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Review

Innovative Pathways in Carbon Capture: Advancements and Strategic Approaches for Effective Carbon Capture, Utilization, and Storage

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Abstract: Due to carbon dioxide (CO_2) levels, driven by our reliance on fossil fuels and deforestation, the challenge of global warming looms ever larger. The need to keep the global temperature rise below 1.5 °C has never been more pressing, pushing us toward innovative solutions. Enter carbon capture, utilization, and storage (CCUS) technologies, our frontline defense in the fight against climate change. Imagine a world where CO_2, once a harbinger of environmental doom, is transformed into a tool for healing. This review takes you on a journey through the realm of CCUS, revealing how these technologies capture CO_2 from the very sources of our industrial and power activities, repurpose it, and lock it away in geological vaults. We explore the various methods of capture—post-combustion, oxy-fuel combustion, and membrane separation—each with their own strengths and challenges. But it is not just about science; economics play a crucial role. The costs of capturing, transporting, and storing CO_2 are substantial, but they come with the promise of a burgeoning market for CO_2-derived products. We delve into these financial aspects and look at how captured CO_2 can be repurposed for enhanced oil recovery, chemical manufacturing, and mineralization, turning waste into worth. We also examine the landscape of commercial-scale CCS projects, highlighting both global strides and regional nuances in their implementation. As we navigate through these advancements, we spotlight the potential of Artificial Intelligence (AI) to revolutionize CCUS processes, making them more efficient and cost-effective. In this sweeping review, we underscore the pivotal role of CCUS technologies in our global strategy to decarbonize and forge a path toward a sustainable future. Join us as we uncover how innovation, supportive policies, and public acceptance are paving the way for a cleaner, greener world.

Keywords: adsorption processes; carbon capture utilization and sequestration (CCUS); global warming; post-combustion capture; enhanced oil recovery (EOR); CO_2 storage; decarbonization; AI in CCS

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1. Introduction

The rise in atmospheric CO_2 from fossil fuel use and deforestation is a major factor in global warming and climate change. Carbon capture, utilization, and storage (CCUS) technologies are crucial for reducing emissions and promoting sustainable development. CCUS captures CO_2 from industrial sources, repurposes it for various applications, and stores it in geological formations. This study reviews the methods of CO_2 capture, including post-combustion, oxy-fuel combustion, and membrane separation, and examines their economic and technological challenges. Utilization strategies, such as enhanced oil recovery (EOR) and chemical production, are explored, alongside long-term sequestration techniques in deep saline aquifers and depleted oil fields. The review emphasizes the need for innovation, regulatory support, and public acceptance to overcome the challenges and enhance the adoption of CCUS technologies globally [1,2].

To mitigate the severe environmental impacts of global warming, the IPCC stresses the need to limit the global temperature rise to below 1.5 °C. In this effort, decarbonization and the advancement of CCUS technologies play a critical role in reducing greenhouse gas emissions and supporting the transition to a sustainable future [3,4].

CCUS technologies involve capturing CO_2 from industrial and power generation sources, utilizing it for various applications, and sequestering it in geological formations. These processes not only help in reducing CO_2 emissions but also offer the potential to convert CO_2 from a waste product into a valuable resource [5,6]. Integrating CCUS with renewable energy sources can significantly enhance the potential to achieve carbon neutrality, contributing to global decarbonization efforts. Carbon capture processes include several methods to isolate CO_2 from industrial emissions: post-combustion capture, where CO_2 is captured after fossil fuel combustion; oxy-fuel combustion, which uses oxygen to produce a flue gas mainly composed of CO_2 and water vapor; and membrane separation, employing selective membranes to separate CO_2 from other gases [7–11].

Each technique has its benefits and limitations, with ongoing research aimed at optimizing these processes to improve efficiency and reduce costs. According to the IEA's Stated Policies Scenario (STEPS), emissions are expected to peak around 2025, slightly declining to 34.7 gigatons (Gt) by 2030. The EIA's projections indicate a potential range between 37.4 Gt and 43.08 Gt by 2030, based on different scenarios [12]. These projections highlight the critical need for enhanced policy measures and an accelerated adoption of clean energy technologies to achieve significant reductions in CO_2 emissions.

Figure 1 provides a comprehensive visualization of global greenhouse gas (GHG) emissions, along with sectoral, regional, and future projections for CO_2 emissions. Figure 1a depicts the distribution of global greenhouse gas emissions by type in 2018. Carbon dioxide (CO_2) is the dominant contributor, accounting for 73.7% of total emissions, followed by methane (18.3%), nitrous oxide (5.6%), and fluorinated gases (F-gases, 2.4%). Figure 1b illustrates the global CO_2 emissions by country from fossil fuel combustion in 2020. China is the largest emitter, responsible for 32.5% of global emissions, followed by the United States at 12.6%, the European Union (EU-27) at 7.3%, India at 6.7%, and the Russian Federation at 4.7%. Other countries collectively contribute 33.3% of emissions. Figure 1c shows the breakdown of global CO_2 emissions by sector in 2020. The power industry is the largest source, contributing 36.6% of emissions. Other notable sectors include industrial combustion (21.8%), transport (20.1%), buildings (9.4%), and other sectors (12.1%). Figure 1d presents projected global CO_2 emissions from fossil fuel combustion through 2030. The projections are based on estimates from the International Energy Agency (IEA) and the U.S. Energy Information Administration (EIA). The IEA's Stated Policies Scenario (STEPS) predicts a steady increase in emissions, while the EIA's projections show a range, with the upper bound indicating a sharper rise compared to the lower bound, suggesting various potential futures depending on policy implementations. Together, these visualizations highlight the major contributors to GHG emissions and underline the critical sectors and regions for addressing emissions, as well as providing an outlook on future emission trajectories based on different policy pathways [12–19].

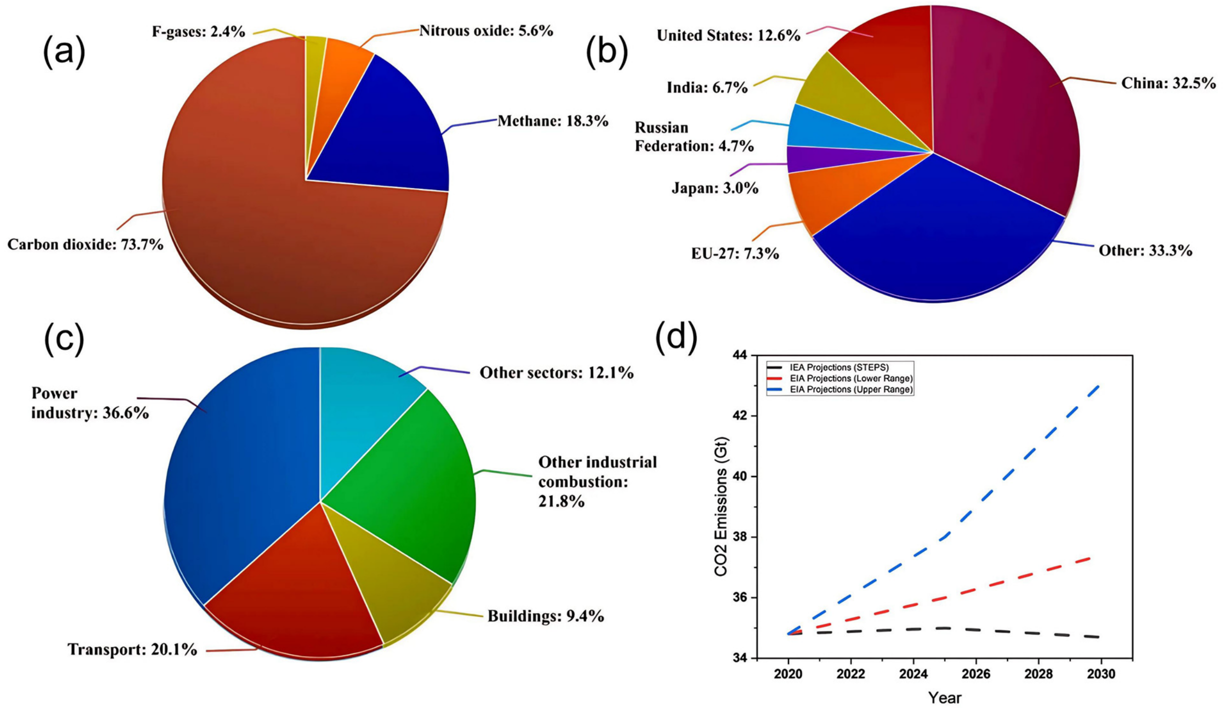

Figure 1. (**a**) Global greenhouse gas emissions by gas in 2018. (**b**) Global CO_2 emissions by country from fossil fuel combustion in 2020. (**c**) Global CO_2 emissions by sector in 2020. (**d**) The graph shows projected global CO_2 emissions from fossil fuel combustion by 2030, based on forecasts from the International Energy Agency (IEA) and the U.S. Energy Information Administration (EIA) [20].

Once captured, CO_2 can be utilized in various ways, transforming it into a resource. Enhanced oil recovery (EOR) is a notable application where CO_2 is injected into declining oil fields to boost production. This not only maximizes the extraction of existing fossil fuel reserves but also offers a storage solution for captured CO_2 [21,22]. Additionally, CO_2 can be used in producing chemicals like urea and methanol, and in mineralization processes where CO_2 reacts with minerals to form stable carbonates, permanently sequestering the CO_2. The long-term sequestration of CO_2 is achieved by injecting it into geological formations such as deep saline aquifers, depleted oil and gas fields, and unmineable coal seams. These formations provide secure storage sites for CO_2, ensuring it does not re-enter the atmosphere. Selecting suitable storage sites requires detailed geological surveys and monitoring to ensure safety and integrity.

Despite the significant potential of CCUS technologies, their implementation faces several challenges, primarily the high costs of capturing, transporting, and storing CO_2. The financial demands of establishing CCUS infrastructure, coupled with operational and maintenance costs, pose significant barriers. Technological limitations related to the efficiency and scalability of current capture methods further complicate widespread adoption. Ongoing research and development aim to address these challenges by enhancing capture technologies, developing cost-effective materials, and improving process efficiencies [8].

Regulatory and policy frameworks are crucial for the deployment of CCUS technologies. Clear policies that provide incentives, such as carbon pricing mechanisms, subsidies, and tax credits, are needed. International cooperation and policy alignment are essential to facilitate the widespread adoption of CCUS. Moreover, public acceptance and trust are critical for the success of CCUS projects. Transparent communication and engagement with the public to address concerns related to safety, environmental impact, and economic implications are vital for building support [23,24].

The hydrocarbon industry can benefit from adopting CCUS technologies. By integrating CCUS into their operations, hydrocarbon companies can reduce their carbon footprint; meet environmental, social, and governance (ESG) criteria; and secure access to capital.

CCUS also offers these companies an opportunity to transition toward more sustainable business models by leveraging their expertise in subsurface operations and infrastructure development [25].

This review provides an in-depth analysis of current carbon capture, utilization, and sequestration (CCUS) technologies. It focuses on various CO_2 capture methods, including post-combustion, oxy-fuel combustion, and membrane separation, as well as transportation techniques via pipelines and shipping. Economic aspects are examined, highlighting capital and operational costs, market potential for CO_2-derived products, and the impact of policy incentives. The review also addresses technological challenges and future prospects for CCUS integration in global decarbonization strategies, emphasizing the need for innovation, supportive regulatory frameworks, and public acceptance to achieve large-scale deployment and carbon neutrality.

2. The Role Carbon Capture Technologies

Innovation in information resources is key to economic development, enhancing productivity and narrowing income disparities between nations. Fast-growing countries are expected to achieve equilibrium with the industrialized world through technological advancements [26]. As energy technologies become more reliable and cost-effective, CO_2 emissions may rise, but modernizing fossil-fueled power production is predicted to reduce CO_2 capture costs significantly [27]. Carbon capture, utilization, and storage (CCUS) technologies are essential for decarbonizing hard-to-electrify sectors like heavy industry and transportation. These systems capture CO_2 from industrial sources, convert it into useful products, or store it in geological formations. CCUS can cut emissions by up to 90%, convert CO_2 into fuels and chemicals, and ensure permanent carbon removal through storage. Despite challenges like high costs, regulatory hurdles, and public resistance, CCUS is increasingly recognized as vital for decarbonization, with global efforts focused on scaling up its use. Key strategies include enhancing energy efficiency, switching to carbon-free electricity, and using cleaner production processes. Evaluation models like MIND and MiniCAM 98.3 assess these options. Solutions for CO_2 capture include aqueous amine scrubbers, porous materials (e.g., silicas and zeolites), and ionic liquids (ILs), with porous materials offering better thermal stability and ILs providing non-volatility and adaptability. However, these materials often struggle to eliminate CO_2 from humid, low-concentration streams due to competition with water for physisorption sites. Low thermal conductivity also complicates the heating and cooling of adsorbents during cycling [28,29].

