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(Review Article)

Advances and Integration of Carbon Capture, Utilization, and Storage (CCUS): A Circular Approach Towards a Net-Zero Carbon Economy

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Abstract

Rising atmospheric carbon dioxide (CO_2) levels from human activities pose a major threat to global climate stability, reinforcing the need for effective mitigation technologies. Carbon Capture, Utilization, and Storage (CCUS) has become a central strategy for advancing a net-zero carbon economy by simultaneously reducing emissions and creating value from captured CO_2. Significant progress in carbon capture and storage has been achieved in energy-intensive and industrial sectors, with geological sequestration serving as the primary long-term storage option. Meanwhile, utilization pathways are gaining traction for converting CO_2 into fuels, chemicals, and construction materials, thereby promoting circular resource flows. Recent advances in CCUS are supported by innovative materials such as metal-organic frameworks (MOFs), solid sorbents, and amine-functionalized membranes, which offer improved selectivity, durability, and energy efficiency. Integrated approaches, including direct air capture (DAC), bioenergy with carbon capture and storage (BECCS), and electrochemical CO_2 conversion, further strengthen system performance and expand utilization potential. However, high energy demand, economic constraints, infrastructure requirements, regulatory uncertainties, and public acceptance continue to limit large-scale deployment. Addressing these challenges will require supportive policy frameworks and interdisciplinary research to enhance techno-economic feasibility and scalability. Most importantly, CCUS represents a critical pathway for achieving deep decarbonization within a circular and resilient global economy.

Keywords: Carbon Capture; CO_2 Utilization; Carbon Storage Technologies; Circular Economy; Net-Zero Emissions; Carbon-To-Value; Green Chemistry

1. Introduction

The accelerating rise in global greenhouse gas (GHG) emissions, particularly carbon dioxide (CO_2), represents one of the most pressing challenges confronting contemporary society. Atmospheric CO_2 concentrations have now exceeded 420 parts per million, markedly surpassing pre-industrial benchmarks and signaling profound disruption of the Earth's climate system [1]. Emissions arising from fossil fuel combustion, land-use change, and industrial production have driven sustained global warming, sea-level rise, increased frequency of extreme weather events, and escalating stress on natural ecosystems [2 ,4, 3]. In response, international climate governance has coalesced around ambitious mitigation targets, most notably through the United Nations Framework Convention on Climate Change (UNFCCC) and the 2015 Paris Agreement, which seeks to limit global temperature rise to well below 2°C, with efforts toward 1.5°C [3, 2]. Despite these commitments, current emission reduction trajectories remain inadequate, highlighting the urgent need for scalable and technologically mature climate mitigation solutions. Within the portfolio of available strategies, Carbon Capture, Utilization, and Storage (CCUS) has emerged as a critical option for achieving deep decarbonization, particularly in hard-to-abate sectors such as power generation, cement, steel, and chemical manufacturing [4, 5]. CCUS

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encompasses technologies that capture CO_2 from point sources or the atmosphere, followed by either long-term storage in geological formations or conversion into value-added products. Unlike approaches focused solely on emissions avoidance, CCUS enables direct emissions reduction and, when coupled with bioenergy or direct air capture, can deliver net-negative emissions [5]. This dual functionality positions CCUS as both a transitional mitigation pathway and a long-term pillar of a climate-neutral energy system. Traditionally, carbon capture and storage was viewed as a linear, end-of-pipe solution primarily aimed at permanent CO_2 disposal. However, the growing integration of utilization pathways has reframed CCUS within a more circular and sustainable paradigm [13]. The circular economy concept, centered on resource efficiency, waste minimization, and value retention, provides a compelling framework for reimagining carbon management. Within this context, captured CO_2 is increasingly recognized as a secondary carbon resource rather than an unwanted waste stream. Through chemical, biological, and mineralization routes, CO_2 can be transformed into fuels, chemicals, polymers, and construction materials, thereby reducing dependence on fossil-derived carbon while stimulating innovation across industrial value chains. This transition toward a circular CCUS model is underpinned by substantial advances in materials science, process engineering, and systems integration. Innovations in capture technologies, including advanced solvents, solid sorbents, and membrane-based separations, have improved capture efficiency while lowering energy penalties. Concurrently, progress in catalytic conversion and electrochemical reduction has expanded the portfolio of CO_2-derived products, such as methanol, urea, synthetic hydrocarbons, and carbonates [13, 8, 7]. Geological storage technologies have likewise matured, with large-scale demonstration projects confirming the safety and effectiveness of storage in deep saline aquifers and depleted hydrocarbon reservoirs. The integration of capture, utilization, and storage components into flexible and scalable systems is increasingly recognized as essential for deployment within industrial hubs and carbon-intensive regions [8]. Beyond technological progress, the policy and economic landscape surrounding CCUS is evolving rapidly. Governments are increasingly incorporating CCUS into climate strategies through policy instruments such as tax credits, emissions trading schemes, carbon pricing mechanisms, and targeted funding for demonstration projects [9]. International initiatives, including those led by the Clean Energy Ministerial and the Global CCS Institute, have further accelerated knowledge sharing, standardization, and capacity building [10]. Nevertheless, significant challenges persist, including high capital and operating costs, limited CO_2 transport infrastructure, public acceptance concerns, and unresolved questions surrounding long-term storage liability [11]. Moreover, integrating CCUS within a circular economy framework necessitates rigorous life-cycle assessment to ensure genuine climate benefits, as the net impact of CO_2 utilization pathways depends strongly on energy inputs, process efficiency, and system boundaries [12, 10, 13].

