obstacle in separation and energy [9]. Bioenergy carbon capture and storage (BECCS) can achieve net-negative emissions if appropriately designed to manage land-use and supply-chain emissions, process energy, storage longevity, and biomass sources [10]. Other options, such as biochar and enhanced weathering and mineralization of rock, have potential for carbon removal, but they differ from point-source CCS in terms of their mechanisms, level of technological maturity and need for measurement, verification, reporting, and accounting, and the permanence of their carbon removal [11]. Subsea approaches (e.g., ocean fertilization) deserve separate treatment given uncertainties of effectiveness, ecology, and governance.

Advances in material science have prompted the investigation of amine-supported silica, porous carbon, metal-organic frameworks, or graphene membranes for improved CO_2 selectivity, capture amount, or regeneration [12]. However, promising laboratory results do not necessarily translate into commercial applicability. Industrial applicability criteria include working capacity and mass transfer rates, tolerance to moisture and contaminants, regeneration energy, durability of materials, cost of manufacture, and compatibility with existing processes [13]. For new ideas (e.g., supersonic separation), simple metrics must be defined and convincing demonstration data provided.

The success of CCS also requires proper conditioning, transportation, and storage of CO_2 to be separated. Captured CO_2 may require purification, dehydration, and compression before pipeline or ship transport. Geological storage sites for longer-term storage are likely to be depleted reservoirs and deep saline formations; in some cases, mineralization of the CO_2 may form stable carbonate minerals [14]. The long-term storage performance varies with the geological characterization, conduct of the caprock and the integrity and pressure of the well, monitoring activities, and well-defined arrangements on long-term responsibility. Other factors including energy consumption, infrastructure requirements, lifecycle emissions, safety, public acceptance, and regulatory limitations are also important in terms of economic viability and environmental performance [15].

The review critically evaluates CO_2 capture technologies, materials, transportation, geological storage options, and implementation barriers in the present and future. It evaluates performance aspects including technology maturity, industrial application, system boundaries, energy requirements, cost assumptions, life cycle impacts, and storage integrity [16]. In this review, we therefore discuss weaknesses and strengths of present approaches to identify research gaps and areas for technical, economic, and environmental improvements. The aim is to expose current strengths of the evidence base for deployment, highlight uncertain areas, and offer avenues along which such necessary technological, economic, and regulatory development can enable the enhanced contribution of CCS to decarbonization globally.

Post-Combustion Capture

Post combustion capture refers to the capture of carbon dioxide (CO_2) after burning fossil fuel or other carbon-containing fuel in a power plant or industrial plant. This is done by means of "selective solvent" or "sorbent" that absorbs CO_2 and passes other gas components [17]. The captured CO_2 is then recovered, conditioned, and transported for storage. It can be retrofitted to existing combustion equipment, making it a good candidate for retrofitting some coal-fired power plants and industrial facilities rather than replacing their entire combustion system [18]. However, retrofitting is limited by space available, flue-gas composition, plant operating conditions, energy integration, and cost of modification of existing infrastructure. CO_2 compression, solvent processing in regeneration or recovery processes, and other auxiliary equipment are also major energy consumers [19]. Other issues include solvent degradation, corrosion, and flue gas contaminants. These limitations have motivated research into improved solvents, new membrane systems, process integration, and alternative separation schemes. Among the principal approaches investigated for post-combustion capture are chemical absorption using aqueous monoethanolamine (MEA) and membrane-based separation (Figure 1).

Chemical Absorption Using Monoethanolamine (MEA)

Chemical absorption in aqueous solutions of a controller amine is the most commonly used method for CO_2 removal: monoethanolamine (MEA) is one of the most profusely studied and high-turnover technologies in post-combustion CO_2 capture and serves as a primary reference against which alternative capture processes are evaluated [20]. The process typically operates in an absorber-strip configuration. In the absorber, flue gas contacts a circulating MEA solution, allowing CO_2 to react reversibly with the solvent, the CO_2-depleted gas leaves the absorber, while the CO_2-rich solvent is transferred to a stripper, where heat supplied through a reboiler releases the absorbed CO_2 [21]. The solvent is regenerated and recycled to the absorber for reuse, and the recovered CO_2 is

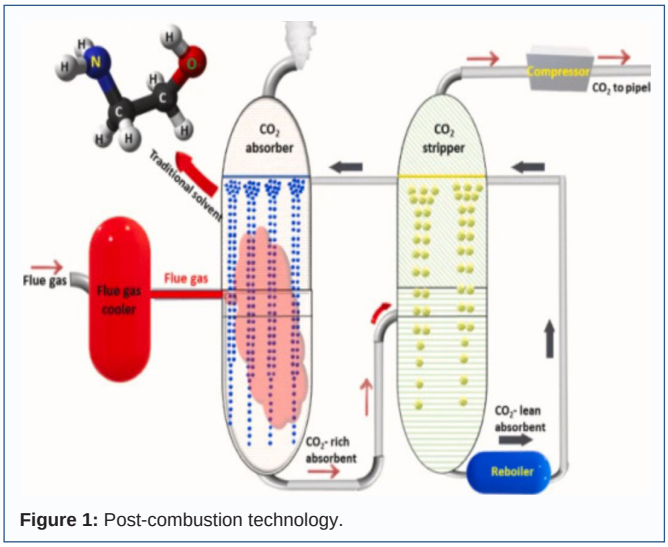


Figure 1: Post-combustion technology.

cooled and compressed, if necessary.

Conventional MEA-based systems generally require large quantities of thermal energy for solvent regeneration. Some processes offer a reboiler duty of as much as 3.8–4.0 GJ/t CO_2 captured [22]. The actual energy requirement is a function of the solvent concentration and CO_2 loading, absorber and stripper operating conditions, potential heat integration, and flue gas characteristics [23]. Thus, this range should be considered as a process-dependent estimate rather than a generic value. Removal of steam (or other heat) from the host facility also decreases net electricity generation/plant efficiency [24].

Absorption of MEA is an established technology, but faces some operational issues. The solvent is subject to thermal and oxidative degradation that can react with oxygen and contaminants in the flue gas, leading to degradation products that require additional solvent replacement and waste management [25]. Other losses, corrosion, and energy for solvent regeneration also contribute to the operational costs. These include better intercooling of the absorber, recovery of solvent concentration, rich and lean solvent loadings, improved heat recovery, and other means of integration of the capture plant into the host facility. Such approaches may improve mass-transfer efficiency or energy consumption but are generally system specific and dependent on plant configuration and design [26]. MEA absorption, therefore, is a useful benchmark for evaluating new solvents and alternative capture technologies.

Membrane-Based Separation

CO_2 membrane separation is another post combustion capture method for CO_2 based on the rate difference across a selective membrane. The feed gas is fed to one side of the membrane and pressure differences (vacuum, pressurization, or both) are sustained on the opposite side of the membrane to drive this separation. The CO_2 membrane permeability is a function of material and structure, preferably with selective permeation for CO_2 and different degrees of retention of other flue-gas components [27]. Unlike traditional chemical absorption, membrane separation does not require solvent regeneration in a heated stripper. Instead, it may demand intense compression or vacuum energy, and the process is ultimately limited by membrane permeability, membrane selectivity, feed composition, pressure ratio, and required CO_2 recovery and purity [28]. Polymeric membranes have been widely investigated for CO_2 separation due to the possibility of fabricating them into hollow-fibre or spiral-wound modules, which allows for a modular design and industrial application [29]. Polymeric membranes (e.g., Polaris™ [30]) have been investigated for post-combustion CO_2 capture. However, CO_2 permeability-selectivity trade-off, plasticization, physical ageing, contamination exposures, and durability of the membrane limit the membrane performance [31]. Inorganic membranes (ceramic and others) are more stable thermally and chemically at the right operating conditions, but design and membrane material can also be the cause of favourable performance, production costs, and mechanical properties and scalability [32].