Novel chemisorptive routes for selective CO_2 capture are emerging. For instance, mounting amines on ILs anions derived from amino acids can double molar adsorption efficiency. Some ILs with alkoxide or phenoxide anions can capture CO_2 without amines. MOF M2 variants functionalized with diamine show promise for post-combustion CO_2 capture due to their stability. Bioinspired approaches, like mimicking carbonic anhydrase enzymes, offer additional avenues for innovation [30,31]. High-valent monodentate metal hydroxides in water-stable MOFs bind CO_2 selectively, but further advancements in computational, analytical, and synthetic chemistry are needed to develop transformative materials and processes to reduce anthropogenic CO_2 emissions [32].

3. Commercial-Scale CCS Projects

The deployment of commercial-scale carbon capture and storage (CCS) projects has been slow, with 37 major projects identified globally. Of these, 17 are operational, 4 are under construction, and the rest are in development. The U.S. leads in both the number of operational projects and CO_2 capture capacity, where most captured CO_2 is stored through enhanced oil recovery [33]. Key projects in carbon capture and storage (CCS) include the Century Plant, capturing 8.4 million tons of CO_2 annually, and the Shute Creek Gas Processing Facility, capturing 7 million tons. China, with the second-largest number of CCS projects, mainly has initiatives in early stages, capturing from 0.4 to 2 million tons per year. Europe ranks third, with two sites in Norway: Sleipner (1 million tons annually) and

Snøhvit (0.7 million tons). In Canada, three out of five projects are operational, including the Great Plains Synfuel Plant and Weyburn-Midale (3 million tons), Boundary Dam (1 million tons), and Quest (1 million tons). Brazil, Saudi Arabia, and the UAE have operational projects capturing from 0.8 to 1 million tons annually. The success of CCS depends on available geological storage, secure funding, and supportive policies to move projects from development to operation. Figure 2 illustrates two aspects of CCS processes: Figure 2a shows a simplified carbon capture and storage (CCS) cycle. Biomass with a high yield is used to capture CO_2 during energy production. CO_2 is then separated and transported to be compressed and stored in geological formations, such as underground reservoirs. This process reduces the carbon footprint by capturing CO_2 emissions before they enter the atmosphere, while also producing non-energy byproducts during energy generation. Figure 2b provides a detailed view of the carbon sequestration cycle involving human-made infrastructure and natural reservoirs. CO_2 is first separated and captured at large-scale emission sources like industrial plants or power stations. After capture, CO_2 is transported via pipelines to storage sites. The diagram highlights two types of storage: onshore aquifers and offshore aquifers. Both types of reservoirs are sealed by impermeable layers to prevent CO_2 from escaping. CO_2 can be injected into these geological formations either from above-ground facilities or offshore platforms, ensuring long-term carbon storage. Together, these images illustrate the full cycle of CCS, from capturing CO_2 at industrial sources to safely storing it underground, mitigating its release into the atmosphere [34–36].

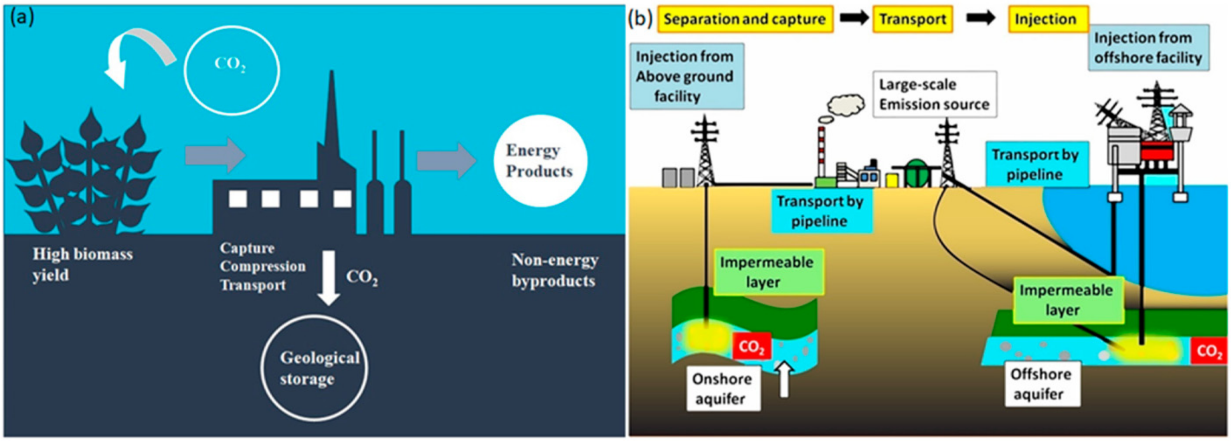

Figure 2. (**a**) The figure depicts the cycle of carbon capture, transportation and further storage. (**b**) The figure shows the cycle of the carbon that it follows after sequestration involving human-made transport lines and the natural flow of carbon [10].

3.1. Oil & Gas Industry

The oil and gas industry, historically a significant contributor to greenhouse gas emissions, is actively working to reduce its carbon footprint and lessen the environmental impact of its operations. These initiatives focus on minimizing emissions at both upstream and downstream stages, integrating renewable energy solutions, and implementing carbon capture technologies. A major focus for the oil and gas sector is the implementation of advanced Leak Detection and Repair (LDAR) programs aimed at addressing methane emissions, a potent greenhouse gas. Companies are adopting state-of-the-art technologies such as infrared cameras, drones, and continuous monitoring sensors to effectively monitor, detect, and repair methane leaks in production, processing, and distribution infrastructure. These advancements enable rapid identification of fugitive emissions, especially in remote areas. By significantly reducing methane leaks, these programs not only mitigate environmental impacts but also enhance operational efficiency by preventing the loss of valuable natural gas. In addition to LDAR programs, many oil and gas companies are making substantial investments in renewable energy projects. Offshore wind farms and solar installations are key areas of focus. Notably, offshore wind projects leverage the expertise of oil and gas companies in offshore drilling and infrastructure development. These investments indicate a strategic transition toward diversifying energy portfolios and supporting the growth of renewable energy sources, positioning the industry as a vital player in the global energy transition. Furthermore, carbon capture and storage (CCS) technology is gaining traction within the oil and gas sector as an essential method for reducing emissions. CCS involves capturing CO_2 emissions produced during fossil fuel extraction and combustion, followed by storing them underground in geological formations. Several major oil companies are investing in CCS infrastructure at production sites and power plants. These projects aim to capture CO_2 directly from industrial processes or from natural gas combustion. The captured CO_2 is then either stored in depleted oil reservoirs or utilized for enhanced oil recovery (EOR). By implementing CCS, the industry addresses both direct emissions from operations and those resulting from end-use products [37–41].

3.2. Steel Industry

The steel industry, one of the largest industrial sources of carbon emissions, is exploring innovative technologies and processes to decarbonize steel production. Traditional steelmaking methods that rely on coal in blast furnaces produce significant CO_2 emissions. The Hydrogen Breakthrough Ironmaking Technology (HYBRIT) project in Sweden represents a groundbreaking advancement in steel production by utilizing hydrogen instead of coal for iron ore reduction. This process generates water vapor as a byproduct rather than CO_2, making it a carbon-neutral method for steelmaking. As hydrogen becomes increasingly available from renewable sources like wind and solar power, hydrogen-based steel production could revolutionize the industry by eliminating emissions at its core. Another promising approach involves using electric arc furnaces (EAF) for steel production. EAFs recycle scrap steel by melting it with electric energy, resulting in significantly lower CO_2 emissions compared to traditional blast furnaces. When powered by renewable energy sources such as wind or solar power, EAFs can achieve near-zero emissions. This method is gaining traction in regions where renewable energy is both abundant and cost-effective, making it a vital component of the industry's decarbonization efforts. In addition to transitioning to hydrogen-based methods or electric arc furnaces, the steel industry is also investigating carbon capture technologies specifically designed for steel production. These technologies aim to capture CO_2 generated during conventional steelmaking processes before it can be released into the atmosphere. Innovations include capturing CO_2 from blast furnace emissions and integrating CCS with existing infrastructure. Although CCS remains energy-intensive and costly, ongoing research aims to improve efficiency and reduce costs, making these systems more viable for widespread application in the steel sector [42–45].

3.3. Cement Industry

Concrete, second only to clean water, is the most widely produced material globally, and the cement industry significantly contributes to global CO_2 emissions, accounting for over 5% of the total. Each ton of cement produced releases approximately 880 kg of CO_2 into the atmosphere. The emissions arise from two primary sources: about 60% of the CO2 comes from the calcination of limestone ($CaCO_3$) into calcium oxide (CaO), a crucial component in cement, while the remainder results from the fuel combusted to heat the kiln. Given the substantial emissions from both sources, carbon capture and storage (CCS) technologies are vital for reducing the industry's carbon footprint and achieving global warming targets. Several CCS technologies are suitable for cement production, including post-combustion methods such as solvent scrubbing, solid sorbents, and calcium looping, as well as oxy-fuel combustion and direct capture. Unlike power generation, pre-combustion technologies are not applicable to cement production because they do not capture the significant process-related emissions from limestone calcination [46–50].

Among these methods, calcium looping presents synergies with cement production since it utilizes CaO, which is also used in making cement. Direct capture is particularly noteworthy as it involves indirect radiative heating of limestone-containing raw materials to generate a pure CO_2 stream. However, a primary challenge for implementing CCS in cement production is ensuring that product quality remains unchanged after applying these systems. Post-combustion capture systems using alkanolamines or other sorbent-based methods can maintain product quality; however, most cement plants lack sufficient low-grade heat to capture more than about 50% of the CO_2 produced without integrating a combined heat and power (CHP) plant. Oxy-fuel systems and direct capture offer potential efficiency gains. Oxy-fuel systems reduce thermal ballast by eliminating nitrogen from the air, while direct capture provides thermodynamic benefits by producing a pure CO_2 stream directly. The conventional cement production process consists of three primary stages: calcination, where limestone decomposes into calcium oxide and CO_2 at 900 °C; clinkering, where CaO reacts with aluminum oxide, silicon oxide, and ferric oxide at temperatures between 140 and 1500 °C to produce clinker; and milling, where clinker is mixed with gypsum and other additives before being ground into cement. Figure 3 illustrates the simplified process. The costs associated with carbon capture technologies in the cement industry vary significantly. For instance, solid sorbent technology can cost approximately EUR 38 per ton of CO_2 captured, while membrane [51,52] systems may cost around EUR 84 per ton. Retrofit costs for implementing these technologies have been estimated at about EUR 80 per ton. However, it is important to note that this carbon capture process alone can increase the base cost of clinker by 49–92%.

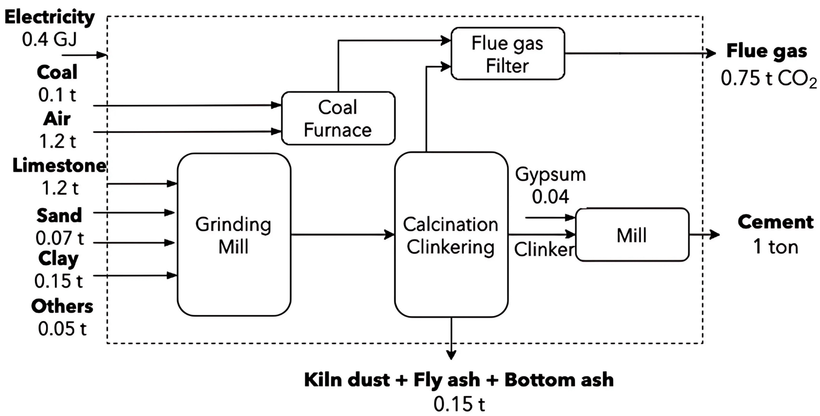

Figure 3. The conventional cement production process involves retrieving dust, bottom ash, and fly ash from the kiln and coal furnace.

In summary, while CCS technologies present significant opportunities for reducing CO_2 emissions in the cement industry, challenges persist regarding maintaining product quality, ensuring adequate low-grade heat for effective capture processes, and managing increased production costs. Innovative solutions and synergies between cement production and CCS technologies are essential for achieving substantial emissions reductions in this sector [47,48].

3.4. Pathway to Net-Zero Carbon Emissions: Climate and Energy Transition Goals (2023–2050)

The global response to climate change necessitates a comprehensive strategy spanning short, medium, and long-term objectives aimed at decarbonizing the world economy. These goals focus on enhancing energy efficiency, expanding renewable energy adoption, and developing innovative technologies to mitigate greenhouse gas emissions [1].