This review provides a comprehensive and multidisciplinary assessment of Carbon Capture, Utilization, and Storage technologies, with emphasis on recent advances, system integration, and their role within a circular carbon economy. It examines technological progress across capture, conversion, and storage pathways, evaluates policy and economic drivers, and identifies key challenges and research gaps related to scalability, sustainability, and socio-economic performance [13]. By synthesizing insights from engineering, environmental science, economics, and policy, this work highlights how CCUS, embedded within a circular and regenerative framework, can contribute meaningfully to the transition toward a resilient, net-zero carbon economy.

2. Fundamentals of Carbon Capture, Utilization, and Storage

As the world confronts the escalating climate crisis, the development and deployment of technologies that can actively reduce atmospheric carbon dioxide (CO_2) levels are of critical importance [6, 70, 14]. One of the most promising sets of solutions is encompassed within Carbon Capture, Utilization and Storage (CCUS). These technologies serve as a bridge between fossil fuel-based energy systems and a sustainable, low-carbon future [8]. CCUS offers a multifaceted approach that not only captures CO_2 emissions at their source but also enables their safe storage or conversion into valuable products, creating a circular carbon economy. Achieving large-scale CCUS deployment by 2050 requires a phased, regionally diverse strategy that balances near-term implementation with sustained innovation. By mid-century, CCUS is expected to evolve from a niche mitigation tool into a central driver of net-zero economies, working in synergy with renewable energy, hydrogen, and circular carbon markets [13].

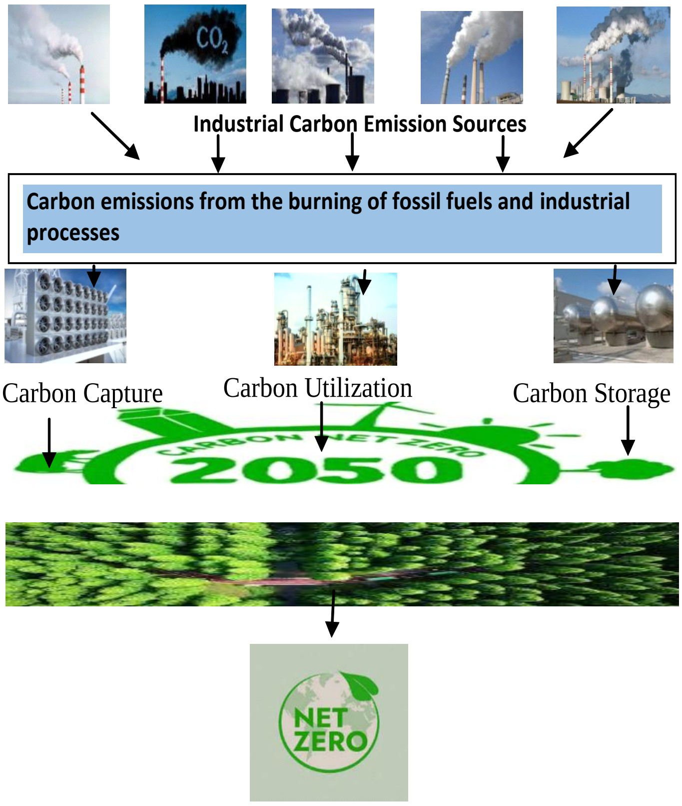

Figure 1 Fundamentals of Carbon Capture, Utilization, Storage and Transition to a Net-Zero Carbon Economy [8]

2.1. Overview of Carbon Capture, Utilization, and Storage Technologies

2.1.1. Carbon Capture and Storage (CCS)

CCS refers to the process of capturing carbon dioxide emissions from large point sources, such as power plants and industrial facilities, and storing them permanently in geological formations deep underground, such as depleted oil and gas fields or deep saline aquifers. This prevents the CO_2 from entering the atmosphere and contributing to global warming [15]. For example, Norway's Sleipner Project, which has been operating since 1996, captures CO_2 from natural gas production and stores it in a deep saline aquifer beneath the North Sea.

2.1.2. Carbon Capture and Utilization (CCU)

CCU involves capturing CO_2 and then repurposing it for commercial or industrial use, rather than storing it underground. This can include the production of fuels, chemicals, building materials (e.g., concrete curing), or even synthetic plastics [16]. For example, CarbonCure Technologies in Canada injects captured CO_2 into concrete during mixing, where it mineralizes and strengthens the material, effectively locking the carbon into a solid form.

2.1.3. Carbon Capture, Utilization, and Storage (CCUS)

CCUS combines both approaches. It represents a holistic strategy for dealing with CO_2 emissions, where carbon is either stored permanently or utilized in industrial processes. The choice between utilization or storage depends on economic feasibility, available infrastructure, and environmental impact [17]. For example, in a coal-fired power plant, a CCUS system can capture CO_2 from flue gas, transport the stream to utilization facilities where it is converted into products such as methanol or urea-based fertilizers, and direct the remaining stream for injection into secure underground storage sites.