Therefore, no single polymeric or inorganic membrane is optimal for all CO_2 capture applications. The implementation of multistage membranes, incorporating proper stages of separation and a vacuum, gas-recycling, and/or compression system, can improve CO_2 separations and product purity [33]. Some process simulations demonstrate that membrane property variation in the multistage membrane configuration results in the differences in the separation performances, required membrane area, and energy consumption efficiency.

However, these advantages are contingent on operating conditions and product specifications. For example, the partial pressure of CO_2 in typical post combustion flue gas is far below unity, which limits the permeation driving force and thus places higher demands on membrane-area or membrane-pressure control [34].

Therefore, membrane system designs should optimize the stage design, pressure configuration, gas recycle, and energy integration. Membrane capture is compact and modular. However, competitiveness should be evaluated in terms of total system energy consumption, minimum CO_2 recovery, product purity, durability, and cost, rather than membrane selectivity alone (Figure 2).

Pre-combustion Capture

In pre-combustion capture, carbon dioxide (CO_2) is separated from a fuel-derived gas stream. The procedure generally initiates with the transformation of carbon-based fuels, like coal or natural gas, into synthesis gas (syngas), which is predominantly composed of hydrogen (H_2) and carbon monoxide (CO_2). The CO_2 is reacted with steam in the so-called water–gas shift reaction to produce additional hydrogen and CO_2. The resulting gas mixture is then treated to remove the CO_2, usually by physical solvents such as Selexol or Rectisol at high pressure, and the hydrogen-rich stream can be used for power generation, industrial heating, etc. The main advantage of pre-combustion capture is that the CO_2 partial pressure is higher in the process gas than in the flue gas from conventional combustion processes, which facilitates separation. The captured CO_2 can be liquefied and transported for underground storage, and the hydrogen-enriched stream may serve as a future energy carrier [35]. However, the environmental advantages of hydrogen production depend on the original fuel source, efficiency of the process, source of

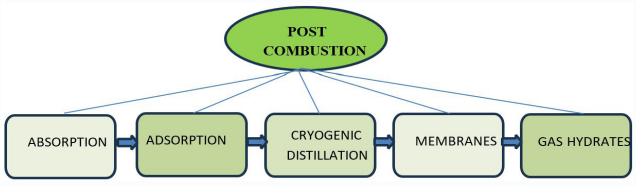


Figure 2: Post combustion capture methods.

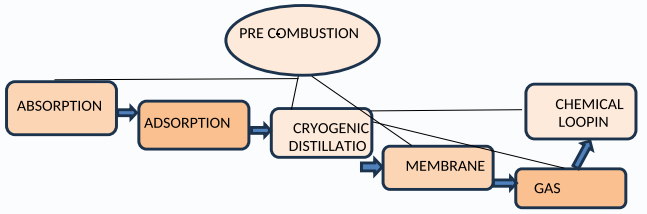


Figure 3: Pre combustion capture.

energy used, upstream emissions, and fraction of CO_2 that is captured and permanently stored.

Pre-combustion capture is of particular relevance for integrated gasification combined cycle (IGCC) systems for power-generating plants, hydrogen production plants, and some chemicals processes [36]. But it can entail high capital costs, complex fuel-conversion equipment, and major plant changes. Its economics is dictated by gasification or reforming, separation technologies, heat integration, hydrogen end-use, and the extent of techno-economic assessment [37]. Thus, in principle, pre-combustion capture is not more advantageous than post-combustion capture and more favourable for the fuel conversion or hydrogen production system (Figure 3).

Oxy-Fuel Combustion

Oxy-fuel combustion is a method of carbon capture, which combusts fossil fuels with oxygen instead of air. The absence of nitrogen at combustion causes the flue gas to be mostly carbon dioxide (CO_2) and water vapour with some residual oxygen and impurities associated with the fuel and the operating conditions [38]. The water vapour may be separated by cooling and condensation into a CO_2-rich stream that can be further purified as appropriate and compressed for distribution for geological sequestration or other uses. This enables minimization of CO_2 into nitrogen and hence separation and the quantity of flue gas to be treated compared to traditional air-fired alternatives [39].

These benefits are balanced, however, by an energy penalty for oxygen production, usually in an air separation unit. Additional energy may be needed to recirculate flue gases, capture pollutants, and purify and compress CO_2. These requirements impose penalties on the efficiency of the plant and the capital and operating costs. Parameters that need to be considered include oxy-fuel system efficiency at oxygen production, combustor design, heat integration, fuel characteristics, and quality standards of the product carbon dioxide. Therefore, while there may be advantages from the approach for certain power and industrial applications, the overall efficiency of the approach has to be assessed across the system and flue gas composition [40] (Figure 4).

Emerging Carbon Capture Technologies

Although technologies for capturing CO_2, such as post-combustion, pre-combustion, and oxy-fuel combustion, have been developed, their energy demands, costs, and specific limitations have led to the search for alternative technologies. Recent efforts have focused on alternative technologies like cryogenic carbon capture; chemical looping; and advanced adsorption, membrane, and direct air capture (DAC) technologies to enhance separation efficiency, applicability to sources of varying emissions, or CO_2 removal from air. However, these technologies differ in principle, in technology maturity, and in energy requirements [41].

Cryogenic capture separates CO_2 based on cooling and phase change and is applicable to certain gas streams, but its feasibility depends on refrigeration needs and feed composition. Chemical looping processes internally transfer oxygen-carrier materials to enhance fuel conversion and generate a CO_2-rich stream that can be separated. Direct air capture (DAC) draws CO_2 out of ambient air; therefore, it can lower carbon levels in ambient air but faces institutional challenges, given the carbon dioxide concentration in air is very low [42]. Ideal scenarios for these technologies are such that they are relatively low on energy, investment, operational needs, and provide longevity, appropriate scale-up, and are amenable to transport and storage.

Future progress will depend on comprehensive assessments of new and existing systems under common operating and life-cycle conditions. Assessments should include capture efficiency, net emissions abatement, resource requirements, environmental impacts, and technology maturity of each approach. Such approaches could provide a useful mechanism to decarbonize industry sectors if they can make an adequate contribution to direct emissions reductions and can provide verifiable climate benefit and could include suitable capture technologies, suitable transport of captured CO_2 and safe long-term storage of CO_2 (Figure 5).