3.5. Short-Term Goals (2023–2030)

Energy Efficiency and Renewable Expansion: In the immediate future, efforts will concentrate on improving energy efficiency across various sectors and rapidly expanding renewable energy infrastructure. The aim is to reduce energy intensity in economic activities without compromising growth, while simultaneously ensuring that at least 50% of global electricity generation comes from renewable sources by 2030. This will require substantial investments in renewable technologies, energy storage systems, and the implementation of supportive policies.

Stringent Efficiency Standards: Concurrently, the implementation of rigorous energy efficiency standards for buildings, appliances, and industrial equipment is crucial. This includes upgrading building codes, retrofitting existing structures, and mandating energy-efficient HVAC systems, insulation, and lighting.

3.6. Medium-Term Goals (2030–2040)

Carbon Capture and Low-Carbon Transition: The medium-term objectives focus on scaling up carbon capture, utilization, and storage (CCUS) technologies, aiming to capture and store or utilize 5–10% of global CO_2 emissions. This period will also see a significant transition to low-carbon fuels in the transportation sector, with widespread adoption of electric vehicles and sustainable biofuels for aviation and heavy transport.

Advanced Nuclear Technologies: Development and deployment of advanced nuclear technologies, including small modular reactors (SMRs) and Generation IV reactors, will be crucial to ensure a stable and clean baseload power source. These technologies offer enhanced safety features, improved efficiency, and reduced waste production.

3.7. Long-Term Goals (2040–2050)

Negative Emissions and Circular Economy: The long-term strategy aims to achieve negative emissions through large-scale Direct Air Capture (DAC) technologies and extensive afforestation programs. By 2050, the goal is to remove more CO_2 from the atmosphere than is emitted. Simultaneously, implementing a circular economy approach across industries will minimize waste and maximize resource efficiency.

Breakthrough Technologies: By 2050, the deployment of breakthrough technologies such as fusion energy and advanced energy storage systems is anticipated. Fusion energy, which mimics the sun's power generation process, promises an abundant and clean energy source. Advanced energy storage technologies will enable widespread adoption of renewable energy by providing long-duration storage for intermittent power sources.

These climate and energy transition goals reflect a holistic approach to decarbonizing the global economy, balancing immediate improvements with long-term technological innovations. The successful implementation of these strategies aims to achieve net-zero emissions by 2050 while fostering sustainable economic growth and ensuring a resilient energy future.

3.8. CO_2 Capture Technologies

(A) Post-combustion Capture

Post-combustion capture involves capturing CO_2 from exhaust gases after combustion in power plants or industrial facilities. This widely used and advanced CCUS technology employs chemical solvents, such as amine-based solutions, to absorb CO_2 from flue gas. The CO_2-rich solvent is then separated and regenerated, and the concentrated CO_2 is compressed for storage or utilization [53]. Post-combustion capture holds great promise for reducing emissions from power plants and industries, but it faces notable challenges. High energy and financial costs for capture and regeneration can reduce facility efficiency and increase operational expenses. Additionally, the use of chemical solvents may pose environmental risks, including hazardous substance release and waste byproducts [54]. Despite these challenges, post-combustion capture is expected to be vital for CCUS, particularly in the power sector. Research is actively working to improve efficiency, lower costs, and address environmental concerns. Additionally, alternative technologies such as membrane-based capture and Direct Air Capture (DAC) are under exploration. See Figure 4 for details. Direct Air Capture (DAC) technology captures CO_2 directly from the atmosphere, offering a potential solution to reduce greenhouse gas concentrations.

Recent advancements have improved DAC's efficiency, scalability, and integration with sustainable technologies. The key advancements in Direct Air Capture technology include:

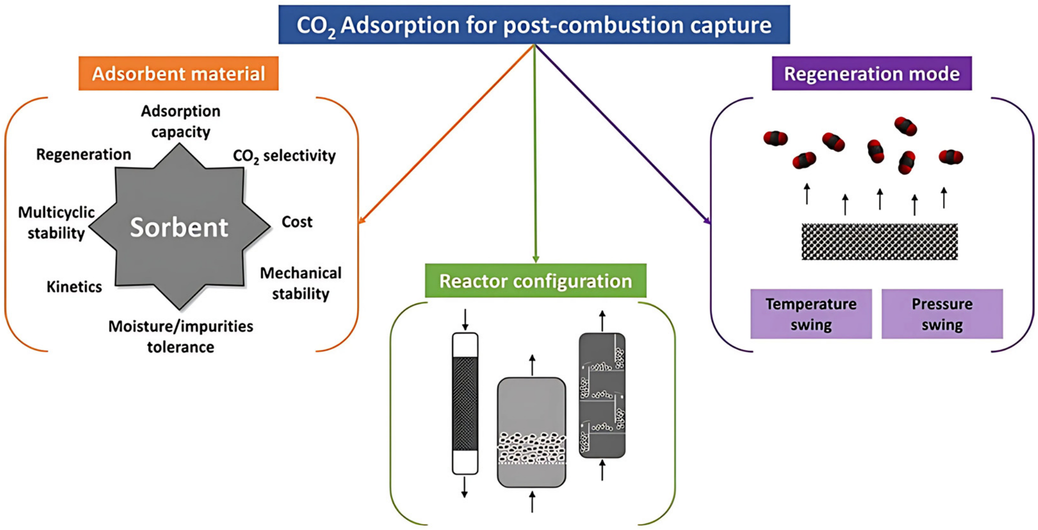

Figure 4. Adsorption of carbon dioxide post-combustion capture [55].

Modular and Scalable DAC Units: Researchers have developed modular, scalable units that can be deployed in various locations, making DAC more flexible and adaptable to different environments. This modularity allows for gradual expansion of DAC operations, increasing CO_2 capture capacity as demand grows.

Integration with Renewable Energy Sources: Recent studies have explored integrating DAC systems with renewable energy sources, such as solar, wind, and geothermal energy, to power the carbon capture process. This integration reduces DAC's carbon footprint and improves overall efficiency by utilizing clean energy.

Advanced Sorbents for Energy Efficiency: Cutting-edge research has led to the creation of new sorbents that require significantly less energy to regenerate, making the entire DAC process more energy efficient. These advanced sorbents have higher CO_2 selectivity, capturing CO_2 more effectively while using less energy during separation and release phases.

Leading companies and research in DAC innovation have put in significant research efforts to improve DAC technologies, with various companies and institutions contributing to advancements in the field. These innovations focus on enhancing CO_2 capture efficiency, reducing energy requirements, and developing more cost-effective DAC systems.

(B) Pre-combustion Capture

Pre-combustion capture involves capturing CO_2 from a gas stream before combustion. The process starts with converting feedstock into synthesis gas (syngas) via gasification, followed by CO_2 extraction using physical or chemical absorption techniques. Pre-combustion capture is particularly advantageous for industries like steel, chemicals, and refining, which use large amounts of hydrogen and produce substantial CO_2 emissions. This method allows captured CO_2 to be stored or used, while the remaining hydrogen acts as a low-carbon fuel. It provides higher efficiency and lower energy penalties compared to post-combustion capture. However, pre-combustion capture faces challenges such as high capital costs, the need for high-purity feedstocks, and technical complexity. Ongoing research aims to enhance efficiency, reduce costs, and tackle these issues, with alternative technologies like membrane-based separation and adsorption-based capture also being explored.

4. Adsorption Processes for CCS

Adsorption processes were first explored as an alternative to solvent-based methods for carbon capture in the early 1990s. Since then, there has been significant progress in this field, with a focus on developing adsorbents that offer higher CO_2 capacity, improved selectivity, and better tolerance to impurities. New adsorbents such as metal–organic frameworks, hydrotalcites, and polymers [56,57] are being actively researched alongside traditional materials like carbons and zeolites [58]. Recent studies have highlighted novel approaches in utilizing sustainable composites for enhanced carbon capture efficiency. For instance, research on high flexural strength rankinite (C_3S_2) cement has shown promising results in CO_2 uptake during carbonation curing. Under optimal manufacturing conditions—such as $MgCl_2$ concentration and reaction temperature—the formation of aragonite whisker (AW) significantly enhances the material's strength while facilitating CO_2 consolidation. Specifically, this process can sequester up to 40.9% of CO_2 by mass in the rankinite paste within 48 h, offering a sustainable method for both CO_2 capture and the production of high-performance materials [59].

Additionally, studies using triethylene glycol (TEG) as a modifier have demonstrated that this process not only enhances CO_2 uptake but also improves the mechanical properties of the material. The TEG-induced formation of aragonite whiskers in cement carbonation contributed to a 28.4% CO_2 uptake after 72 h, further highlighting the potential of organic modifiers in improving gas uptake efficiency in sustainable composites [60,61].

Over the past thirty years, various cyclic processes for CO_2 capture have been developed, utilizing temperature, pressure, vacuum, steam, and moisture for regeneration. Innovations in adsorbent structures and device geometries, such as hollow fibers and fluidized beds, have been proposed [62]. Hybrid technologies that combine adsorption with other methods are also being explored. The application of adsorption has expanded to include industries like cement, steel, and natural gas, as well as direct air capture. Adsorption is advantageous for CO_2 capture due to its adaptability and potential cost benefits. It can be retrofitted to existing power plants and is suitable for a range of temperature and pressure conditions. It is especially effective for air capture, which involves low CO_2 concentrations. Although direct comparisons of the costs and benefits of adsorption versus absorption are complex, adsorption generally has a lower environmental impact and can utilize waste materials as adsorbents [63].

5. Recent Advances in CO_2 Adsorbents

CO_2 adsorbents are typically categorized into zeolites, metal–organic frameworks (MOFs), carbonaceous materials, and functionalized adsorbents. Each type has unique properties, advantages, and limitations in CO_2 capture. A lot of research has focused on identifying the best materials for CO_2 adsorption [64–66]. An ideal adsorbent possesses several critical properties. Firstly, it must have a high adsorption capacity for CO_2, which refers to the amount of CO_2 adsorbed (in mmol g^{-1}) at operating pressure and varies with temperature. Secondly, it should have a high working capacity for CO_2, which is the difference between adsorption capacity at operating and regeneration pressure (or temperature). A higher working capacity means less adsorbent is needed, reducing equipment size and cost. While high adsorption capacity is crucial for high working capacity, the latter also depends on the operating and regeneration conditions, making comparisons across zeolites challenging. Thus, adsorption capacity is often used for comparing zeolite performance in CO_2 adsorption [66].

Additionally, an ideal adsorbent should exhibit selective adsorption of CO_2 over CH_4, N_2, and other gases, which improves product purity and reduces capture costs. Fast adsorption/desorption kinetics are also important; the breakthrough curve, showing CO_2 concentration in the effluent over time, indicates kinetics [67]. Fast kinetics result in a sharp curve, affecting the cycle time of the adsorption system. Furthermore, the adsorbent should allow for easy regeneration, interacting optimally with CO_2. The enthalpy of adsorption, typically from -25 to -50 kJ mol^{-1} for physisorption and ≤ -60 kJ mol^{-1} for chemisorption, affects regeneration costs. Higher enthalpy means higher desorption energy and costs, while an enthalpy that is too low reduces CO_2 adsorption capacity.

High mechanical strength and thermal stability are crucial for the adsorbent to withstand operational pressures and temperatures without structural damage, ensuring longer life and cost-effectiveness. Chemical stability and impurity tolerance are also essential, as impurities like water vapor and sulfides in the raw feed gas can compete for adsorption sites [55]. Pretreatment may be needed to remove these impurities or dry the gas. For large-scale applications, production costs must be competitive with other CO_2 separation processes. The adsorbent should be easily scalable for industrial applications, meaning the synthesis or production process should be straightforward, reproducible, and capable of being upscaled without significant loss of performance or increase in cost [41].

Moreover, the overall process of adsorption and regeneration should be energy efficient, involving not only the energy required for CO_2 adsorption and desorption but also the energy consumption during the production and processing of the adsorbent material. Durability is another key factor; the adsorbent should maintain its structural integrity and performance over many cycles of adsorption and desorption, including resistance to physical wear and tear, as well as chemical degradation over time. Finally, the adsorbent should be adaptable to various operating conditions and feed gas compositions, being effective across a range of temperatures, pressures, and in the presence of different gas mixtures [68].

Currently, carbon-based materials, zeolites, and metal–organic frameworks (MOFs) are the most promising and extensively studied adsorbents. Carbon-based materials stand out due to their low cost, high thermal stability, and wide availability.