Table 1 Extensive overviews of Carbon Capture and Storage (CCS), Carbon Capture and Utilization (CCU), and Carbon Capture, Utilization, and Storage (CCUS) [15, 16, 17, 19]

Aspect	**Carbon Capture and Storage (CCS)**	**Carbon Capture and Utilization (CCU)**	**Carbon Capture, Utilization, and Storage (CCUS)**
Definition	A climate mitigation technology that involves capturing CO_2 emissions from industrial or energy-related sources and permanently storing it underground (e.g., in geological formations).	A process that captures CO_2 and converts it into commercially valuable products such as fuels, chemicals, and construction materials.	An integrated approach that encompasses both utilization and storage of captured CO_2, aiming for maximum climate and economic benefits.
Distinction	Focused solely on *permanent storage* of CO_2 to prevent its release into the atmosphere.	Focused on *recycling or converting* CO_2 into useful products, potentially generating revenue.	Combines *both utilization and storage* pathways, offering flexibility in carbon management strategies.
Advantages	• Permanent removal of CO_2 from the atmosphere • Established in large-scale applications (e.g., saline aquifers, depleted oil fields) • Vital for hard-to-abate sectors (e.g., cement, steel).	• Creates marketable products from waste CO_2 • Encourages innovation and industrial symbiosis • Can offset capture costs through revenue generation.	• Optimizes CO_2 management by offering both reduction and resource valorization • Aligns well with circular economy principles • Enhances economic viability and sectoral integration.
Disadvantages	• High capital and operational costs • Requires secure long-term storage sites • Public resistance due to safety and leakage concerns • No direct economic return.	• Often leads to short-term carbon cycling (e.g., CO_2 used in fuels is re-emitted) • Technologically immature for some products • Market limitations for CO_2-derived products.	• Complexity in system design and regulation • Requires coordinated infrastructure for both utilization and storage • Balancing environmental benefits with economic returns is challenging.
Extensive Overview	CCS is central to many climate models and pathways (e.g., IPCC scenarios) that limit global warming below 2°C. It is critical for decarbonizing sectors with process-related CO_2 emissions and for negative emissions when combined with bioenergy (BECCS). CCS is often supported by government incentives and carbon pricing.	CCU is emerging as a bridge between carbon mitigation and industrial productivity. It enables CO_2 to be used in enhanced oil recovery (EOR), urea production, plastics, and synthetic fuels. While its climate impact depends on life-cycle analysis, it provides a pathway for industrial decarbonization and circular economy integration.	CCUS represents a hybrid strategy that maximizes the utility of captured CO_2. It enables dynamic decision-making between utilization and storage based on technical, environmental, and economic factors. CCUS supports net-zero and even negative-emission targets when applied across sectors and integrated with renewable energy systems.

2.1.4. Technology Chain: Capture → Transport → Utilization /Storage

The technology chain capture → transport → utilization/storage represents the systematic process by which carbon dioxide (CO_2), or other industrially significant gases and products, are managed to mitigate environmental impacts while enabling resource recovery. CCUS technologies operate across a value chain that includes three main stages: carbon capture, transport, and either utilization or storage [18].

2.1.5. Carbon Capture

This is the first and most crucial stage in the carbon management chain. Capture technologies are specifically designed to extract CO_2 from gas streams produced by power generation and industrial processes such as cement manufacturing, steel production, and chemical refining, or in some cases, directly from the ambient atmosphere through Direct Air Capture (DAC). Among the established approaches, three methods dominate: post-combustion capture, pre-combustion capture, and oxy-fuel combustion [19]. Post-combustion capture, which is the most widely deployed technique, removes CO_2 from flue gases after fuel combustion. The separation is typically achieved using chemical solvents, most commonly amine-based scrubbers, that selectively absorb CO_2. A landmark example of this method in practice is the Petra Nova Project in Texas, which, until its suspension in 2020, stood as the world's largest post-combustion capture facility attached to a coal-fired power plant. The project was capable of capturing about 1.4 million tonnes of CO_2 per year, which was then used for enhanced oil recovery in nearby oil fields [20]. Pre-combustion capture, on the other hand, takes place before fuel is combusted. In this method, fossil fuels are gasified to produce a synthetic gas, or syngas, composed mainly of hydrogen and carbon monoxide. The carbon monoxide is further processed with steam to yield hydrogen and CO_2, after which the CO_2 can be separated. This method is particularly well-suited for hydrogen and ammonia production, where the separation of CO_2 is an inherent step in the industrial process. For instance, pre-combustion capture is already being applied in integrated gasification combined cycle (IGCC) power plants, such as the now-retired Kemper Project in Mississippi, which, despite operational setbacks, highlighted the potential and challenges of integrating this technology on a commercial scale [21].