Novel Carbon Capture Technologies

Cryogenic Carbon Capture

Cryogenic carbon capture is a method of removing CO_2 from gas mixtures by cooling and phase change (and, if needed, change in pressure). Thus, CO_2 can be condensed or DE sublimated and separated from other gases under suitable operating conditions. The separated CO_2 can then be further purified and compressed for utilization and storage in the underground. It can generate the high-concentration CO_2 stream and low solvent chemical usage/as well as elimination of solvent chemical use (also known as traditional solvent-based separation), but this can only occur under the favourable feed composition and operating conditions [43]. However, its effectiveness is highly dependent on the initial CO_2 concentration, gas pressure, humidity, impurity concentrations, and cooling needs. Pretreatment to remove condensable compounds (e.g., water) is almost always required to avoid operational issues, and refrigeration and compression can contribute significantly and disproportionately to the total energy demands. Thus, the value of cryogenic capture relative to conventional technology is not one of effectiveness per se. Rather, it should be carried out on a case-by-case basis depending on energy requirements of separation, capital cost, and achievability to the host plant [44].

Chemical Looping

Chemical looping is a process intensification strategy that uses solid oxygen-carrier materials (typically metal oxides) to transfer

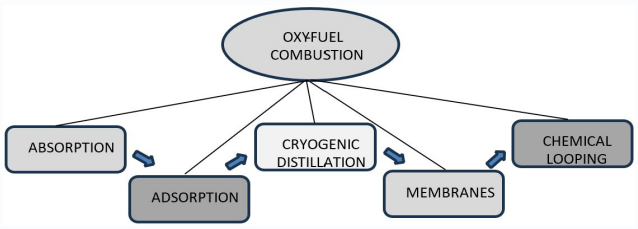


Figure 4: Oxy-fuel combustion capture methods.

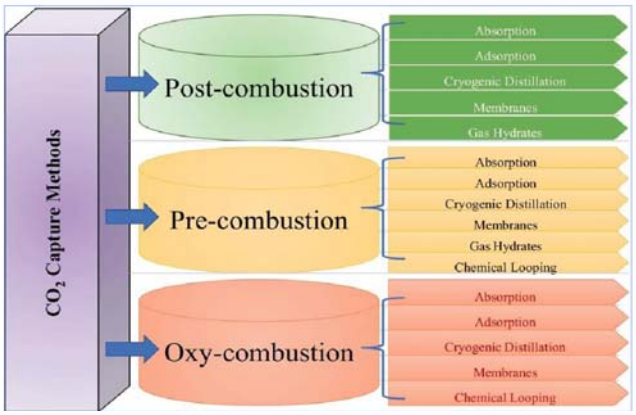


Figure 5: CO_2 Carbon Capture Methods.

oxygen between reaction sites. In chemical looping combustion, the carrier is reoxidised with air and then reacted with the fuel to produce a stream of carbon dioxide and water vapor in a fuel reactor [45]. The spent carrier is then re-oxidized in an air reactor and recycled back to the fuel reactor. In the step of the fuel reactor, the fuel would not make any contact with the air nitrogen; thus, the generated CO_2 enriched stream can be easily separated after extraction of water [46]. Such a configuration may also decrease space requirements in conventional combustion. However, success is tied to the reactivity/resistance to sintering and attrition of oxygen carriers, cyclic stability, heat management and solid recirculation, and design of reactors. Material degradation and upscaling of solids-handling systems and reactors present further challenges [47]. Chemical looping, therefore, should be evaluated based on operating time, energy efficiency, material lifetime, and integration in processes, not simply assumed better than other capture technologies.

Direct Air Capture

Direct air capture (DAC) is a technology to capture CO_2 from the ambient air by chemical solvents, solid sorbents, or other selective separation agents. Liquid-solvent systems chemically bind CO_2, but CO_2 is released upon regeneration [48]. In solid-sorbent systems, typically thermal, vacuum, or hybrid adsorption and regeneration are employed [49]. The captured CO_2 is then compressed for underground storage or application as appropriate. Direct air capture (DAC) could lower atmospheric CO_2 concentration independently of the location and mass flux of promoting industrial major emission sources as compared with point-source capture. However, its role in preventing climate change depends on CO_2 storage and assessment of net removal, and the availability of low-carbon energy [50]. The low concentration of CO_2 in the air means that large volumes must be treated, and it puts greater importance on contactor design, energy use, material performance, and operating cost. Sorbent or solvent degradation, water use, equipment manufacture, and emissions associated with energy supply are also important [51]. DAC can complement direct emissions reductions, especially for residual emissions, but the climatic benefit of DAC must be demonstrated by life-cycle assessment and not by the quantity captured [52].

Anthropogenic and Nature-Based Carbon-Removal Approaches

Biochar Production and Application

Biochar is a carbon-rich product produced by thermal treatment of biomass under oxygen-limited conditions (pyrolysis). Depending on the feedstock and process conditions, carbon in the biomass can be converted into a solid form that remains relatively stable for a long time in soils. Biochar has been proposed as a carbon sequestration strategy to capture carbon and affect soil properties, such as water holding capacity, nutrient availability, and soil structure [53]. However, these effects vary depending on feedstock, temperature of production, properties of the biochar, soil type, climate, and application rate [54]. The net climate benefit is determined by the fraction of carbon sequestered and sequestration timescale, the emissions that would result from harvesting and processing the biomass used, transportation needs, energy use, and perhaps competing uses of the biomass. Issues of impurities may arise from nonideal feedstocks and variable effects of soil and cropland productivity. Biochar applications should not be presumed to result in net-negative emissions but should be determined on an individual case-by-case basis through lifecycle analysis and local agricultural knowledge (Figure 6).

Ocean Fertilization

Ocean fertilization involves adding nutrients like iron to areas of the ocean to stimulate the growth of phytoplankton and therefore biological uptake of CO_2 from the atmosphere. Some of the carbon fixed by photosynthesis can sink as organic matter to deeper waters. Increase of biological productivity does not, however, necessarily affect atmospheric CO_2 concentrations in the longer term. Rather, effectiveness depends on (1) the degree of carbon fluxes below surface waters, (2) residence time, (3) nutrient cycling, and (4) further carbon exchange between the ocean and atmosphere [55]. Potential consequences include modified marine food webs, decreased oxygen, altered nutrients, and shifted ecosystems. The efficacy, permanence, and cost-effectiveness of ocean fertilization are uncertain, and net carbon removal may be challenging to quantify and attribute. It should therefore be considered an emerging ocean intervention rather than an effective approach to scaling carbon removal [56]. Also, it should address its environmental risks, their management and international regulation [57].

Enhanced Rock Weathering

Enhanced rock weathering (ERW) attempts to replicate this process at greater speed through the application of suitably reactive silicate or other minerals to land or water in an effort to accelerate the extent of chemical weathering. These minerals weather in acidic environments due to CO_2 and water, possibly transforming carbon into extractable bicarbonate, which can be drained from the system and/or, if conditions are suitable, may precipitate out as long-term carbonate minerals [58]. Mineralogy and grain size, climate, soil chemistry, water, and kinetics and mobilities of weathering products

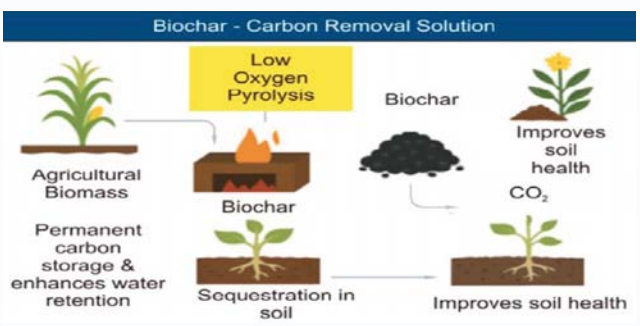


Figure 6: Biochar for carbon removal as a CCS alternative.

will determine the efficiency of ERW. Depending on the mineral, the application, and potential improvements in soil chemistry, the right minerals can be applied with positive effects in some circumstances. However, mining, milling, transportation, and distribution of the minerals can also consume energy and generate greenhouse gases. Other challenges relate to quantifying direct weathering rates, isolating anthropogenic carbon removal from the natural background, and assessing the downstream effects and permanence of carbon sequestration. ERW must be evaluated using life stage assessment, measurement, and clear carbon-accounting methods for net removal potential and cost-effectiveness [59].