Zeolites: Zeolites are microporous aluminosilicate minerals with crystalline structures, typically having pore sizes from 4 to 15 Å and surface areas of 200–500 m^2/g. Both natural and synthetic zeolites are used for CO_2 capture. CO_2 adsorption in zeolites is mainly driven by interactions between CO_2 molecules and the electric field generated by cations in the zeolite structure. Factors like the Si/Al ratio and extra-framework cations affect CO_2 adsorption. Recent advances include the "selective trapdoor effect", which allows CO_2 to enter and be adsorbed while excluding other molecules. Zeolites are well understood and modeled easily, making them a standard for evaluating CO_2 adsorbents. Moisture can reduce the effectiveness of adsorption materials by competing with CO_2 for adsorption sites. Chabazite (CHA), a small-pore zeolite with stacked double 6-rings (D6Rs) forming an elongated supercage (see Figure 5), features six 8-membered ring (8MR) windows for access. Figure 6a illustrates the cation sites in chabazite: smaller cations (Li^+, Na^+, Ag^+, Ca^{2+}, Cu^{2+}) occupy sites I, II, and III, while larger cations (K^+, Rb^+, Cs^+) are positioned at site III′ within the 8MR. These larger cations at site III′ limit the access of CO_2, CH_4, and N_2 to the supercage.

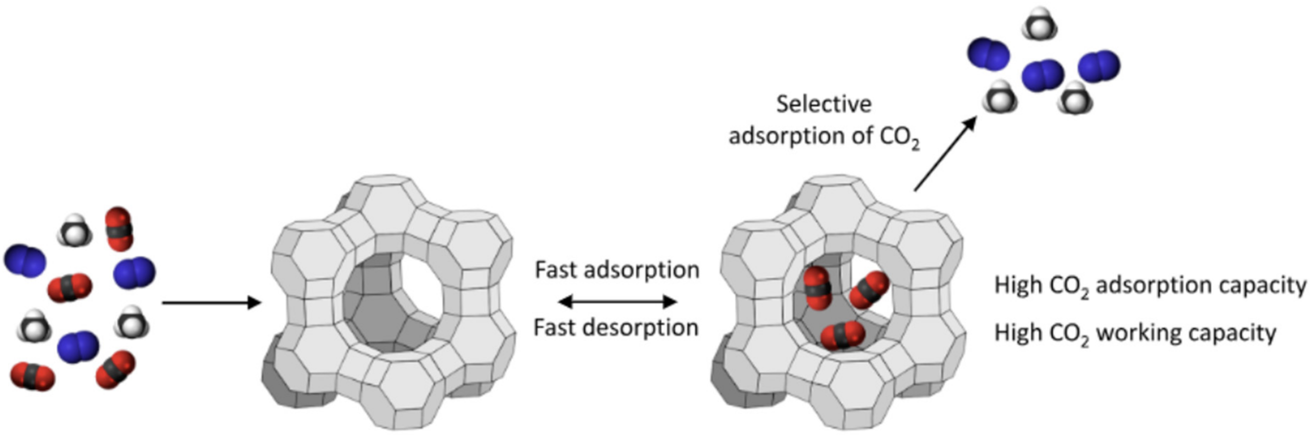

Figure 5. Zeolites as selective adsorbents for CO_2 separation: key properties for effective CO_2 capture [66].

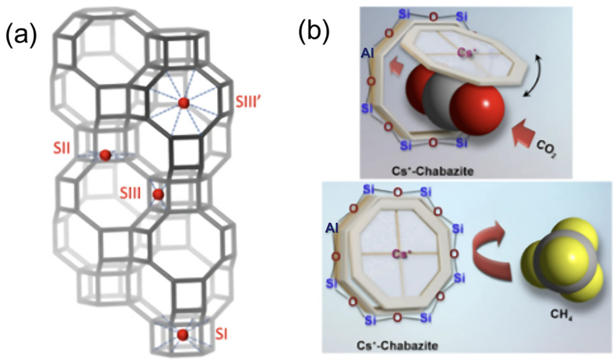

Figure 6. (**a**) Adsorption sites in chabazite: Site I is within the D6R, site II is at the 6MR window, site III is in the supercage at the 4MR window, and site III′ is at the 8MR window. (**b**) Trapdoor effect in chabazite [66].

CO_2 adsorption in chabazite is influenced by the Si/Al ratio. In all-silica chabazite, two adsorption sites are identified: one at the center of the 8MR and another within the supercage, with CO_2 interacting with framework oxygens in both. For aluminosilicate chabazites in Li- and Na-forms (Si/Al = 6 or 12), CO_2 also adsorbs at two sites: the center of the 8MR and a cation site at type II.

In K-form chabazite (Si/Al = 6 or 12), the adsorption includes a bridging mechanism where one CO_2 oxygen interacts with a type II cation, and the other interacts with cations at site III′ or another type II site. This bridging is more pronounced in K-chabazite with Si/Al = 6 due to more cations. The bridging mechanism is absent in Li- and Na-forms, likely due to their closer proximity to the 6MR center, which prevents bridged complexes.

For chabazites with Si/Al $\leq$ 3, a temperature-dependent molecular trapdoor mechanism is proposed, where CO_2 temporarily displaces cations at the 8MR windows, enabling its diffusion through the pores.

6. Metal–Organic Frameworks (MOFs) and Advanced Membrane Technology

Innovative materials for CO_2 adsorption, particularly metal–organic frameworks (MOFs) and advanced membrane technologies, are revolutionizing the field of carbon capture. Refs. [69–72] studied MOFs, or metal–organic frameworks, which are porous crystalline materials made from metal ions and organic linkers. They stand out for having high surface areas and large pore volumes, making them ideal for applications like gas storage and separation.

The adsorptive properties of MOFs are influenced by the size and shape of their pores, as well as interactions between CO_2 molecules and the metal sites or functional groups on the ligands. Recent advancements in this area include the development of water-stable MOFs that maintain their structural integrity and adsorption capacity in humid environments, significantly extending their lifespan for industrial applications. Additionally, researchers have designed MOFs with precise pore sizes and chemical environments that enhance CO_2 affinity while excluding other gases, which is crucial for applications like natural gas sweetening [71]. MOFs can have their CO_2 uptake and selectivity adjusted by varying the metal sites or using amine-containing ligands. Some MOFs, like MOF-74(Mg), have shown high CO_2 adsorption capacities. However, MOFs are often criticized for their chemical instability and are not yet widely manufactured at scale. Recent advancements include more robust MOFs like UiO-66 and SIFSIX-6_Zn, as shown in Figure 7b [73,74].

Kumar et al. [11] explored SIFSIX analogues with TiF_6^{2-} pillars to enhance CO_2 affinity at lower pressures while preserving thermal stability and water resistance. They developed TIFSIX-3-Ni, a hybrid ultramicroporous material (HUM) combining TiF_6^{2-} and pyrazine with Ni nodes, which showed minimal CO_2 uptake decrease after 14 days of stability tests due to improved thermal stability.

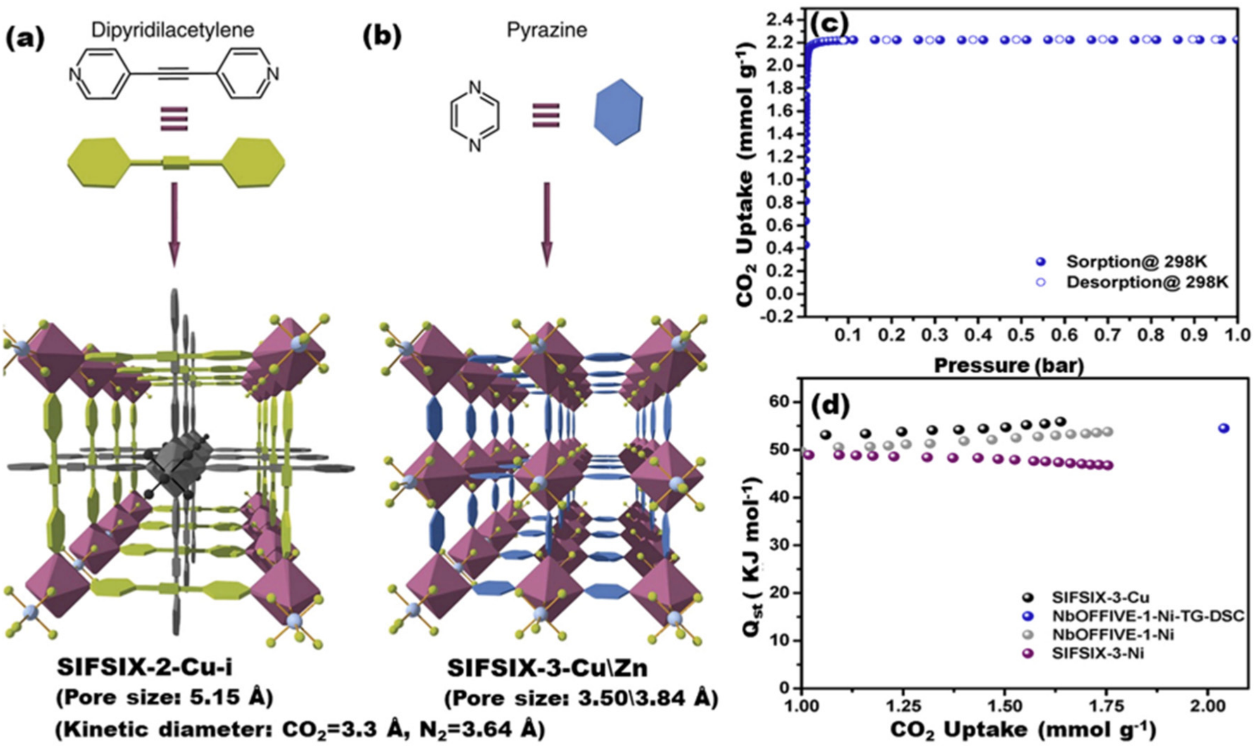

Figure 7. Crystal structures of (**a**) SIFSIX-2-Cu-i (**b**) SIFSIX-3-Cu/Zn, (**c**) CO_2 sorption isotherm for NbOFFIVE-1-Ni at 25 °C, and (**d**) comparison of CO_2 heat of adsorption for selected HUMs [73,74].

Li et al. [75] introduced SIFSIX-14-Cu-i, featuring a copper-coordinated network with a pocket-like pore structure, $SiF6^{2-}$ anions, and 4,4′-azopyridine ligands. Mukherjee et al. [76] developed SIFSIX-18-Ni-β with 3,3′,5,5′-tetramethyl-1H,1′H-4,4′-bipyrazole ligands, showing high CO_2 uptake at low pressures and high adsorption heat with low water affinity compared to other materials.

Liang et al. [77] recently synthesized dptz-CuTiF6 using 3,6-di(4-pyridyl)-1,2,4,5-tetrazine (dptz) as the ligand. This MOF demonstrated stable CO_2 capture capacities (~2.86 mmol g^{-1} at 100 mbar, 25 °C) under both dry and humid conditions, indicating robustness against moisture.

In parallel to MOF advancements, membrane technologies for CO_2 separation have evolved rapidly, providing energy-efficient alternatives to traditional capture methods. Mixed-matrix membranes (MMMs) combine the flexibility of polymers with the high selectivity of inorganic materials like zeolites or MOFs. This hybrid approach improves the separation of CO_2 from other gases by incorporating the excellent gas separation properties of inorganic fillers while maintaining high permeability. Facilitated transport membranes (FTMs) utilize carrier molecules that actively bind with CO_2, effectively increasing the membrane's permeability to CO_2 while limiting the passage of other gases. This technology is particularly effective in low-pressure environments, such as in post-combustion CO_2 capture.

Moreover, the exploration of two-dimensional (2D) materials like graphene oxide has opened new possibilities for creating ultra-thin, highly selective membranes for CO_2 separation. Graphene oxide-based membranes are incredibly thin—often just a few nanometers thick—which allows for rapid gas transport while maintaining excellent selectivity for CO_2. As these innovative materials continue to evolve, they hold great promise for improving the efficiency and scalability of CO_2 capture systems. This progress plays a critical role in reducing global greenhouse gas emissions and supporting the transition to a low-carbon economy [69].

Carbonaceous Materials: This category encompasses materials like activated carbons, carbon molecular sieves, aerogels, and carbon nanomaterials. These materials primarily use physisorption for CO_2 capture, relying on their porous structure to increase adsorption capacity. The presence of heteroatoms, such as oxygen-containing groups, can enhance chemisorption interactions. Carbon-based materials benefit from their industrial maturity, though their effectiveness varies depending on their specific structure and preparation methods.

7. Composition of the CO_2 Stream

The composition of a CO_2 stream, including the types and amounts of impurities, can significantly influence the fluid's thermophysical properties and phase behavior. Key impurities of concern for pipeline transport include water, which can cause corrosion of pipe materials, and non-condensable gases such as nitrogen, oxygen, or argon, which can affect the vapor–liquid equilibrium of the mixture.