Oxy-fuel combustion offers a third approach, where fossil fuels are burned in nearly pure oxygen rather than air. This modification results in a flue gas that consists primarily of CO_2 and water vapour, both of which can be easily separated through condensation. Demonstrations of oxy-fuel combustion have been carried out in pilot projects such as the Callide Oxy-fuel Project in Queensland, Australia. This project successfully showed that retrofitting existing power stations with oxy-fuel technology is possible and that high-purity CO_2 can be generated for subsequent storage or utilization [22]. Although still less commercially mature than post-combustion and pre-combustion capture, oxy-fuel systems continue to be refined as potential large-scale options for decarbonizing power production. Beyond these point-source technologies, direct air capture (DAC) represents a fundamentally different strategy because it targets diffuse atmospheric CO_2 rather than concentrated industrial emissions. DAC technologies typically rely on chemical sorbents or solvents to selectively bind CO_2 from ambient air, after which it can be released, compressed, and stored. While the energy requirements for DAC remain high, the advantage lies in its flexibility and independence from specific emission sources. A leading example is Climeworks' Orca plant in Iceland, which began operation in 2021 as the world's largest DAC facility. The plant is capable of capturing up to 4,000 tonnes of CO_2 annually, which is subsequently injected into nearby basaltic rock formations. Through natural mineralization processes, the CO_2 reacts with the basalt and is permanently converted into stable carbonates. Considering the example illustrate how carbon capture has moved from theoretical concepts to real-world applications across different contexts. Post-combustion capture is being applied to retrofit coal plants, pre-combustion capture is integrated into hydrogen and ammonia production, oxy-fuel combustion has been tested in demonstration projects, and DAC is emerging as a flexible, scalable option that can complement traditional point-source strategies. The combination of these technologies highlights the diverse pathways available to address CO_2 emissions and demonstrates the growing role of carbon capture as a key pillar in global climate mitigation strategies [19, 22].

2.1.6. CO_2 Transport

Once CO_2 has been successfully captured, it must be transported to designated storage or utilization sites. The mode of transport selected largely depends on the scale of operations, the distance to be covered, and the infrastructure available. Among the options, pipelines remain the most cost-effective and widely deployed technology, particularly for short-to medium-distance transfers [23]. They are especially efficient when linking multiple capture facilities to centralized storage hubs, thereby enabling economies of scale. The United States provides the most notable example, with an extensive CO_2 pipeline network spanning over 8,000 kilometers [24]. This network has been developed primarily to supply CO_2 for Enhanced Oil Recovery (EOR) operations in states such as Texas and New Mexico, where captured CO_2 is injected into depleted oil reservoirs to boost crude production while simultaneously storing significant amounts of CO_2 underground [25]. The scale and success of this infrastructure underscore the maturity and reliability of pipeline-based CO_2 transport, which continues to serve as the backbone of many carbon management strategies worldwide. In regions where pipeline infrastructure is unavailable or impractical, CO_2 is increasingly being transported by trucks or ships. For such modes, CO_2 is first compressed into liquid form, which reduces its volume and makes it more manageable for handling and distribution [26]. This approach is particularly suitable for small-scale projects, pilot demonstrations, or instances where capture facilities are located far from potential storage sites. An example is found in several European initiatives, where liquefied CO_2 is shipped across national borders to offshore storage sites in the North Sea. The Northern Lights project in Norway, for instance, represents a pioneering effort in this area. It involves capturing CO_2 from industrial plants in Norway and other European countries, transporting it in liquid form by ship, and then injecting it into deep saline aquifers beneath the seabed [27]. This project highlights the flexibility of maritime CO_2 transport and its potential to establish international carbon storage networks. Rail transport has also been considered as a viable option for medium-scale operations, particularly in regions with established industrial clusters but limited pipeline networks. By utilizing existing railway infrastructure, CO_2 can be efficiently moved from dispersed industrial facilities to centralized hubs for storage or utilization [28]. While large-scale railway-based CO_2 transport is still at an early stage, feasibility studies have been undertaken in Europe and Asia to evaluate its potential in connecting industries located inland with coastal storage sites [29]. Such developments indicate that rail could become a complementary transport option in future carbon management systems, particularly during the transitional period before large-scale pipeline or shipping networks are fully developed. Overall, the choice of transport method is dictated by a balance of economic, geographical, and infrastructural considerations. Pipelines dominate in regions with mature networks and large-scale storage operations, ships and trucks provide flexibility for smaller or geographically dispersed projects, and railways present an emerging solution for medium-scale scenarios. Together, these modes of CO_2 transport form a critical link in the carbon capture, utilization, and storage (CCUS) chain, enabling captured CO_2 to be securely delivered from emission sources to sites where it can be permanently stored or converted into valuable products.

2.1.7. CO_2 Utilization or Storage

Once CO_2 reaches its destination, it undergoes one of two pathways: permanent storage in geological or mineral formations, or utilization as a feedstock in various industrial applications. Both strategies form the final stage of the carbon capture, utilization, and storage (CCUS) chain and play an equally important role in reducing atmospheric concentrations of greenhouse gases [23]. Geological storage remains the most established and widely studied option. In this process, CO_2 is injected into porous rock formations located between one and three kilometers beneath the Earth’s surface, where impermeable caprock layers trap the gas and prevent leakage. Depleted oil and gas reservoirs, deep saline aquifers, and unmineable coal seams are among the primary geological formations used for this purpose [24]. In the North Sea, for instance, depleted offshore oil and gas fields have become promising storage sites under initiatives such as the Sleipner Project in Norway. Since 1996, Sleipner has successfully injected over one million tonnes of CO_2 annually into a saline aquifer beneath the seabed, making it one of the longest-running and most significant demonstrations of large-scale geological storage [25]. Mineralization provides an alternative form of permanent storage, in which CO_2 reacts with naturally occurring minerals such as basalt or olivine to form stable carbonates. Unlike geological storage, mineralization results in the irreversible conversion of CO_2 into solid rock, providing one of the most secure forms of sequestration [26]. The CarbFix project in Iceland is a leading example of this technology. In this project, captured CO_2 is dissolved in water and injected into underground basaltic formations, where it undergoes rapid chemical reactions and is transformed into solid carbonate minerals within just two years [27]. This contrasts sharply with earlier expectations that mineralization would require centuries, and it highlights the potential for replicating this method in other regions with abundant volcanic or ultramafic rock formations. Alongside permanent storage, CO_2 utilization technologies are gaining traction as part of a circular carbon economy, in which captured carbon is transformed into valuable products. One key route is chemical conversion, where CO_2 is used to manufacture chemicals such as methanol, urea, and polycarbonates. Large-scale CO_2-to-methanol plants are already operational in China, such as the Shanxi Province facility, which converts CO_2 emissions from coal-based chemical plants into methanol used for fuels and chemicals [28]. In Iceland, Carbon Recycling International has developed a similar process, producing renewable methanol branded as "Vulcanol" by combining captured CO_2 with hydrogen derived from renewable energy [29].