Comparative Assessment and Research Priorities

These technologies operate differently, vary in maturity, and play different climatic roles. Cryogenic capture and chemical looping target CO_2 removal in engineered systems, while DAC is aimed at CO_2 capture from the atmosphere. Biochar, ocean fertilization, and enhanced rock weathering enhance the carbon capture through biological, geochemical and rock mechanisms. They cannot be compared against a single capture-efficiency metric because they are implemented in different conditions and have different accounting parameters [60].

The net benefit assessment includes coverage of net sequestered or avoided CO_2 tonne equivalents, energy and material requirements, life-cycle greenhouse gas emissions, persistence, environmental hazards, monitoring and verification needs, costs, and technology maturity. For engineered capture systems, it should also consider conditioning and transport and, where applicable, final storage. For carbon-removal pathways, the analysis should encompass baselines, additionality, duration of sequestration, and collateral environmental effects. Such distinctions are important in part to signal to the world which technologies can credibly deliver a quantifiable climate benefit, as well as to indicate future research directions for improving efficiency, for credible validation, and for clear ethical justification of deployment [61].

Cutting-Edge Technologies For Carbon Capture

Supersonic CO_2 Separation

Supersonic CO_2 separation is a novel gas-separation process that utilises rapid gas expansion, thermodynamic effects, and phase separation in a specially designed nozzle or separator. It does not involve transfer across a membrane as most membrane processes do [62]. Interestingly, gas expansion can favour CO_2 condensation at an appropriate pressure, temperature, and composition range, and the centrifugal separation can assist in removing condensed droplets. This method has interested researchers for its low footprint and for its ability to rely less on conventional separation and solvent-recovery systems. However, its performance is sensitive to feed-gas composition, pressure, temperature, nozzle system, condensation kinetics and efficient downstream separation. Other problems include the absence of data on some process conditions and the uncertainties of multiphase flow model application and coupling in existing industrial processes [62]. Supersonic separation is thus an emerging alternative that needs further market feasibility validation against conventional capture technologies [62].

Graphene-Based Membranes

Separation of CO_2 with G-based membranes presents an interesting opportunistic research area, as the structure of G can be tailored to restrict the transport of molecules and increase the selectivity to gases [63]. Graphene-based materials can be engineered with optimal pore sizes, surface modifications, or selective transport channels for separation, depending on the design of the membranes. Such features are promising for designing thin membranes with good permeability and separation performance [64]. However, challenges such as sealing and module design, mechanical stability, scalability of the membrane, control of defects, and reproducible pore development remain for real-life applications. In mixed-gas separations (which are necessary for the true evaluation of the performance of membranes), the separation behaviour may be affected by pressure, temperature, humidity, and impurities [64]. Energy requirements of the overall membrane process strongly depend on feed pressure (and the need for compressor/vacuum) and the desired CO_2 purity and recovery. Graphene membranes are an interesting research area, but their industrial application cannot be based only upon the material characteristics. For practical feasibility, pilot scale validation, durability testing and cost analysis of the manufacturing and comparison with conventional polymeric membranes are required.

Metal–Organic Frameworks for CO_2 Capture

Metal-organic frameworks (MOFs) are crystalline materials characterizing porosity built by metal-based nodes, which are connected by organic connectors. Those having easily tunable pore architectures, high internal surface areas, and versatile chemical environments are famous candidates for selective CO_2 capture [65]. The unusual combinations of organic linkers, metallic centers, and functionalization are amenable to modification to carefully control their particular gas adsorption for specific conditions and gas mixtures. Applications include natural gas purification, direct air capture, and post combustion capture [66]. However, it is still difficult to translate lab scale performance into the industry. Some MOFs may be moisture sensitive, and other practical considerations include synthesis cost, shaping and palletization, mass transfer limitations, energy/time-consuming regeneration, and metallic durability upon repeated cycles. Moisture, in sensitive frameworks, can compete for CO_2 use sites or degrade structural integrity [66]. Therefore, future developments should focus on materials with good working capacity and selectivity as well as moisture resistance, good regeneration, long life, and easy make and low cost.

Comparative Assessment and Prospects for Deployment

Other technologies to improve CO_2 separation include supersonic separation, graphene membranes and Metal Organic Frameworks (MOFs). These technologies make use of gas expansion and phase change, selective permeation and a wide range of sites for adsorption respectively. It is unlikely that these will be focused on how efficient they are at capturing CO_2 but their performance requirements. A number of factors will influence the decision including CO_2 recovery, purity, energy demands, material resilience, cost of capital and running, maturity of technology and if it can be used with current capture and transportation infrastructure [67]. There will be research required to ensure that the technology can be demonstrated on a lab scale. However, to ensure the technology is economical and can reduce emissions during capture as well as life cycle emissions compared to conventional technologies, reliable performance will be important in real scenarios.

Industrial Case Studies and Deployment Experience

Industrial and field scale projects can offer useful insights into opportunities and challenges of carbon capture, utilization,

and storage (CCUS) against real-world contexts. In addition to demonstrating technical feasibility, these projects emphasize the significance of site selection, operational flexibility, monitoring, risk assessment, and long-term storage management [68]. However, due to the differences among the various projects in terms of CO_2 sources, capture facilities, geology, objectives, operational scopes, the performance of such projects should be reviewed on a case-by-case basis.

CarbFix, Iceland: Mineral Storage in Basalt

The CarbFix project in Iceland demonstrates a novel way of geological CO_2 sequestration by mineralization in basalt [69]. It involves dissolving the CO_2 in water such that this solution is injected into reactive basalt, where it reacts with the rocks to form stable carbonates [70]. Unlike storage methods that mainly aim at keeping CO_2 as a gas or dissolved in a reservoir, mineralization aims at converting the injected carbon into stable mineral forms.

In the appropriate geological and geochemical environment, studies at the CarbFix site demonstrated that injected CO_2 may mineralize rapidly into carbonate minerals. This isotopic study indicated that around 165 ± 8.3 t of the CO_2 (estimated) mineralized as calcite during the studied injection experiment, yielding an estimated carbon-storage efficiency of 72 ± 5% [71]. These results are promising for basalt-hosted mineralization as a longer-term storage option, but the results of one experiment may not be applicable to other geological settings.

Its application is limited by basalt reactivity, water availability, injection conditions, reservoir permeability, and the ability to demonstrate mineral growth. Water management, pumping requirements, site assessment, and monitoring can influence total energy consumption and costs [72]. CarbFix is also a model of what is possible with mineral sequestration and emphasizes the need to develop site-specific technical and economic feasibility.