The impact of impurities on the phase envelope is crucial for both shipping and pipeline transport. Increasing non-condensable gases can expand the phase envelope considerably, affecting the energy needed for compression or liquefaction and raising the cricondenbar, which requires higher pipeline operating pressures. This expansion also introduces uncertainty in the fluid's behavior during transient operations, prompting a focus on how compositional variations affect dynamic flow behavior. Figure 8 presents scanning electron microscope (SEM) images of L485MB steel coupons from a pipeline section exposed to various dense-phase CO_2-impurity mixtures over seven days at 10 MPa and 278 K. The different mixtures, containing varying levels of sulfur dioxide (SO_2), nitrogen dioxide (NO_2), hydrogen sulfide (H_2S), water (H_2O), and other impurities, were used to examine their effects on steel surface corrosion. Figure 8a shows the surface of the steel exposed to a mixture containing 50 ppm of H_2S and 1% H_2, along with water (200 ppm). The SEM images reveal a relatively smooth surface with some signs of localized corrosion and the formation of thin iron sulfide layers, indicated by the small-scale surface irregularities visible at higher magnification. Figure 8b displays the steel surface exposed to a mixture with higher concentrations of impurities: 70 ppm of SO_2, 100 ppm of NO_2, 6700 ppm of O_2, and water (200 ppm). The low-magnification image shows widespread corrosion products, and the higher-magnification image highlights complex, irregular structures, suggesting the formation of hydrated iron nitrates, sulfates, and oxyhydroxides, indicating more extensive and aggressive corrosion. Figure 8c presents SEM and energy-dispersive spectroscopy (EDS) analysis for steel exposed to a mixture with 220 ppm of SO_2, 6700 ppm of O_2, and a lower water content (5 ppm). The SEM image shows significant localized corrosion, with dark patches indicating corrosion spots. The EDS analysis confirms the presence of hydrated iron sulfates as the primary corrosion product. Additionally, the inset provides a closer look at the corrosion layers and their elemental composition, which consists mainly of iron, oxygen, and sulfur. This figure provides a detailed comparison of corrosion mechanisms under varying impurity conditions, revealing that the impurity concentration and composition significantly influence the type and extent of corrosion on pipeline steel in dense-phase CO_2 environments.

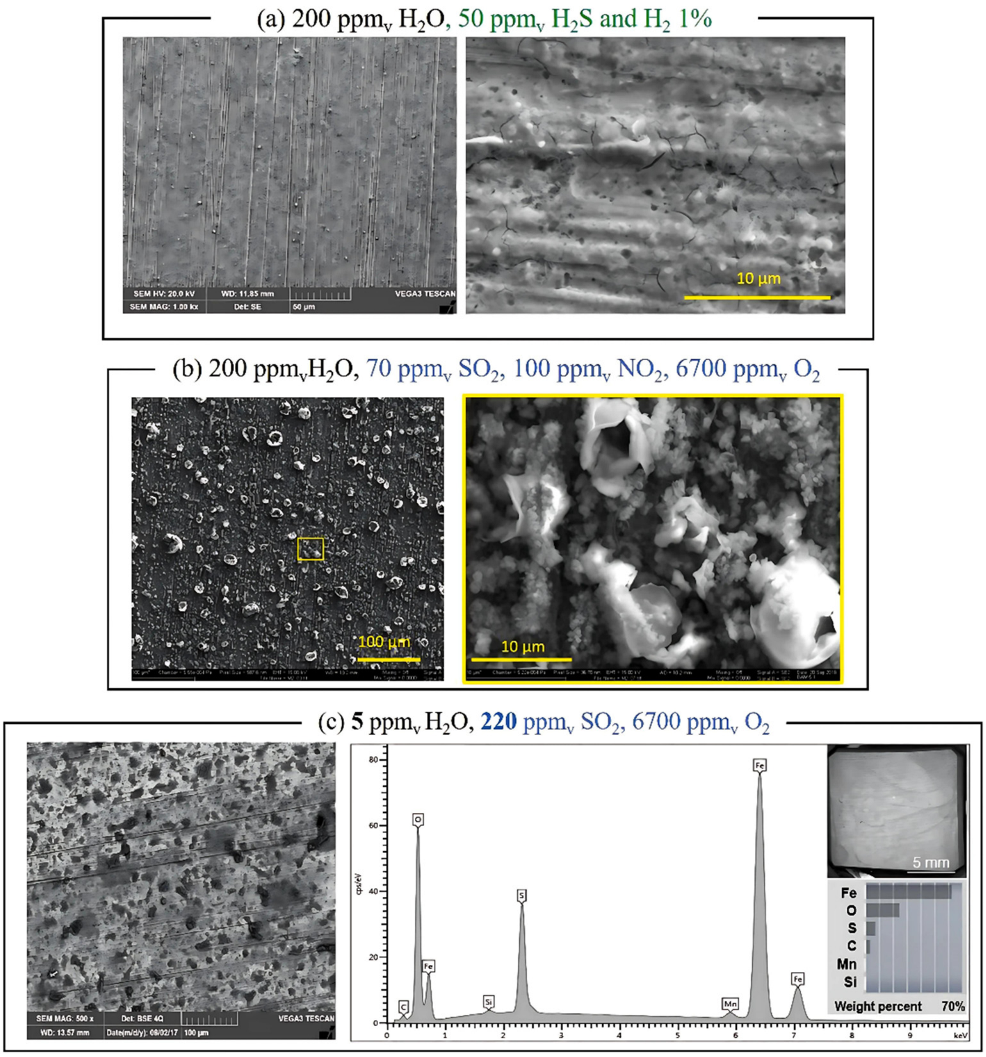

Figure 8. Scanning electron microscope (SEM) images of L485MB coupons were obtained from a pipeline section exposed for seven days to dense-phase CO_2-impurity mixtures (see (**a**–**c**)). The exposure conditions were 10 MPa and 278 K. For mixture c, the energy-dispersive spectroscopy (EDS) analysis of the corrosion products is also included [78].

8. Compression

Compression or liquefaction, the initial stage of transportation, represents a significant energy expense, potentially leading to a 12% loss in power plant efficiency. Selecting an efficient compression strategy is vital for the overall performance of the carbon capture and storage (CCS) system. Research has explored various compression strategies, including multistage compression with intercooling, combined compression and liquefaction, and innovative techniques like supersonic shockwave compression. Studies have shown that using integrally geared compressors can save over 20% in energy compared to conventional methods. Other research has focused on enhancing efficiency by reusing heat from the intercooling process. Recent analyses have examined how the composition of the CO_2 stream affects compression energy and process requirements. Findings indicate minimal differences for relatively pure CO_2 streams (over 95% purity), but substantial increases in power requirements (12–30%) for streams with lower purity. For impure streams, conditioning costs can rise by 13%, or 2.3 h per ton of CO_2. Given the high energy demand of the compression stage, further research is needed to improve efficiencies and assess how dynamic operations at CCS plants impact compression system design.

9. CO_2 Transportation

The study by Wei et al. [79] proposed a cost-effective and reliable pipeline network for carbon capture and storage (CCUS) to support China's carbon neutrality targets. To achieve an annual CO_2 reduction of 654 million tons from coal-fired power plants, the authors recommended building 17,589 km of pipelines with diameters of 8, 12, and 16 inches, covering a radius of 58 km. Key regions for construction include northeast, North, and northwest China. The optimization model, utilizing the C3IAM/NET framework, aimed to reduce costs by evaluating capital, maintenance, and operational expenses, along with socio-economic and geological factors. For a lower reduction target, 172 power clusters would connect to 182 storage hubs through 305 pipelines at a cost of USD 178.36 billion. For a higher target, 240 clusters need to connect to 254 hubs via 435 pipelines, costing USD 303.57 billion. The study underscores the importance of early planning, extensive retrofitting, and regional collaboration to achieve China's climate targets. During pipeline transport, CO_2 streams from different sources can mix, potentially increasing localized H_2O concentration due to cross-reactions, such as $2\ H_2S + SO_2 \rightarrow 3\ S + 2\ H_2O$. Experiments showed that increasing H_2O concentration from 50 to 200 ppmv resulted in significant metal surface coverage by corrosion products, including iron sulfides (Figure 8a) and hydrated iron nitrates, sulfates, and oxyhydroxides/oxides (Figure 8b) after seven days. Conversely, when H_2O levels were kept at 5 ppmv and NO_2 was absent, a SO_2 concentration of 220 ppmv (three times the maximum in CCS cluster scenarios) only led to localized corrosion products of hydrated iron sulfate, as indicated by energy-dispersive X-ray spectroscopy (EDS, Amethi, India) (Figure 8c). These results highlight the need to carefully manage H_2O and reactive impurity concentrations in pipeline networks, as outlined in technical reports such as ISO/TR27921:2020 [80].

10. Pipeline Transportation

CO_2 pipelines must prioritize reliability, safety, and cost-effectiveness. Design requirements are influenced by flow rates and the CO_2 stream's properties, including density, compressibility, and viscosity. A key consideration is avoiding phase transitions, which can cause operational issues such as liquid slugs [81]. To prevent this, the pipeline must be designed so that the CO_2 remains in a single-phase state throughout its length under normal operating conditions. Additionally, since the CO_2 stream is rarely pure, its composition affects the design by altering the fluid's thermophysical properties and vapor–liquid equilibrium, which can change the permissible operating conditions. The type and level of impurities can also impact the material requirements for the pipeline, affecting both the strength of the steel to prevent fractures and its susceptibility to corrosion [82].

CO_2 can be transported using different types of pipelines depending on factors such as distance, volume, and geography. Onshore pipelines are typically used for large-volume, long-distance transport, as they are generally more economical for continuous CO_2 flow between capture and storage or utilization sites. In contrast, offshore pipelines are used to transport CO_2 to storage sites in deep saline formations or depleted oil and gas reservoirs beneath the seabed, which require special material considerations due to high-pressure, low-temperature environments and the increased risk of corrosion.

Dense-phase transportation is the most efficient and commonly used method for CO_2 transport. In this phase, CO_2 behaves like both a liquid and gas, allowing for higher density and reducing the need for large pipeline diameters. For this method, operating conditions must be maintained above the critical pressure of 73.8 bar, keeping CO_2 in a supercritical or dense state, enhancing mass flow and overall efficiency. This phase also minimizes the risk of phase transitions, ensuring stable and cost-effective transport over long distances.

The composition of the CO2 stream is crucial for pipeline design and material selection. Impurities such as water (H_2O), hydrogen sulfide (H_2S), sulfur dioxide (SOx), nitrogen (N_2), oxygen (O_2), and methane (CH_4) can increase risks of corrosion and phase transitions. Water, for instance, reacts with CO_2 to form carbonic acid, which is highly corrosive, requiring strict limits like $\leq$30 ppm in projects such as Northern Lights. Similarly, H_2S

and SOx, restricted to ≤9 ppm and ≤10 ppm respectively, necessitate the use of corrosion-resistant materials to avoid pipeline damage. Non-condensable gases like nitrogen and oxygen raise CO_2's critical pressure, requiring higher operating pressures to maintain stability, with oxygen limited to ≤10 ppm.

Material selection is influenced by CO_2 composition and operating conditions. While carbon steel is commonly used, pipelines exposed to high levels of impurities may need more corrosion-resistant materials, such as stainless steel or alloy coatings. Pipelines typically operate at pressures between 83 and 152 bar to keep CO_2 in a dense phase and prevent phase transitions. Additionally, special care must be taken to prevent hydrate formation, especially in offshore pipelines, as hydrates can block pipelines and increase maintenance costs [83].

11. Pipeline Network Layout by Region

In a low carbon capture scenario, the northeast, north, and northwest regions—collectively known as the 'Three Norths'—dominate pipeline construction, accounting for 81.3% of the total pipeline length (14,300 km) and incurring a transportation cost of USD 164.52 billion. These areas face significant seismic activity, influencing the longer transportation distances and larger pipeline capacities, which range from 8 to 36 inches in diameter. Despite the high costs, the well-developed pipeline network in these regions, including planned networks in the Songliao Basin, Ordos Basin, and Junggar Basin, presents substantial potential for profitable carbon capture, utilization, and storage (CCUS).

In contrast, the southwest, east, central, and south regions have new pipelines totaling 3289 km, with a transportation cost of USD 13.84 billion. Pipeline construction in these areas is affected by challenging terrain, protected areas, rivers, and population centers. The pipelines here are generally smaller in diameter (6 to 12 inches) and have shorter transportation distances compared to the Three Norths. While East and Central China offer better transportation convenience, their pipeline networks are less integrated, and the potential for profitable storage sites is lower than in the northern regions.