Bio-conversion represents another avenue, where CO_2 serves as a feedstock for algae cultivation. The biomass generated can be converted into biofuels, food supplements, or animal feed. Algenol Biofuels in the United States developed systems where algae use CO_2 to produce ethanol directly, demonstrating the potential of this approach for sustainable fuel production. Although still in the development phase, such projects underline the role of biological systems in valorizing captured carbon. The construction industry also offers opportunities for CO_2 utilization. One emerging application involves injecting CO_2 into concrete during the curing process. This not only enhances the strength of the material and reduces the required amount of cement, a major source of CO_2 emissions, but also traps carbon within the final product. CarbonCure, a company based in Canada, has successfully commercialized this technology, with its CO_2-treated concrete being used in public infrastructure projects across the United States and Canada, including airport runways and residential buildings. A further frontier in utilization lies in the production of synthetic fuels. In processes collectively known as Power-to-X, renewable hydrogen is combined with CO_2 to produce carbon-neutral fuels such as methane, gasoline, or jet fuel. This technology has attracted growing interest as a way to decarbonize hard-to-abate sectors like aviation and shipping. The German "Kerosene for the Future" project and partnerships between companies such as Audi and Sunfire have already demonstrated the production of synthetic hydrocarbons at pilot scale. These fuels close the carbon loop by recycling CO_2 emissions, especially when powered entirely by renewable electricity. Taken together, storage and utilization represent complementary strategies in addressing global CO_2 emissions. While geological and mineral storage focus on permanent sequestration, utilization technologies seek to integrate captured carbon into valuable industrial cycles [23]. Case studies such as Sleipner, CarbFix, CarbonCure, and CO_2-to-methanol plants in China and Iceland demonstrate that these solutions are no longer limited to theory but are increasingly being implemented at scale [24]. The balance between utilization and storage will ultimately depend on regional infrastructure, economic incentives, and technological maturity, but both remain essential components of a global strategy to achieve net-zero emissions [25].

2.2. Circular Carbon Economy Concept

The circular carbon economy (CCE) is a climate mitigation framework that treats carbon as a resource to be managed in a continuous cycle rather than as waste to be released into the atmosphere. It builds on the principles of the circular economy by promoting strategies to reduce emissions, reuse and recycle captured carbon in industrial processes, and remove excess carbon through storage or natural sinks [26]. Unlike the traditional linear model of "extract–use–emit," the CCE creates closed carbon loops where carbon is captured and reintegrated into productive systems [27]. Carbon Capture, Utilization and Storage (CCUS) plays a central role in enabling this cycle by preventing emissions, creating value-added products, and supporting long-term storage [28]. In this way, the circular carbon economy provides a sustainable pathway that balances economic development with climate goals [29].

2.2.1 Principles of Circularity

The circular carbon economy (CCE) is rooted in the broader philosophy of the circular economy, which emphasizes minimizing waste, maximizing resource efficiency, and regenerating natural systems. In the carbon context, circularity seeks to shift away from the conventional linear model of "take–make–dispose," where fossil carbon is extracted, combusted, and released into the atmosphere as greenhouse gases. Instead, carbon is continuously cycled through reduction, reuse, recycling, and removal strategies, treating it as a valuable resource rather than an inevitable waste stream [30].

Reduction

Reduction involves minimizing the release of carbon emissions at the source through improved efficiency, clean energy adoption, and sustainable industrial practices. For instance, the European Union has made significant progress in reducing emissions by integrating renewable energy sources into its power grids, achieving more than 34% of electricity generation from renewables in 2022. Similarly, Japan's Top Runner Program has reduced industrial and household energy consumption through efficiency standards [31]. These initiatives demonstrate how reducing carbon output at source is a foundational principle of circularity.

Reuse and Recycling

The reuse and recycling principle focuses on capturing CO_2 and repurposing it within industrial and commercial applications. One prominent case is CarbonCure Technologies (Canada), which injects captured CO_2 into concrete during production. The process not only permanently stores CO_2 but also strengthens the concrete, offering both economic and environmental benefits. Likewise, Covestro (Germany) has pioneered the conversion of captured CO_2 into polyurethane foams used in furniture and insulation. In the energy sector, enhanced oil recovery (EOR) projects in the United States, such as those in the Permian Basin (Texas), employ captured CO_2 to increase oil extraction efficiency while simultaneously storing substantial amounts of carbon underground [32]. These examples illustrate how circularity transforms CO_2 from a pollutant into a feedstock for new value chains.