Lessons for Future CCUS Deployment

An example of the synergies of CCUS and geology is the Salah case with CarbFix. Salah has experience in deep reservoir uncertainty with the coupled monitoring and injection of CO_2 into a deep sandstone reservoir. In basalts, carbon dioxide can transform into stable carbonate minerals, as evidenced by CarbFix [73]. While neither demonstration has proved a "better" storage option, in principle options will depend on geology, injection details, infrastructure, extent of monitoring, and costs. The trajectory of CCUS will hinge on the compatibility of storage with low-carbon energy portfolios, technological variety, and the connections between capture facilities and storage assets. When routes and capacities are sufficient, communal transport infrastructure can be lucrative. The policy should delineate the conditions for site licensing, leak surveillance and management, decommissioning, and enduring liability. Public involvement is critical, where public confidence will be founded on risk transparency, environmental protection, and accountability [74].

Ultimately, successful CCUS is more than just promising capture materials or technically feasible storage formations. Successful deployment, however, requires that the effectiveness of capture be balanced with energy usage and the cost of transport and storage as well as emissions in a lifecycle context, environmental risks, and assurance of long-term containment. Operating projects should inform future design, and emerging technologies should be continually evaluated by independent validation and transparent reporting of performance

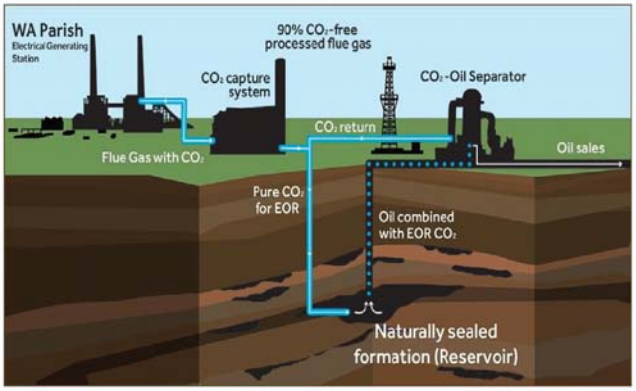


Figure 7: CO_2 Capture system.

and limitations (Figure 7).

Carbon Capture and Storage: Challenges and Economic Assessment

CCS can abate CO_2 emissions from energy and industrial processes but faces considerable economic, technical, infrastructure, environmental, and regulatory challenges. Major economic challenges were high capital costs and the energy penalty of capture, while infrastructure for transport and storage was limited by few demonstration projects and ongoing uncertainty about identification and characterization of potential storage projects and concerns about leakage and long-term containment at storage sites, all of which limited deployment. Public acceptance is a key issue for project implementation, especially in regions where communities are concerned about pipeline safety, CO_2 leakage, groundwater protection, land use, and long-term liabilities. These challenges imply the need for a sustainability assessment of CCS not only at the capture stage but for the entire value chain (e.g., processing, transport, geological storage, monitoring, and verification) [75].

Economic Challenges and Cost Competitiveness

Capture costs vary widely among industries, depending on CO_2 concentration, facility size, energy needs, financing, transport distance, and availability of appropriate geology for storage. Plants with relatively concentrated CO_2 emissions can have much lower capture costs compared to those needing to separate CO_2 out of less concentrated exhaust gases. As an example, a 2025 study of industrial sectors in Saudi Arabia found widely varying expected capture costs, suggesting that prioritization of facilities should be based on technical and economic characteristics.

A retrofit of existing power and industrial plants may require capex, additional equipment, and process changes. Energy to regenerate the solvent, power to compress CO_2, and CO_2 conditioning may reduce overall efficiency and increase operation costs. These factors require consideration of the entire capture-transportation-storage continuum and not just the capture cost in isolation. Similarly, a study of CCS deployment to 2025 in Germany stated, "Investment and operation costs are highly uncertain, and the risk of project failure is significant … the cost assessment depends on assumptions about future cost reductions, the price of carbon, and the success of their application."

Cost should be measured in terms of cost per tonne of carbon dioxide captured, avoided, and destroyed. Interchanging these is not possible because capture has its cost in energy and resources, and transport and storage plus residual emissions affect the total climatic

benefit. Cost assessments should take into account their system's inputs, such as plant size, financing, energy cost, capture rate, and infrastructure.

Carbon pricing, tax credits, public funding, and sharing of transport and storage infrastructure could improve viability of projects but are very policy- and context-dependent. CCS must therefore be weighed against other options for decarbonization, including energy efficiency, electrification, renewable energy, fuel switching, and improved industrial processes. Clustering projects within relevant industrial hubs along with targeting industrial facilities with the best capture conditions could improve prospects in cost reduction and deployment [75].

Environmental and Energy-Related Trade-Offs

CCS can reduce emissions at industrial sites, but the net climate benefit of CCS depends on the energy and resources used to capture, condition, transport, and store CO_2. For solvent capture systems, energy is required for solvent regeneration, whereas membrane and adsorption systems may require heat, cooling, compression, or vacuum. If the energy inputs use carbon-intensive energy resources (e.g., coal for electricity generation), emissions of the host facility may increase. But a lifecycle assessment is needed to ensure that a project results in net emissions reductions.

This environmental aspect, however, is not limited to GHGs. They will also include solvent degradation products (where applicable), chemical waste, water use, equipment fabrication, pipeline construction, and possible impacts upon aquifers and ecosystems. So-called geological storage will need to account for the possibility of unintended CO_2 displacement [76] and will require careful site characterization, caprock and well integrity analysis, pressure control, and long-term monitoring. Geological storage is a potentially robust long-term storage strategy, but it must be proven through site characterization and monitoring, not based on theoretical storage potential, assuming that formations are chosen and managed appropriately.

The environmental sustainability cost (implied in the title of the original manuscript) approach of EESA could be a good frame to undertake the analysis of the balance of the financial, environmental and social cost. However, it is unclear to what extent the authors actually used EESA, or is this a cited approach from the literature [76]? If implemented, it should clarify the metrics, parameters, assumptions, and ways of attributing weights used in the evaluation and the results. It should be described as a prospective assessment framework and not as a completed analysis.

Technological Limitations and Opportunities for Improvement

The state-of-the-art amine absorbents in post-combustion capture, e.g., aqueous solution of monoethanolamine (MEA), are still an important benchmark; however, the energy demand, solvent degradation, corrosion, and solvent management of the amine absorbents can result in high operating costs. Amine-based solid adsorbents with tunable and tailorable target architectures and surface chemistries for CO_2 loading/regeneration have attracted research attention [77]. However, their practical advantages depend on capacity, cyclic stability, moisture tolerance, thermal and mass transfer, production costs, and lifetime.

Separation membranes offer modular equipment and selective transport of the gas but are limited by membrane permeability, selectivity, feed composition, pressure differentials, as well as beverage purity and recovery requirements of CO_2. In some applications, cryogenic separation, chemical looping, graphene-origin membranes, or metal–organic frameworks (MOF)-derived membranes can be advantageous [78]. However, whether they can compete remains to be established in future techno-economic and lifecycle assessment evaluations. Selectivity/capture capacity looks promising at lab scale but industrial scale competitiveness or performance/cost needs to be scrutinized [79].