Figure 9 provides an overview of the pipeline network layout and cost analysis for CCS in China under low and high carbon capture scenarios. Figure 9a shows the geographic distribution of coal-fired power plants, represented by purple triangles, and various types of CCS hubs, including CO_2-enhanced oil recovery (EOR), CO_2-enhanced gas recovery (EGR), CO_2 injection into unmineable coalbeds, and deep saline aquifer storage. Two major pipeline networks are highlighted: Pipelines_6 (green lines) represent a lower-emission reduction target of 654 million tons of CO_2 annually, while Pipelines_15 (red lines) represent a higher-emission reduction target of 1536 million tons. The map also includes a cost surface gradient, indicating the relative cost of pipeline construction across different regions, with darker colors showing areas where construction is not feasible. Figure 9b breaks down the cost, length, and diameter of pipelines by region under the low carbon capture scenario. The regions are categorized by their pipeline lengths, with the northwest having the largest network (7217 km, 101 pipelines), representing 44.1% of total costs, predominantly consisting of 16-inch and 24-inch pipelines. The northeast (3748 km, 53 pipelines) accounts for 24.2% of total costs, while North China (3335 km, 52 pipelines) contributes 23.9%, both with significant portions of 16-inch pipelines. The southwest (1503 km, 40 pipelines) and East, Central, and South China (1786 km, 59 pipelines) contribute smaller portions of total costs at 3.8 and 4.0%, respectively, with a mix of pipeline diameters. The pie charts display the distribution of pipeline diameters in each region, providing insights into the infrastructure planned for future CCS development across China.

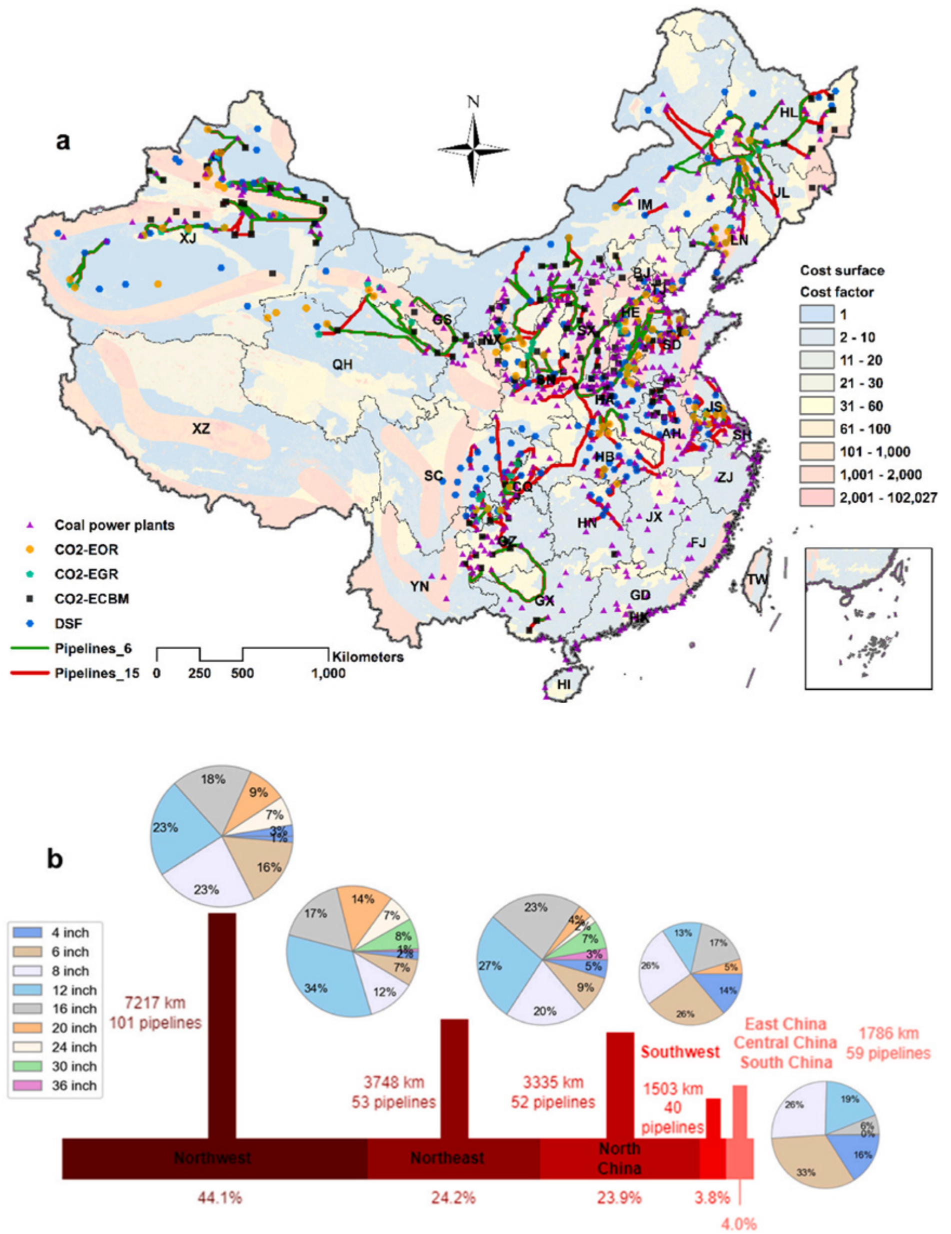

Figure 9. (**a**) Layout: The figure illustrates pipeline configurations for low and high carbon capture. Symbols represent coal-fired plants (purple triangles), CO_2-EOR hubs (yellow circles), CO_2-EGR hubs (cyan pentagons), CO_2 injection into coal beds (black squares), and saline aquifers (blue hexagons). Green lines show emission reduction targets of 654 million and 1536 million tons of CO_2. Cost factor indicates construction feasibility compared to ideal conditions. (**b**) Specifications: Details include pipeline costs, lengths, and diameters for the low carbon capture scenario, with high carbon capture details in the Supplementary document. The figure shows cost distribution, pipeline lengths, and diameter proportions [79].

12. CO_2-Based Enhanced Oil Recovery (EOR)

Carbon dioxide enhanced oil recovery (CO2-EOR) has been a crucial technique for increasing oil extraction from depleted reservoirs for decades, and more recently, the use of nanoparticles has gained traction in the oil and gas industry [84–86]. This method is most effective when CO_2 is injected in a liquid or supercritical state, making it miscible with the reservoir oil. This miscibility lowers the oil's viscosity, allowing for efficient single-phase drainage. To achieve this, the reservoir conditions must meet or exceed the minimum miscibility pressure (MMP), which is around 75 bar for light crudes at 70 °C and increases with temperature. While CO_2 can also enhance recovery through immiscible displacement, the most efficient results are obtained when CO_2 is miscible, which is only possible if the reservoir pressure stays above the MMP [87]. Due to the lower viscosity and density of injected CO_2 compared to the in situ oil, some CO_2 tends to bypass the oil and breakthrough occurs, resulting in about 50% being recycled. To improve oil displacement and recovery, alternating injection of water and gas (WAG) is commonly used.

Carbon capture and storage enhanced oil recovery (CCS-EOR) builds on the principles of CO_2-EOR with dual objectives: increasing oil recovery from depleted reservoirs while permanently storing a portion of the injected CO_2. This approach offsets the high costs of CCS, estimated at around USD 70 per ton of CO_2 stored, by generating revenue from additional oil production. Unlike traditional CO2-EOR, which prioritizes maximizing oil recovery with minimal CO_2 use and emphasizes recycling, CCS-EOR seeks a balance between oil recovery and CO_2 storage. The economic viability of CCS-EOR depends on ensuring that the amount of CO_2 stored significantly exceeds what is needed for oil displacement, making it a valuable form of large-scale CO_2 utilization.

Oil recovery can be divided into three stages:

1. Primary Production: Utilizes the natural energy of the reservoir, such as the gas cap drive, water drive, or gravity drainage, often supplemented with artificial lift techniques. This method recovers about 10% of the original oil in place (OOIP).
2. Secondary Production: Involves injecting water or gas into the reservoir to maintain pressure and displace more oil, resulting in the recovery of 20–40% of the OOIP.
3. Tertiary Production (Enhanced Oil Recovery, EOR): Extracts an additional 30–60% of the OOIP through advanced techniques such as:
    - Thermal Injection: Heats the oil to reduce viscosity and improve flow.
    - Chemical Injection: Uses polymers, surfactants, or microbes to increase sweep efficiency and reduce residual oil by lowering surface tension (Farajzadeh et al., 2021) [88].
    - Gas Injection: Introduces gases like methane (CH_4), nitrogen (N_2), or carbon dioxide (CO_2) to enhance recovery. CO_2 is particularly valuable because it is cost-effective, aids in carbon storage, and mixes well with hydrocarbons (Bert Metz et al., 2005) [89].

CO_2-EOR can be classified into:

- Miscible CO_2 EOR: CO_2 fully dissolves in the oil, reducing viscosity and improving flow.
- Immiscible CO_2-EOR: CO_2 does not dissolve but increases pressure, displacing the oil for recovery.

Miscible CO_2-EOR: This method is effective when CO_2 can fully mix with the oil, significantly reducing interfacial tension and viscosity, making oil extraction easier. Ideal conditions for miscibility include depths less than 1200 m and oil with an API gravity greater than 22 degrees (Elhoshoudy and Desouky, 2018) [90]. Miscibility is achieved through various processes:

1. First Contact: The solvent mixes completely with the reservoir oil, creating a single phase. 2. Vaporizing Gas Drive: Light to intermediate hydrocarbons in the oil vaporize into the injected CO_2. 3. Condensing Gas Drive: CO_2 dissolves into the oil, improving miscibility dynamically.

Challenges include maintaining pressure above the Minimum Miscibility Pressure (MMP) and managing asphaltene precipitation, which can lead to reservoir plugging (Fakher et al., 2019) [91].

Immiscible CO_2 EOR: This happens when CO_2 cannot mix with the oil due to conditions like low pressure or the presence of heavy hydrocarbons. Instead of creating a single phase, CO_2 dissolves into the oil, causing it to swell and become less dense. This improves oil mobility and enhances recovery, but in heavy oil reservoirs, CO_2 and oil remain as separate phases throughout the process (Perera et al., 2016) [92].

13. Reservoirs Suitable for CO_2-EOR and CO_2 Storage (CCUS)

Carbon dioxide enhanced oil recovery (CO_2-EOR) has been used for years to increase oil extraction from depleted reservoirs. It works best when CO_2 is injected in a liquid or supercritical state and mixes completely with the reservoir oil [66–71]. When CO_2 is fully miscible with the reservoir oil, it lowers the oil's viscosity, enabling it to be displaced from the rock pores in a single-phase drainage process. To achieve this, reservoir conditions must surpass the minimum miscibility pressure (MMP), roughly 75 bar for light crudes at 70 °C, which increases with temperature. Although CO_2 can enhance recovery even when not fully miscible, the most efficient extraction happens when CO_2 is miscible, and this is only possible if the reservoir pressure remains above the MMP. Due to the lower viscosity and density of CO_2 compared to the in situ oil, some CO_2 may bypass the oil, leading to breakthrough and approximately 50% being recycled. To enhance oil displacement and recovery, alternating water and gas injections (WAG) are often employed.

Carbon capture and storage enhanced oil recovery (CCS-EOR) is similar to CO_2-EOR but has dual goals: recovering more oil from reservoirs with reduced production and permanently storing some of the injected CO_2. This approach aims to mitigate the high costs of CCS, which can be about USD 70 per ton of CO_2 stored, by maximizing revenue from the additional oil extracted. Unlike CO_2-EOR, which focuses on maximizing oil recovery with minimal CO_2 usage and extensive recycling, CCS-EOR must balance between oil recovery and CO_2 storage. For CCS-EOR to be economically viable, the amount of CO_2 stored must significantly exceed the quantity required for efficient oil displacement. Consequently, CCS-EOR offers a substantial method for CO_2 utilization, adding value to CO_2 on a large scale [73].

Stefan Bachu explored the identification of oil reservoirs suitable for CO_2 enhanced oil recovery (CO_2-EOR) and CO_2 storage (CCUS) using reserves databases, focusing on Alberta, Canada. The objective was to determine which reservoirs could effectively use CO_2 captured from anthropogenic sources for EOR, providing a revenue stream to offset costs and facilitate deployment. The methodology involved developing 14 screening criteria based on operational and reservoir characteristics, including oil gravity, minimum miscibility pressure, and reservoir size. These criteria helped screen oil reservoirs for their suitability for CO_2-EOR. Using published data from 31 CO_2-EOR operations in Texas, the study estimated the incremental oil recovery factor and the net CO_2 utilization factor for suitable reservoirs. Additionally, for CCUS, two more criteria were added to match the size and location of large CO_2 sources with the potential CO_2 storage capacity of the reservoirs. Applying these criteria to Alberta's reserves database, which recorded around 13,000 oil reservoirs, the study identified 136 reservoirs in 85 oil fields suitable for CO_2-EOR. Key impacting criteria were oil gravity, minimum miscibility pressure, and reservoir size, while factors like porosity and initial oil saturation had minimal impact. The study estimated that these reservoirs could cumulatively produce 759, 1742, and 2858 Million Stock Tank Barrels (MMSTB) of incremental oil with CO_2 storage capacities of 213, 868, and 1742 Mt CO_2 at P10, P50, and P90, respectively. Considering the proximity of large CO_2 sources, 29 oil fields were identified as suitable for both CO_2-EOR and CO_2 storage, indicating a significant opportunity for CCUS in Alberta. This comprehensive methodology for screening and ranking oil reservoirs can be adapted to any region, providing a valuable tool for policymakers and stakeholders in advancing CCUS projects to achieve carbon neutrality targets.