Removal

Removal strategies are designed to extract excess CO_2 from the atmosphere and store it safely in natural or engineered sinks. Nature-based solutions, such as China's large-scale afforestation projects, have added millions of hectares of forest cover, acting as significant carbon sinks. On the technological front, Climeworks (Switzerland) operates one of the world's largest direct air capture (DAC) plants in Iceland, which extracts CO_2 from ambient air and mineralizes it in basalt rock formations through the CarbFix project. Similarly, the deployment of biochar insub-Saharan Africa has shown promise both in improving soil fertility and sequestering carbon over long timescales [33]. These approaches exemplify the removal pillar, ensuring that unavoidable emissions are balanced by deliberate carbon withdrawal from the atmosphere.

Integration of Principles

These interconnected strategies, reduction, reuse and recycling, and removal, form the backbone of the CCE. For example, Saudi Arabia's Circular Carbon Economy National Program integrates renewable energy, carbon capture, utilization technologies, and afforestation efforts into a cohesive national strategy. By keeping carbon in controlled loops, such integrated approaches help mitigate its release, enhance sustainability, and align economic development with climate commitments under frameworks such as the Paris Agreement [34].

2.2.1. CCUS as a Circular Carbon Loop

Carbon Capture, Utilization and Storage (CCUS) represents the most practical embodiment of circularity within the carbon economy framework. By intercepting carbon dioxide emissions from industrial processes, fossil-fuel power generation, and waste treatment facilities, CCUS prevents atmospheric release while reintegrating carbon into productive or storage cycles [26]. Unlike the traditional “emit and discard” approach, CCUS creates a controlled loop where carbon either re-enters value chains through utilization or is permanently locked away through storage.

CCUS in Utilization Pathways

Utilization pathways focus on converting captured CO_2 into valuable products, reducing reliance on virgin fossil resources while creating opportunities for long-term carbon management. One example is fuel production, where captured CO_2 is transformed into methanol, as demonstrated by the George Olah Renewable Methanol Plant in Iceland. The methanol produced serves both as a transportation fuel and a chemical feedstock [35]. In the construction sector, companies like CarbonCure Technologies in Canada and Solidia Technologies in the United States inject CO_2 into concrete, where it mineralizes and strengthens the material, offering the dual benefit of lowering emissions and permanently storing carbon within infrastructure. Similar innovations are taking place in the chemical industry. Covestro in Germany has pioneered methods to incorporate CO_2 into the synthesis of polyurethane foams used in everyday products such as mattresses, insulation, and textiles. In the fertilizer industry, several plants in India have integrated CO_2 capture systems into urea production, where the captured gas functions as a raw material in fertilizer synthesis [36]. Together, these initiatives demonstrate how CO_2 can be repositioned as a resource rather than a waste product. By treating carbon dioxide as a feedstock, utilization pathways close the carbon loop, delivering both environmental benefits and economic value across multiple sectors.

CCUS in Storage Pathways

Storage pathways are designed to provide long-term sequestration of CO_2 in stable geological formations, ensuring that captured carbon is permanently isolated from the atmosphere. This approach plays a vital role in addressing hard-to-abate emissions by offering a reliable means of keeping carbon out of the climate system. Several large-scale projects illustrate the progress and challenges of this pathway [37].

Integration of Utilization and Storage in the Circular Loop

The dual function of CCUS, utilization and storage, makes it a cornerstone of the circular carbon economy. By converting waste CO_2 into marketable products and securely storing excess emissions underground, CCUS ensures that carbon remains in controlled loops. Countries such as Saudi Arabia, through its Circular Carbon Economy National Program, are advancing CCUS as part of a national climate strategy, aligning industrial development with global emission reduction goals [34]. In this way, CCUS operationalizes the circular carbon economy, turning what was once viewed as a liability into a resource while providing a mechanism for net-zero and carbon-negative pathways.

2.2.2. Benefits vs. Linear Carbon Strategies

The advantages of adopting a circular carbon economy over conventional linear carbon strategies extend across environmental, economic, and energy dimensions. In a linear carbon economy, fossil fuels are extracted, combusted, and released into the atmosphere with little consideration for reuse or recycling. This model has historically fueled industrialization but at the cost of accelerated greenhouse gas accumulation, air pollution, and worsening climate change [38]. By contrast, the circular carbon economy (CCE) not only reduces emissions at source but also enables the capture of released carbon, reintegrating it into industrial value chains. This transformation re-positions CO_2 from being a harmful byproduct to a resource that supports sustainable development.

Climate Change Mitigation

One of the clearest benefits of circular strategies over linear ones lies in climate impact. For instance, the Sleipner CCS project in Norway has successfully stored over 25 million tonnes of CO_2 since 1996, preventing its release into the atmosphere. This illustrates how CCE practices directly contribute to climate change mitigation by lowering net emissions, an outcome unattainable under a linear system that allows emissions to accumulate [39].

Resource Efficiency

The circular carbon framework treats CO_2 as a feedstock rather than waste, thereby improving resource efficiency. It highlights how circularity reduces reliance on virgin fossil resources while creating closed carbon loops in industrial production [30].