Therefore, improvement strategies should focus on energy reduction, material durability, reuse of process heat, optimal equipment configuration, and coupling of capture systems with appropriate low-carbon energy sources. Demonstrations at pilot and commercial scales will be needed to test long-term reliability, maintenance requirements, and performance in real conditions. Such evidence is needed to determine if new technologies can provide quantifiable benefits over traditional capture technologies.

Deployment Scale, Policy, and Public Acceptance

Currently the carbon capturing & storage (CCS) is growing around the world but has a negligible effect compared with the demand of reducing global numbers. The Global CCS Institute (2026) issued a CCS monitor report with updated figures on the number of commercial facilities in operation and their capture capacity. However, capture capacity is not always equal to CO_2 capture and sequestration, as the efficiency varies among projects [80].

Government incentives (carbon pricing, tax credits, research funding, and support for shared transport and storage infrastructure) could help promote investment. The Gorgon project reminds us of the challenges of larger-scale CO_2 injections, whereas the Otway International Test Center in Australia has stimulated research into geological storage and monitoring [81].

The implementation is also shaped by the public acceptance. Strong regulation and information are needed for pipes, smoking, leakage, groundwater protection, and long-term liability. Transparent site approval, monitoring, remediation and decommissioning, and long-term liability standards are vital to building public trust and ensuring safe storage [82].

In general, more widespread use of CCS will require long-lived infrastructure, binding regulations (including regulations), co-investments, and wide participation of affected communities.

Integrated Economic Assessment and Future Priorities

CCS comparative analyses should consider relative technical performance, cost, life-cycle emissions, environmental risk, and social impacts. These can then be compared under common social, economic, and operational assumptions such as plant size, energy prices, capture efficiencies, CO_2 purity, finance, transport distances, storage costs, and facility life. Sensitivity analysis can then evaluate the effect of changes in these assumptions on project viability and net emissions reduction [83]. Evidence suggests that CCS can be a useful mitigation option in some hard-to-abate sectors, especially where other production processes are not feasible to eliminate process emissions by electrification or efficiency measures. However, it should not be presumed to be the lowest cost/most spatially advantageous option in all cases. Policymakers should be prepared to compare CCS with other mitigation options across the full value chain, including

energy used by the capture technology and the permanence of CO_2 storage [84].

Enhanced deployment will depend on improved capture performance and transport, suitable geological storage, clear life-cycle assessment, and effective policies. Other important elements will include independent performance verification, transparent long-term liability arrangements, and extensive consultation with affected communities. A deliberate strategy of direct emission reduction with few, well-designed CCS approaches is a more defensible strategy than promotion of CCS as a climate cure-all [84].

CO_2 Transportation

The transport of captured CO_2 is an essential step in the CCS value chain that links emission sites with utilization or geological storage. The transportation options are determined by the volumes of CO_2, distance of transportation, pressure-temperature requirements, stream composition, topography, and existing infrastructure [85]. Pipelines are normally suitable for large continuous CO_2 currents on fixed routes, while shipping provides flexibility for large volumes and source connection to remote or offshore storage sites. Rail and road can be suitable for smaller volumes, pilot projects, or areas without dedicated pipelines but may be constrained for large-scale applications due to capacity and logistics.

Pipeline and Ship Transportation

Pipelines are often appropriate for transporting large volumes of CO_2, since the high and predictable throughput may be amortized over the cost of the plant. Pipeline economics depend on a number of factors such as pipeline diameter and length, terrain, operating pressure, requirement for compressors, construction and maintenance costs, and utilization of infrastructure [86]. Dedicated CO_2 pipeline networks would enable the synchronization of several industrial units to centralized storage hubs and sharing of transportation infrastructure. However, pipeline design should take into account CO_2 phase behaviour, impurities in the stream, materials compatibility, corrosion issues, and impacts of accidental leaks. In cases where other cases are not technically feasible or cost-effective or just do not make sense for pipelines, shipping is the possible alternative. Shipping involves CO_2 conditioning and liquefaction, adequate storage tanks, loading and unloading terminals, and interface to receiving terminals and injection facilities [87]. In offshore cases and international routes, a ship largely imposes the transport flexibility; however, shipping costs depend on distance, the trend in shipment volume, energy required for liquefaction, ship filling, port infrastructure, and intermediate storage. Therefore, pipes and ships are not always the cheapest solution, and both must be compared based on consistent assumptions of cost, distance, throughput, and conditioning. In early CCS networks, smaller emission sources and pilots may be served by road and rail transit. They may be practical for facilities without pipelines, but could become costly with increasing volumes associated with time for loading / unloading, use of fuel, handling, and limited amount of cargo per trip. Consequently, a reliable transport strategy should assess projected increase in capture facilities, accessibility of storage sites, and access to shared infrastructure.

Material Compatibility and the Integrity of CO_2 Transportation Systems

Elastomers and engineered thermoplastics (polymers) are significant items for the CO_2 transportation chain. Elastomers and engineering thermoplastics can be utilised as seals, gaskets, liners, valves, and other devices operating in extreme conditions. However, some polymers may experience changes in physical and mechanical properties at high-pressure CO_2, leading to a loss of integrity in transport and storage systems [88].

The most important is swelling, which occurs due to the dissolution of CO_2 in the polymer and hence influences its dimensions or mechanical properties. Plasticization can decrease the stiffness of a material or alter its dimensional stability, and leaching of additives might impact long-term performance. Another problem is rapid gas decompression (RGD) when high-pressure CO_2 is introduced into the polymer and subsequently depressurized to liberate the trapped gas in the polymer matrix, which can evolve and cause internal damage that gives rise to blistering and cracking. These effects are a function of polymer composition, pressure, temperature, time of exposure, rate of decompression, and component geometry [89].

Material selection must therefore be based on the entire working envelope and not only on pressure resistance. Components can experience a range of physical and mechanical stresses from high-pressure transit, depressurization events, temperature variation, and maintenance [89]. Materials to be used in liquefied CO_2 systems working at low temperatures must also be considered for flexibility, sealing capability, and thermal cycle stress tolerance

Impurities, Corrosion, and Research Needs

The composition of the transported CO_2 stream can influence both material compatibility and transportation safety. Impurities such as hydrogen sulfide (H_2S), sulfur oxides (SO_x), nitrogen oxides (NO_x), oxygen, and residual process chemicals may affect phase behavior, chemical stability, and corrosion risk [90]. In particular, the presence of water alongside certain impurities can promote the formation of acidic species and increase the potential for corrosion in susceptible materials [90]. The significance of each impurity depends on its concentration, the water content, operating conditions, and the materials used throughout the system.

Examined the behavior of polymeric materials in the CO_2 transportation chain and highlighted uncertainties associated with their performance under demanding pressure and temperature conditions [90]. These concerns emphasize the need for material qualification procedures that reproduce realistic operating environments rather than relying exclusively on conventional laboratory tests [91]. Testing should assess swelling, changes in mechanical properties, additive extraction, permeation, chemical compatibility, and resistance to rapid gas decompression over relevant exposure periods.

Particular attention is warranted for low-temperature CO_2 handling near the CO_2 triple point, approximately −56.6°C and 5.18 bar under equilibrium conditions. These values describe a specific thermodynamic point, not the operating conditions of every transportation system. The potential for phase transitions, thermal stresses, and material-property changes must be evaluated according to the actual pressure–temperature pathway [91]. Future research should prioritize long term testing of polymers and elastomers under realistic combinations of pressure, temperature, impurities, moisture, and decompression conditions. Improved material standards and more representative testing protocols would support safer, more reliable, and economically sustainable CO_2 transportation infrastructure.