13.1. Is There Sufficient Storage Capacity for CO_2-EOR?

In short, the answer is 'Yes, but perhaps not in the ideal locations'. Currently, CO_2 emissions total around 36 Gt per year, which translates to approximately 100 million barrels of CO_2 per day. This contrasts with oil production levels of about 90 million barrels per day. To achieve global carbon reduction goals, we need to capture 15–20% of total CO_2 emissions. The remaining reductions will come from energy efficiency measures (up to 50%) or increased use of renewables and nuclear energy (about 30%). To meet the COP21 target of limiting global temperature rise to 1.5–2 °C by capping atmospheric CO_2 at roughly 450 ppm, we need storage capacity for 120–160 $GtCO_2$, with an annual rate of about 10 $GtCO_2$ by 2050, which equates to approximately 3000 major facilities. By 2100, the storage requirement could reach 1200–3300 $GtCO_2$. The global storage potential for CO_2-EOR+ Light is estimated at 70–140 $GtCO_2$, potentially yielding about 470 billion barrels of additional oil. However, this may be an overly optimistic estimate. Most of this potential is in the Middle East/North Africa and the USA, accounting for 50 and 13%, respectively, while South Asia shows minimal potential, and the Asia Pacific region contributes only about 3%. This suggests a mismatch between regions with significant CO_2-EOR potential and those facing high population growth, fossil fuel dependency, and the need to sequester CO_2 in the coming century [74]. The Middle East and Africa are the only regions with sufficient CO_2-EOR capacity to meet the 2050 storage needs, with North America and the Former Soviet Union also coming close. Given the scale and growth of the CO_2-EOR industry in the USA, this region is likely to lead. If we consider that CO_2 injection may be limited by availability rather than capacity, a more realistic estimate is around 40 $GtCO_2$ stored via CO_2-EOR, aligning with recent International Energy Agency (IEA) estimates. Adjusted for net emissions from additional oil production, the effective CO_2-EOR+ Light capacity is about 35 $GtCO_2$, which accounts for roughly 30% of the 2050 target and 4–5% of the total CO_2 mitigation goal. The IEA's U-Cube capacity database estimates global CO_2-EOR+ 'Balanced' capacity at around 240 Gt and CO_2-EOR 'Heavy' capacity at about 360 Gt, which is between two and three times higher than the IEA's CO_2 storage estimates. Significant CO_2-EOR capacities outside North America are found in the Middle East (1000 Gt), Russia (70 Gt), North Africa (35 Gt), and Central Asia (20 Gt) [12,16,19,93].

Figure 10 illustrates the global distribution and capture capacity of operational carbon capture and storage (CCS) projects, focusing on regions and countries actively involved in reducing carbon footprints, particularly within the oil and gas, steel, and cement industries. The United States leads with 17 operational projects, including major sites like the Century Plant (8.4 Mt/year) and Shute Creek (7 Mt/year), resulting in a total capture capacity of 15.4 million tons per year. Canada follows with a capture capacity of 5 million tons annually, supported by projects like Great Plains Synfuel and Boundary Dam. Europe (Norway) and China have smaller capacities, with Norway capturing 1.7 Mt/year and China capturing between 0.4 and 2 Mt/yr. Brazil, Saudi Arabia, and the UAE have emerging projects with capacities ranging from 0.8 to 1 Mt/year. This data highlights the significant role of CCS projects in industrial emissions mitigation efforts, with the United States as the largest contributor to global carbon capture capacity.

a)

Region/Country	Number of Projects	Key Projects	Capture Capacity (Million Tons/Year)
United States	17 operational	Century Plant (8.4 Mt/yr), Shute Creek (7 Mt/yr)	15.4
China	Several in early stages	Projects capturing 0.4 to 2 Mt/yr	0.4 to 2
Europe (Norway)	2 operational	Sleipner (1 Mt/yr), SnÃ¸hvit (0.7 Mt/yr)	1.7
Canada	3 operational	Great Plains Synfuel (3 Mt/yr), Boundary Dam (1 Mt/yr), Quest (1 Mt/yr)	5
Brazil, Saudi Arabia, UAE	Operational projects	Projects capturing 0.8 to 1 Mt/yr	0.8 to 1

b)

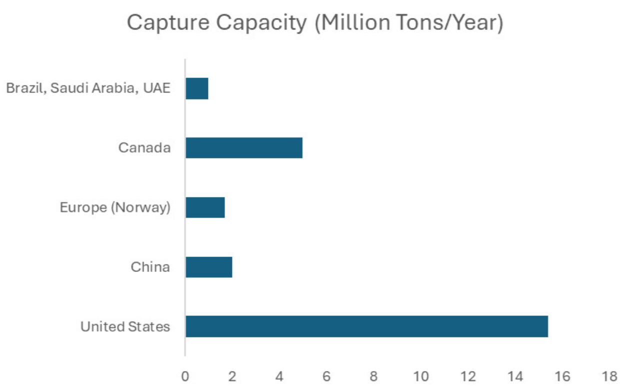

Figure 10. Industrial perspective on net-zero carbon footprint: oil and gas, steel, and cement industry. (**a**) Overview of major operational carbon capture projects by region, highlighting capacities led by the U.S. at 15.4 Mt/yr. (**b**) Bar chart comparing total carbon capture capacities by region, with the U.S. as the highest.

13.2. Technology Readiness Level (TRL) for Net-Zero Carbon Footprint

In the pursuit of achieving net-zero carbon emissions, it is crucial to evaluate the current status of various carbon capture technologies using the Technology Readiness Level (TRL) scale. This assessment provides insights into the maturity of these technologies, ranging from basic principles (TRL 1) to full-scale commercial deployment (TRL 9). A diverse portfolio of technologies at different developmental stages is essential for reducing or eliminating CO_2 emissions and reaching net-zero goals.

13.3. Post-Combustion Carbon Capture

Technology Overview: Post-combustion capture, with a TRL of 9, represents the most mature carbon capture technology. This process involves capturing CO_2 from flue gases generated after fossil fuel combustion in power plants or industrial processes, typically using chemical solvents like amines. The captured CO_2 is then separated for storage or utilization.

Readiness Level: This fully commercialized technology is widely deployed globally, with large-scale projects such as the Boundary Dam CCS project in Canada and Petra Nova in the United States demonstrating its commercial viability. Post-combustion capture plays a critical role in short-term strategies for reducing emissions from existing infrastructure.

Challenges and Opportunities: Despite its maturity, widespread adoption faces challenges related to high energy consumption and operational costs. Ongoing research and innovation focus on improving the energy efficiency of solvent regeneration and reducing costs to accelerate deployment.

13.4. Pre-Combustion Carbon Capture

Technology Overview: Pre-combustion capture, currently at TRL 7–8, involves removing CO_2 from fossil fuels before combustion. This process converts fossil fuels into syngas (a mixture of hydrogen and carbon monoxide), followed by a shift reaction producing hydrogen and CO_2. The CO_2 is then captured, while the hydrogen can be used as a clean fuel source.

Readiness Level: Several large-scale demonstration projects are underway, primarily in integrated gasification combined cycle (IGCC) power plants and hydrogen production facilities. Examples include the Kemper County project in the U.S. and the Hydrogen Energy California (HECA) project.

Challenges and Opportunities: The main challenges for pre-combustion capture include high capital costs of gasification plants and process complexity. However, it offers significant opportunities for decarbonizing hydrogen production and power generation, particularly as hydrogen production expands in the transition to a low-carbon economy.

13.5. Oxy-Fuel Combustion

Technology Overview: Oxy-fuel combustion, at TRL 7, involves burning fossil fuels in pure oxygen instead of air. This process generates a flue gas primarily consisting of CO_2 and water vapor, facilitating easier capture and purification of CO_2 for storage or utilization. Oxy-fuel combustion has potential applications in power plants, steel production, and cement manufacturing.

Readiness Level: Pilot projects have demonstrated the technology's feasibility, with efforts now focused on larger-scale demonstrations. The Callide Oxyfuel Project in Australia successfully demonstrated the technology in a retrofitted power station.

Challenges and Opportunities: Oxy-fuel combustion faces technical challenges related to the energy-intensive process of oxygen production, typically via air separation units (ASUs). However, it has significant potential for reducing emissions from hard-to-abate sectors like cement and steel. Continued innovation in oxygen production, such as membrane-based air separation, could improve its economic viability (Figure 10).

13.6. Direct Air Capture (DAC)

Technology Overview: Direct Air Capture (DAC), at TRL 6–7, is a negative emissions technology that captures CO_2 directly from ambient air using chemical sorbents or filters. The captured CO_2 can be stored geologically or utilized in products like synthetic fuels. DAC has the potential to remove historical CO_2 emissions from the atmosphere and achieve negative emissions, making it a critical long-term tool for reaching net-zero goals. Readiness level: Several small-scale commercial DAC plants are operational, such as Climeworks' plant in Switzerland and Carbon Engineering's pilot facility in Canada. Larger-scale DAC plants are under construction, with some targeting the capture of millions of tons of CO_2 per year.

Challenges and Opportunities: The primary challenge for DAC is the high cost and energy demand of capturing CO_2 from dilute atmospheric concentrations. However, technological improvements and integration with renewable energy sources are expected to reduce costs over time. As governments and corporations commit to net-zero targets, DAC will likely see increased investment and deployment, particularly for offsetting residual emissions from hard-to-decarbonize sectors.

The varying Technology Readiness Levels of carbon capture technologies reflect the diverse approaches and timelines needed to achieve a net-zero carbon footprint. While post-combustion capture is fully commercialized and ready for widespread deployment, pre-combustion capture, oxy-fuel combustion, and Direct Air Capture are at earlier stages of development. Continued research, demonstration projects, and investments will be crucial for scaling up these technologies, ensuring they become integral components of the global effort to reduce and eventually eliminate CO_2 emissions.

14. A Role of Artificial Intelligence in CCS

Artificial Intelligence (AI) holds significant promise in enhancing carbon capture, utilization, and storage (CCUS) technologies, offering innovative solutions to some of the most challenging aspects of mitigating climate change. By leveraging advanced algorithms and Machine Learning, Ref. [94] showed that AI could optimize various stages of the CCUS process, from capturing carbon dioxide emissions to storing and utilizing them in an efficient and cost-effective manner. One of the primary applications of AI in CCUS is in the optimization of capture processes [57,95]. AI can analyze vast datasets to identify patterns and predict the behavior of carbon capture systems under different conditions. This predictive capability allows for the fine-tuning of operations to maximize capture efficiency while minimizing energy consumption and operational costs. For instance, AI algorithms can optimize the operation of amine scrubbing processes by continuously adjusting parameters to ensure optimal performance. In the realm of carbon storage, AI can enhance the accuracy and reliability of subsurface monitoring and modeling. Machine Learning techniques can process geological data to predict the best sites for CO_2 injection and storage, ensuring the long-term stability and safety of stored carbon. AI can also improve the detection and monitoring of potential leaks, providing real-time data that allows for rapid response and mitigation measures [96] Furthermore, AI can facilitate the utilization of captured carbon by optimizing chemical processes that convert CO_2 into valuable products, such as fuels and chemicals. By simulating various reaction pathways and conditions, AI can identify the most efficient and sustainable methods for CO_2 utilization, thereby contributing to a circular carbon economy. Priya et al., in their review article, explored how Artificial Intelligence (AI) is revolutionizing carbon capture technology by enhancing the efficiency, accuracy, and cost-effectiveness of CO_2 capture, utilization, and storage processes [95]. AI, particularly through Machine Learning (ML) and Deep Learning (DL), optimizes various stages of carbon capture, including the prediction and monitoring of CO_2 behavior in different environments. By leveraging large datasets, AI algorithms can analyze ad predict the performance of carbon capture systems, adjusting operational parameters in real-time to maximize capture efficiency and minimize energy consumption. One significant advantage of AI in carbon capture is its ability to process complex data from multiple sources, enabling precise control and optimization of capture processes. For instance, AI can optimize the operation of amine scrubbing processes by continuously adjusting parameters to ensure optimal performance, thus reducing operational costs and improving efficiency. Additionally, AI models can predict the thermodynamic properties of CO_2 in solutions, aiding in the design and optimization of new capture materials and methods.