Economic Opportunities

Circular carbon strategies also generate economic value by creating new markets for carbon-derived products and services. According to the Global CCS Institute, over 40 large-scale CCUS projects are in operation or development worldwide, fostering industries in carbon-based fuels, chemicals, and materials. This shows how circular carbon strategies foster innovation, generate green jobs, and enhance global competitiveness in low-carbon industries [8].

Energy Security and Sustainability

CCE also supports energy security by complementing renewable energy systems and decarbonizing hard-to-abate sectors. By recycling captured CO_2 into synthetic fuels, such as e-fuels developed in Germany's POWER-to-X initiatives, the circular model provides energy carriers compatible with existing infrastructure. This stabilizes energy systems while ensuring industrial productivity, unlike linear models that remain dependent on finite fossil reserves [40].

Linear vs. Circular Outcomes

While the linear carbon model locks economies into pathways of rising emissions, resource depletion, and environmental degradation, the circular approach balances economic growth with planetary health. By reducing emissions, enhancing efficiency, generating economic opportunities, and ensuring energy sustainability, circular carbon strategies position Carbon Capture, Utilization and Storage (CCUS) as a cornerstone of climate and energy policies globally. The shift from linear to circular carbon pathways is not only a necessity for meeting Paris Agreement targets but also a driver of innovation and long-term resilience in global economies [40, 8, 30, 39].

3. Advances in Carbon Capture Technologies

The rapid development of carbon capture technologies has been pivotal in enabling the transition towards a circular carbon economy. These technologies aim to intercept carbon dioxide (CO_2) emissions at various stages of the energy and industrial process chain or directly from the atmosphere, reducing their contribution to climate change [41]. The main capture approaches include post-combustion capture, pre-combustion and oxy-fuel methods, and direct air capture (DAC), each of which has undergone significant advances in recent years.

3.1. Pre-Combustion and Oxy-Fuel Capture

Pre-combustion and oxy-fuel combustion technologies represent alternative approaches to post-combustion capture, targeting CO_2 removal before or during fuel combustion. Both methods offer potential efficiency gains and reduced capture costs under specific applications, though large-scale deployment has faced both technical and economic hurdles [42].

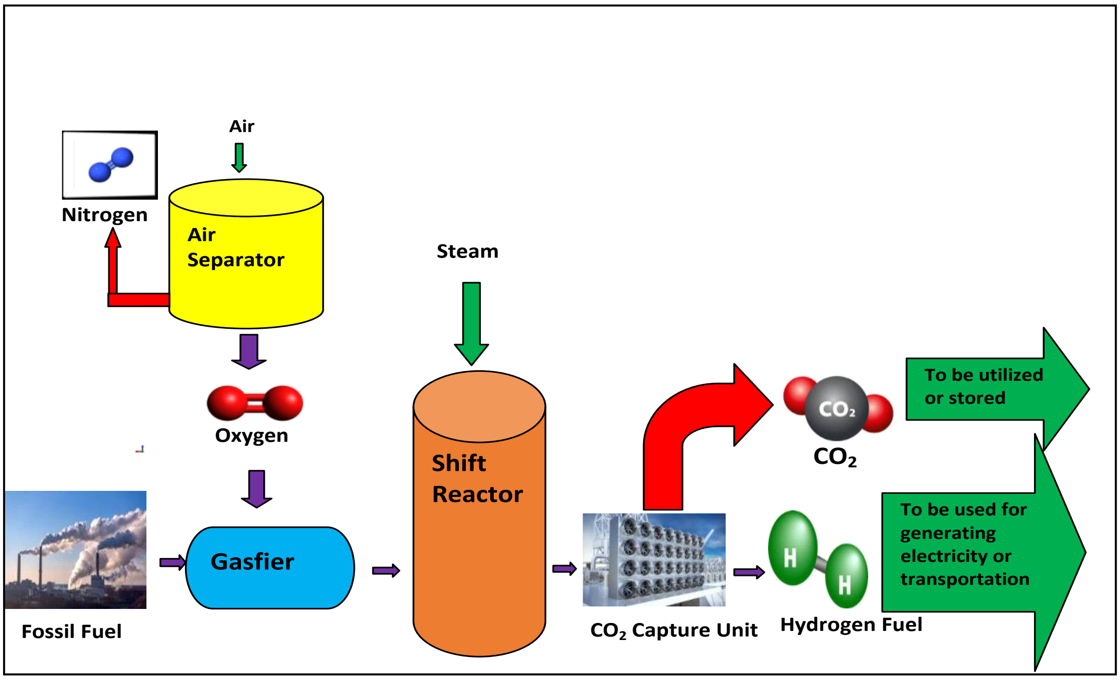

Figure 2 Pre-combustion carbon capture process [168]

3.1.1. Pre-Combustion Capture: Gasification and Reforming

Pre-combustion carbon capture systems work by converting fossil fuels such as coal, petroleum coke, or natural gas into synthesis gas, a mixture of carbon monoxide and hydrogen, through processes like integrated gasification combined cycle or steam methane reforming [168]. The carbon monoxide is then shifted into carbon dioxide and hydrogen via the water-gas shift reaction, allowing the CO_2 to be separated under high pressure. This high-pressure environment reduces capture costs compared to post-combustion methods, while the hydrogen-rich gas produced serves as a low-carbon fuel for power generation or industrial applications [43]. Several large-scale projects have tested the feasibility of this pathway [44].