CO_2 Geological Storage

Geological storage of carbon dioxide (CO_2) is a key element of CCS since it can offer sequestration of collected carbon from the atmosphere over long time periods. Potential sites for storage include deep saline formations, depleted oil and gas reservoirs, coal-beds, and organic-rich shales (if suitable in geological and geomechanical terms). Apart from storage capacity, suitability of a storage site is based on several factors, including injectivity, reservoir pressure, integrity of a caprock, fault systems, existing wells, and capability for monitoring and risk management [92].

CO_2 can be trapped by structural and stratigraphic trapping, residual trapping, dissolution trapping, and mineral trapping. Structural and stratigraphic trapping occurs when geological barriers capture CO_2 from moving upwards. Residual trapping is CO_2 being trapped in isolated pores; dissolution trapping is where CO_2 is trapped in formation water. Mineral entrapment occurs if conditions are favourable, when dissolved carbon reacts geochemically to form solid carbonate minerals. However, their relative contribution is a function of formation features, composition of injected stream, and considered time range [93].

Wettability and Its Influence on Storage Performance

Wettability is an attribute controlling CO_2 , formation water, and reservoir mineral behaviour. It is the tendency of one fluid to spread across or stick to a solid surface in the presence of other fluids. Wettability in geological storage can affect capillary pressure, fluid distribution in pore spaces, residual trapping, and CO_2 movement in porous rocks [94].

Rock mineralogy, reservoir temperature and pressure, brine chemistry, surface organic compounds, and surface roughness can affect the behaviour of CO_2 in a geologic formation. In rare instances, organic acids (natural pollutants) can be adsorbed, altering the mineral surface characteristics and the wettability of the reservoir rock. Such changes in wettability can influence the distribution of CO_2 and water and hence the storage capacity and containment [95]. This effect is formation specific and cannot be generalized without experimental or field data.

The surface of natural rocks is chemically diverse, and wettability has been studied in laboratory conditions. Surface modification, organic matter, brine composition, and mineral impurities can cause behaviours that differ from those of chemically pure mineral surfaces [95]. Future studies should therefore evaluate wettability under reservoir-relevant conditions and test the relevance of measured contact angles/interfacial characteristics to changes in capillary pressure, residual trapping, injectivity, and storage security.

Nanoparticles and Wettability Modification

In geological storage, NPs may be used for mineral surface modification and fluid control. NPs can alter wettability, interfacial tension, and fluid transport in porous media depending on NP chemistry, concentration, surface chemistry, and interaction with formation waters [96]. Hence, their application has been of study interest to modify several features of CO_2 storage performance.

Nevertheless, the employment of nanoparticles to generate more waterwet conditions should be regarded as a new research technique rather than an established storage-enhancement technology [96]. The efficiency of nanoparticle treatment depends on the mineralogy of the formation, nanoparticle stability, brine composition, adsorption behavior, transport through pore networks, and compatibility with reservoir conditions. Aggregation, retention near the injection well, variations in permeability, and other environmental consequences all require assessment.

Laboratory data alone are insufficient to establish that nanoparticle treatment will increase the secure storage capacity of a geological formation. Further study should combine wettability data with core-flooding experiments, multiphase-flow analysis, geochemical characterization, and reservoir-scale modelling. Field trials, when justified, would also need to consider nanoparticle transport, long-term stability, environmental safety, and the realistic economics of deployment [96]. These experiments could show whether wettability modification delivers measurable benefits beyond those possible through standard site selection, injection management, and monitoring.

Synergies Between Capture, Utilization, and Storage

CCUS represents an integrated approach for CO_2 emission reduction in which capture technologies, industrial applications and permanent geological storage are integrated to CCUS (carbon capture, utilization and storage). This approach can increase resource efficiency, reduce the cost of infrastructures, and make carbon management projects more economically viable.

Sequestered CO_2 can be used to produce chemicals, synthetic fuels, building materials, and mineral carbonates. However, the environmental benefits are dependent on the energy consumption, product lifetime, and amount of carbon sequestered. Mineral carbonation to carbonates can utilise suitable raw materials containing calcium and magnesium such as basalt as well as industrial wastes such as fly ash for long-term CO_2 storage [97].

Injected CO_2 can also be used for enhanced oil recovery (EOR), where CO_2 can be injected into suitable reservoirs to extract oil. EOR revenues could provide incentives to invest in CO_2 infrastructure and to recover some of the costs of capture and injection. However, injected CO_2 is partly produced in recovery, and EOR can lead to new emissions [98]. The climate benefits of CO_2-EOR therefore depend on how much CO_2 is retained in the subsurface and on total lifecycle emissions, including emissions from the oil recovered.

Other approaches being investigated for mineralization in combination with direct air capture would remove CO_2 from the atmosphere and sequester permanently, possibly in more stable forms. However, energy demands, reaction efficiency, availability of materials, and economics of these approaches need to be further assessed [98].

Carbon capture and utilization/storage might enhance carbon management approaches by making the source of emissions and technology deployment work hand in hand between the industrial sector and geological storage sites [98]. Successful implementation will require life cycle assessment, robust infrastructure, and verification of emission reductions to ensure economic gains are realized as long-term climate benefits.

Challenges in CCS Implementation

Despite advances in capture technologies and geological storage, the widespread implementation of CCS remains constrained by economic, technical, social, and policy-related barriers. High capital and operating costs can make CCS less competitive than alternative emissions-reduction options in some applications [99]. Energy

requirements for CO_2 separation, compression, and transportation can reduce net emissions benefits, while inadequate pipeline networks and uncertainty regarding storage-site availability can delay project development [99]. The viability of individual projects therefore depends on the integration of the entire CCS value chain rather than the performance of the capture unit alone.

Economic and Infrastructure Barriers

The costs of a CCS project will depend, but not be limited to, emissions source and type, type of capture technology, size of facility, energy cost, transport distance, and storage geology. For example, capture costs for industrial plants (emitting concentrated CO_2) may be different from coal-fired plants or plants emitting diluted flue gases [100]. If sufficient throughput can be supplied, there is potential for economies of scale in combined pipeline and storage construction for many emitters, but this is a gamble if captures are delayed or not pursued.

Economically, comparisons should separate the economic price per tonne captured from the economic price avoided per tonne and should include the energy price, conditioning price, and transportation/injection/monitoring price of any additional carbon dioxide as appropriate [100]. This should be the case for renewables, electrification, efficiency gains, and re-engineering and should include the technical feasibility of each option. CCS may be relevant particularly where process emissions are difficult to avoid, but should not be assumed to be the lowest-cost option in all cases.

Public Acceptance and Storage Safety

Public acceptance is vital to the successful implementation of CCS, especially in areas near transport chains or storage sites and in areas of habitation or other sensitive environments. Issues can include pipe leakage, CO_2 escape, protection of aquifers, induced earthquakes, land uses, and the long-term liability for sequestered carbon. Well-designed projects require long safety discussions, acceptance of emergency-response plans, third-party verification, and very precise limitations on environmental and economic issues.