In carbon storage, AI enhances the accuracy and reliability of subsurface monitoring and modeling. By processing geological data, AI algorithms can predict the best sites for CO_2 injection and storage, ensuring the long-term stability and safety of stored carbon. This includes the detection and monitoring of potential leaks, providing real-time data that allow for rapid response and mitigation measures. AI's predictive capabilities also extend to the behavior of CO_2 in various geological formations, facilitating more efficient and secure storage solutions. Furthermore, AI contributes to the utilization of captured carbon by optimizing chemical processes that convert CO_2 into valuable products such as fuels and chemicals. By simulating various reaction pathways and conditions, AI can identify the most efficient and sustainable methods for CO_2 utilization, promoting a circular carbon economy. The integration of AI in carbon capture and storage systems also supports system-wide optimization. AI-driven platforms can coordinate the various components of CCUS infrastructure, ensuring seamless operation and reducing overall costs. For example, AI can manage the logistics of transporting captured CO_2 from industrial sources to storage or utilization sites, optimizing routes and schedules to minimize emissions and transportation costs. Table 1 presents a comprehensive overview of various AI-based algorithms applied in carbon capture processes, detailing their operational parameters, prospective applications, and references. The algorithms include Artificial Neural Networks (ANN), Machine Learning (ML), Deep Learning (DL), Fuzzy Logic, Adaptive Neuro-Fuzzy Inference System (ANFIS), Support Vector Machine (SVM), Genetic Algorithm (GA), and Deep Reinforcement Learning, among others. Each entry highlights the specific variables these algorithms optimize, their intended applications in enhancing carbon capture efficiency and reliability, and pertinent references for further reading. In conclusion, AI offers transformative potential for the advancement of carbon capture, utilization, and storage technologies. By enhancing the efficiency, reliability, and economic viability of these processes, AI plays a crucial role in the global effort to reduce greenhouse gas emissions and combat climate change. The integration of AI in CCUS also extends to system-wide optimization. AI-driven platforms can coordinate the various components of CCUS infrastructure, ensuring seamless operation and reducing overall costs. For instance, AI can manage the logistics of transporting captured CO_2 from industrial sources to storage or utilization sites, optimizing routes and schedules to reduce emissions and costs associated with transportation. In conclusion, AI offers transformative potential for the advancement of CCUS technologies. By enhancing the efficiency, reliability, and economic viability of carbon capture, storage, and utilization processes, AI can play a crucial role in the global effort to reduce greenhouse gas emissions and combat climate change.

Table 1. Summary of different AI-based algorithms in carbon capture.

AI Algorithm(s)	Operational Parameters (Variables)	Prospective Application(s)	Ref
ANN	Electrochemical cell temperature, the temperature differential between the cell and absorption column, and chloride-induced copper shift.	**Energy performances and optimization of flue gas CO_2 capture**: Enhancing energy efficiency and optimizing the process for capturing CO_2 from flue gases.	[97]
ML and DL â€" R	-	**Reducing the carbon footprint in the healthcare sector**: Minimizing carbon emissions within the healthcare industry.	
ANN, ANFIS and Bayesian regression model	-	-	

Table 1. *Cont.*

AI Algorithm(s)	Operational Parameters (Variables)	Prospective Application(s)	Ref
ANN, Convolutional neural network, SVM, DL and Long short-term memory (LSTM), Decision tree and random forest	-	Predicting physical properties, assessing mechanical stability, tracking CO_2 plume movement and leakage during storage, and estimating the success rate of CCS.	[98]
Fuzzy	Carbonation temperature, carbonation duration, and H_2O-to-CO_2 flow rate ratio	Maximization of CO_2 capture capacity	[96]
ANFIS	Tetraethylenepentamine, imidazole, and adsorption temperature	Boosting CO_2 adsorption capacity	[99]
ML	Net present value and hydrogen recovery factor	CO_2 storage optimization	
ANN	Carbon capture limitation model, carbon emission penalty factor, CO_2 production restrictions, and installed capacity of renewable energy.	Investigating the intricate dynamics between carbon, heat, and electricity in the carbon capture system, minimizing operational costs, reducing renewable energy usage, and studying carbon emissions.	
Hybrid ANFIS	Temperature, pH, CO_2%, and amount of nitrogen and phosphorous	Forecasting the CO_2 fixation of microalgae	[95]
ANN	Transport properties, mole fraction and temperature	Post-combustion carbon capture studies	
Ensemble interpretable neural network	-	Carbon neutrality research	[100]
Ensemble empirical mode decomposition -LSTM-SVR	-	Carbon capture in industrial power plants toward low carbon emission	
ANN	Liquid flowrate, gas flowrate, CO_2 concentration in the gas, CO_2 concentration in the liquid, monoethanolamine concentration in the liquid and nozzle diameter	Optimization of carbon capture in spray columns	[101]
Gradient Boosting	Various parameters specific to CO_2 reduction electrocatalysts	Predicting CO_2 reduction efficiency in electrocatalysts	[87]
Support Vector Machine (SVM)	Solubility of CO_2 in brines	Modeling CO_2 solubility for sequestration	[102]
Genetic Algorithm (GA)	Optimization of adsorbent materials	Discovering high-performing adsorbents	[103]
Deep Reinforcement Learning	Scheduling of CO_2 capture and storage processes	Optimizing CO_2 capture and storage processes	[104]

14.1. Environmental and Economic Impact of Carbon Capture, Utilization, and Storage (CCUS) Technologies

Carbon capture, utilization, and storage (CCUS) technologies present a promising approach to mitigating climate change by reducing carbon dioxide (CO_2) emissions. These technologies offer significant environmental benefits while posing economic challenges and opportunities. As CCUS technologies advance, they will play a crucial role in achieving global climate goals, preserving ecosystems, and shaping future economies.

14.2. Environmental Benefits of CCUS Technologies

14.2.1. Significant Reduction in Global CO_2 Emissions

CCUS technologies have the potential to substantially reduce global CO_2 emissions by capturing and either storing or utilizing CO_2 from industrial processes and power generation. Projections indicate that by 2050, CCUS could contribute to reducing up to 14%

of global emissions, helping to keep global temperature rise well below 2 °C in alignment with the Paris Agreement. These reductions are particularly crucial for industries such as cement, steel, and chemical production, which are challenging to decarbonize through other means.

14.2.2. Preservation of Ecosystems and Biodiversity

By mitigating climate change through substantial CO_2 reductions, CCUS technologies indirectly contribute to the preservation of ecosystems and biodiversity. Reduced global warming can help minimize habitat loss due to rising temperatures, sea level rise, and extreme weather events. Stabilizing the climate can also prevent ecosystem disruption, which is critical for maintaining biodiversity and the balance of natural ecosystems that provide essential services such as carbon sequestration, oxygen production, and water regulation.

14.2.3. Improvement in Air Quality

The widespread deployment of CCUS can improve air quality by reducing reliance on fossil fuel combustion. Traditional energy production from fossil fuels releases not only CO_2 but also harmful pollutants such as particulate matter (PM), nitrogen oxides (NOx), and sulfur oxides (SOx). These pollutants contribute to respiratory and cardiovascular diseases, as well as environmental problems like acid rain. By capturing CO_2 at the source or reducing the need for fossil fuels altogether, CCUS technologies can contribute to cleaner air, particularly in urban and industrial areas.

14.3. Economic Challenges and Opportunities

14.3.1. Job Creation in the Green Technology Sector

The transition to a low-carbon economy, driven by the adoption of CCUS technologies, is expected to create substantial employment opportunities. Estimates indicate that 11–13 million new jobs could be generated by 2050 across the green technology sector, including jobs in research and development, construction of CCUS infrastructure, operation and maintenance of capture and storage facilities, and related industries. These jobs will play a critical role in supporting the shift away from fossil fuel-dependent industries, providing opportunities for re-skilling and workforce transition.

14.3.2. Cost Analysis of CCUS Technologies

While CCUS technologies offer immense potential for reducing emissions, their current costs are a key challenge. A cost comparison of different CCUS technologies provides insight into their economic feasibility:

Post-Combustion Capture: Currently, the cost of capturing CO_2 from post-combustion processes ranges from USD 40 to USD 80 per ton of CO_2. This method is relatively mature and is being deployed in power plants and industrial facilities. However, reducing these costs further is essential to enable broader adoption.

Direct Air Capture (DAC): DAC, which captures CO_2 directly from ambient air, is currently more expensive, with costs ranging from USD 600 to USD 1000 per ton of CO_2. However, as DAC technology matures and benefits from technological improvements and economies of scale, costs are projected to fall to between USD 100 and USD 300 per ton by 2030. This cost reduction will be key to making DAC a viable solution for achieving negative emissions and offsetting residual emissions from hard-to-abate sectors.

Although CCUS technologies are expensive in the near term, continued technological advancements, such as more efficient sorbents and optimized process designs, along with scaling up deployment, will lead to cost reductions. These reductions will improve the economic viability of CCUS technologies, making them more competitive with other low-carbon technologies.

14.3.3. Economic Viability and Scale-Up

The economic viability of CCUS technologies is improving as technological advancements reduce costs and economies of scale are realized through larger deployments. Early investments in research, development, and infrastructure are critical to drive down costs and enhance efficiency. As more CCUS projects become operational, both private and public sectors are likely to benefit from cost savings, spurring further investment in CCUS.

14.3.4. Policy Incentives for CCUS Development

To accelerate the deployment of CCUS technologies and ensure their long-term success, governments must implement policy frameworks that incentivize investment and innovation in the sector. Key policy mechanisms include:

Carbon Pricing Mechanisms: Carbon pricing, including carbon taxes and emissions trading systems, is essential to create a level playing field for low-carbon technologies, such as CCUS. By assigning a cost to CO_2 emissions, carbon pricing incentivizes industries to adopt cleaner technologies and makes CCUS more financially attractive. As the cost of emitting CO_2 increases, industries will seek to reduce their emissions either by adopting CCUS or by transitioning to renewable energy sources.

Tax Credits and Grants for CCUS Projects: Government support in the form of tax credits and grants can significantly lower the financial barrier to entry for CCUS projects. In many countries, tax credits for captured and stored CO_2, such as the U.S. 45Q tax credit, are already being used to incentivize investment in CCUS. By providing direct financial support to developers, governments can encourage the private sector to invest in and scale up CCUS technologies.

Regulatory Frameworks for Safe CO_2 Storage: Ensuring the long-term safety and effectiveness of CO_2 storage is crucial for the success of CCUS. Governments must establish robust regulatory frameworks to monitor, verify, and report the safe and permanent storage of captured CO_2 in geological formations. These frameworks should also include guidelines for assessing the environmental risks associated with CO_2 storage, as well as mechanisms to ensure that stored CO_2 remains secure over time. Clear regulatory structures will also provide confidence to investors and developers, encouraging further investment in CCUS.

The deployment of CCUS technologies offers substantial environmental benefits, including significant reductions in CO_2 emissions, the preservation of ecosystems, and improvements in air quality. However, the economic challenges of high costs and the need for large-scale investments must be addressed through technological advancements, economies of scale, and supportive policy incentives. With the right mix of public and private sector support, CCUS can become a key pillar in the global strategy to achieve net-zero carbon emissions by 2050 while simultaneously creating jobs and driving economic growth in the green technology sector.

15. Conclusions

As global CO_2 emissions continue to rise due to human activities, the urgency for effective strategies to combat climate change has never been greater. This review highlights the transformative potential of CCUS technologies in mitigating these emissions. By integrating emerging technologies such as DAC, MOFs, and advanced membrane systems, this paper presents a comprehensive synthesis of current advancements that are reshaping the landscape of carbon capture.

A distinctive feature of this review is its focus on industry-specific decarbonization strategies tailored for sectors such as oil and gas, steel, and cement. This targeted approach not only provides actionable insights for stakeholders but also emphasizes the unique challenges and opportunities faced by each industry in achieving net-zero emissions. Furthermore, the inclusion of a detailed TRL analysis offers valuable guidance on the maturity and commercial viability of various CCUS technologies, facilitating informed decision-making for policymakers and investors. The proposed roadmap for achieving net-zero emissions articulates clear short-, medium-, and long-term goals, effectively linking

CCUS technologies to broader global decarbonization efforts. This strategic framework enhances our understanding of how these technologies can be deployed in a coordinated manner to maximize their impact.

Moreover, the exploration of AI within CCUS processes introduces a forward-thinking perspective that is rarely addressed in existing literature. By leveraging AI to optimize capture processes and enhance monitoring capabilities, we can significantly improve the efficiency and cost-effectiveness of CCUS technologies. In assessing both the economic and environmental impacts of CCUS, this review underscores the dual benefits of reducing greenhouse gas emissions while simultaneously creating market opportunities for CO_2-derived products. However, it also acknowledges the persistent challenges posed by high costs and regulatory hurdles that must be addressed through supportive policies and public engagement. Ultimately, this review emphasizes that CCUS technologies are not merely an option but a necessity in our collective effort to achieve a sustainable, low-carbon future. As we look ahead, continued innovation, interdisciplinary collaboration, and robust policy frameworks will be essential to unlocking the full potential of CCUS in our fight against climate change. By bridging technological advancements with strategic implementation, we can pave the way for a cleaner and more resilient world.

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