All safety claims for storage should be supported by credible evidence. The Norwegian Sleipner project is often cited in geological offshore CO_2 storage and monitoring studies [101]. However, a general leak cannot be claimed at Sleipner—rather, it must be a documented event with a credible source. Of the ongoing and monitored field projects, the results should be circulated and interpreted in appropriate context of the individual site as they may give a better indication of how the plume behaves in terms of migration, reservoir, and containment.

Policy and Regulatory Support

Government policies may facilitate CCS adoption through carbon pricing, tax credits, research funding, infrastructure investment, and regulation of geologic storage. For instance, in the United States, the Section 45Q tax credit provides a financial incentive for eligible carbon capture and storage projects, subject to certain eligibility criteria. In the European Union, the Emissions Trading System (EU ETS) sets a price on regulated greenhouse gas emissions, which may improve the business case for qualifying CCS projects [101].

Their efficacy depends on the design of regulations (e.g., carbon price, costs of eligible projects for the mechanisms, criteria for qualifying projects, and regulatory stability) and on the availability of infrastructure. Regulations should cover permits, specifications for streams of CO_2, transportation safety, approval of storage sites, monitoring, reporting, remediation of sites, closure, and long-term liability [101]. Policies must reward real climate benefits not simply sequestered volumes of CO_2 as proof of emissions mitigation.

Integrated Assessment and Future Directions

Carbon captured and storage (CSS) principles will depend on the efficiency of technology, social efficiency, cost efficiency, and environmental efficiency. Better solvent recovery, adsorbent life, membrane performance, CO_2 handling, transportation, and storage medium may help to reduce costs and economics. However, innovations must be demonstrated in practice and under normal conditions of systems before one can claim performance improvement.

Future work should focus on the relationship between capture technology, transport, and geological storage. These include material compatibility to realistic CO_2 mixtures, reservoir characterization, monitoring, and life cycle emissions and cost variability. There may be opportunities for threads of international cooperation to exchange knowledge and to develop technical standards (where appropriate) and trans-national transport and storage systems.

Overall, CCS can contribute to climate change mitigation when applied to suitable sources of emissions and when supported by appropriate infrastructure, safe geological storage, suitable regulation, and transparent evaluation of its effectiveness. It should be additional to direct emission reductions from such sources as renewable energy, energy efficiency, electrification, and cleaner industrial processes. Overall, long-term climate thinking and responsible deployment of carbon capture and storage should herald sober reflection on the part of measures necessary with carbon capture and storage and other viable mitigation options.

Cost Reduction Through Technological Integration

CCUS can be made less expensive through improved capture, transport, and store. Need to consider low-cost materials, thermal recovery, process improvement, and shared infrastructure. [102] Capture systems combined with renewable energy and appropriate waste heat from related industries could potentially lower emissions as well as costs, depending on the system. New AI and digital technologies to optimize predictive-maintenance and as add-ons to monitoring require more field exploitation.

Another dimension is economic modelling and policy making. Other studies might focus on the impact of carbon pricing, fiscal benefits, infrastructure support, and the regulatory certainty of projects across various sectors. Such analysis can help in striking a balance between the economic viability and the actual environmental effects [103].

Capture Efficiency, Scalability, and Deployment

Further research is required to improve the capture efficiency with low energy consumption. Solvent problems should be investigated (degradation, lifetime, regeneration) and post-, pre-, and oxy-combustion methods should be considered [104]. The main issue is scaling up small-scale laboratory systems to create robust large-scale systems. As such, pilot-scale testing should be carried out to consider the long-term performance, cost, energy consumption and compatibility with existing industrial systems [104]. Comparisons can be made between new technologies by using the same criteria to compare capture efficiency, CO_2 purity, energy consumption,

lifetime and cost of $ per tonne captured/abated. This will help determine if there are significant improvements in the new materials and processes.

Transportation, Storage, and CO_2 Utilization

Future studies should strengthen the pipeline design and the materials used so as to provide a safer and economic source of CO_2 transportation alternative to marine transport. Geologic storage research should emphasize better site characterization, injection management, monitoring, and evaluation of leakage risks.

More must be known about CO_2 -utilization pathways (chemical, biological, mineralization). Climate benefits depend on energy sources, lifetime of the product, market demand, and final fate of the carbon. Economic analyses should consider the net environmental benefit of CO_2 -based products and their substitution in economically attractive product markets [105]. Short-term carbon utilization vs long-term carbon sequestration strategies have to be distinguished.

Socio-Environmental Impacts, Policy, and Regulation

Technical assessments of life cycles are critical to estimating (i.e., quantifying) greenhouse gas emissions, energy use, the demand for resources, and impacts on the environment in CCUS systems [106]. Community and stakeholder engagement is crucial for managing pipeline risks, protecting groundwater, and ensuring the integrity of long-term storage.

Successful implementation will require commitment to clear rules, appropriate incentives, credible oversight, and international cooperation as a means of improving security of investment and assurance of proper application. Further examination of policy options should focus on whether such regulatory regimes can resolve the trade-offs between costs and liability risks, encourage the development of verified emissions reductions, and clarify the protocols for monitoring storage sites and defining long-term liabilities.

Life Cycle Assessment of CCUS Pathways

Life cycle assessment (LCA) is employed to investigate the environmental impacts of CCUS from cradle to grave (capture, conditioning, transport, utilization, and storage). However, the LCA results are not comparable between studies due to differences in system boundaries, energy assumptions, functional unit, and allocation method.

Capacity for capture processes may be different in terms of energy, and combining capture with chemical conversion or hydrogenation and mineralization involves different energy and material requirements. Net environmental impact will depend on the carbon intensity of the energy sources, conversion efficiency, and product offsets. Carbon sequestration may be stored in a variety of well-defined geological formations (under geological control and regulation) over time [106].

Future life cycle assessments should rely on consistent assumptions and distinguish between sequestered CO_2, emission reductions, and permanent carbon removals. Do not mix and match. Sensitivity analyses should also cover storage conditions, product lifecycle, capture efficiency, and energy source. Such assessments are therefore important for technology choice and for investment and policymaking and are important to identify CCUS technology options with real climate benefits [106].

Conclusion

Carbon capture and storage (CCS) is an important strategy for reducing carbon dioxide (CO_2) emissions from industrial processes and energy production, particularly in hard-to-abate sectors. CCS can help decarbonize the world by capturing CO_2 and storing it in suitable geological formations. Carbon capture, use and storage (CCUS) can transform the captured CO_2 into valueadded products with benefits in addition to energy requirements, product permanence choices, and opportunities to sequester carbon.

Broad use of CCS is hampered by costs; by the energy required; by infrastructure needs; and by safety issues and public opinion. Furthermore, progress in capture material, transport networks, and monitoring technologies enables increased efficiency and reliability. But their ultimate potentials and economics remain to be evaluated at a larger scale.

Future development will rely upon the further development of low-cost capture technologies, increased transport infrastructure, better supervision of geological storage, and more robust regulatory schemes. Life-cycle assessments will be critical to ensure emissions reductions and separate captured CO_2 from avoided emissions and sequestered carbon.

CCS should be a complement, not a substitute, for renewable energy, energy efficiency, electrification, and other emission reduction measures. Addressing these current challenges will require collaboration among governments, industries, and researchers to ensure that CCS delivers actual environmental benefits in a low-carbon world.

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