3.1.2. Membrane and Cryogenic Separation Approaches

Alternative pre-combustion separation technologies are under active development, with emphasis on membrane- and cryogenic-based systems:

- **Membranes:** Polymeric, mixed-matrix, and ceramic membranes can be engineered for selective CO_2/H_2 separation. Membranes offer lower energy penalties and modular scalability, but issues such as plasticization, thermal stability, and fouling under real flue gas conditions limit large-scale adoption [45].
- **Cryogenic Distillation:** Particularly suited to high-purity CO_2 recovery, cryogenic systems cool gas streams to very low temperatures to liquefy and separate CO_2. While effective, these systems are energy intensive and are primarily suited to niche industrial applications where high-purity CO_2 is required (e.g., food and beverage, chemical feedstocks). Pilot-scale demonstrations in Europe and North America have validated their potential in low-volume but high-value capture scenarios [46]**.**

3.1.3. Oxy-Fuel Combustion

Oxy-fuel combustion systems operate by burning fossil fuels in pure oxygen rather than air, producing a flue gas made up mainly of carbon dioxide and water vapor. After the water is condensed, the remaining CO_2 stream is nearly pure, which greatly simplifies the separation process and makes this pathway attractive for carbon capture and storage [47]. Projects have demonstrated the potential of this approach while also revealing its challenges. Current research efforts are focused on overcoming the energy penalties of oxygen supply. Advances in air separation units and the development of membrane-based oxygen production are being pursued to reduce costs and improve efficiency, which will be critical for the future deployment of oxy-fuel systems on a larger scale.

3.1.4. Critical Assessment

Pre-combustion and oxy-fuel systems offer significant advantages in hydrogen co-production and the generation of high-purity CO_2 streams, making them attractive alternatives to post-combustion capture in certain industrial applications. Despite their promise, large-scale deployment has been constrained by high capital costs, operational risks, and substantial energy requirements. Challenges have included cost overruns and technical failures in integrated gasification projects such as Kemper, reliance on enhanced oil recovery markets as seen in Air Products' Texas facility, and the high cost of oxygen production in oxy-fuel systems [48]. Questions also remain about the durability and scalability of supporting technologies such as membranes and cryogenic systems under industrial conditions. Looking ahead, opportunities exist to strengthen these approaches through integration with broader decarbonization strategies. Pre-combustion capture could be paired with low-carbon hydrogen production to accelerate the growth of the hydrogen economy, while coupling renewable energy with air separation and reforming units could help reduce energy penalties. Hybrid methods that combine membrane separation with cryogenic polishing are also being developed to achieve a balance between efficiency and gas purity. Although these technologies have not yet reached the same level of deployment as solvent-based post-combustion capture, they remain strategically important. Their role is particularly relevant for advancing hydrogen production, supporting industrial decarbonization, and establishing high-purity CO_2 supply chains essential for a net-zero future [48].

Table 2 Comparative Analysis of Pre-Combustion vs. Oxy-Fuel Capture with Future Outlook [47, 46, 168, 43]

Aspect	**Pre-Combustion Capture**	**Oxy-Fuel Combustion**	**Future Outlook**
Mechanism	Fuel converted to syngas (CO + H_2) via gasification or SMR → CO shifted to CO_2 + H_2 via water-gas shift → CO_2 separated at high pressure.	Fuel burned in pure oxygen instead of air, producing a flue gas of CO_2 + H_2O → water condensed to yield nearly pure CO_2.	Hybrid and flexible configurations combining hydrogen production with CCS and integration of renewable energy (e.g., solar/biomass-assisted gasification, green hydrogen blending).
Key Projects / Demonstrations	- Kemper County IGCC (USA): targeted 3 $MtCO_2$/year, suspended due to costs. - GreenGen (China): IGCC + CCS pilot. - Air Products SMR Facility (Texas, USA): 1 $MtCO_2$/year CO_2 captured for EOR.	- Schwarze Pumpe Pilot (Germany): 30 MWth oxy-fuel trial (2008–2014). - Callide Oxyfuel Project (Australia): 30 MW retrofit with CO_2 compression. - Ongoing R and D in oxy-fuel retrofits.	Large-scale demonstrations planned with low-carbon hydrogen hubs (USA, EU, Asia). Development of renewable-powered ASUs and membrane-based O_2 production to cut costs. Hybrid systems combining oxy-fuel with supercritical CO_2 power cycles.
Advantages	- CO_2 separation at high pressure lowers cost. - Produces hydrogen-rich gas for power/industry. - High-purity CO_2 stream. - Lower energy penalty than post-combustion.	- Nearly pure CO_2 stream after water removal. - Simplified separation. - Retrofit potential for existing plants. - Potential for high-efficiency cycles.	Coupling with the hydrogen economy (blue hydrogen as transitional fuel). Integration with CCUS industrial clusters. Scaling through international climate funding and public-private partnerships.
Limitations	- High capital and technical risk (IGCC complexity). - Dependence on hydrogen/EOR economics. - Membrane/cryogenic systems not fully mature. - High-profile failures (e.g., Kemper).	- High oxygen production cost (ASUs energy-intensive). - No full-scale commercial plants yet. - Material compatibility issues at high O_2 levels. - CCS infrastructure required.	Research in modular membrane–cryogenic hybrids for efficient separation. Exploration of bioenergy with CCS (BECCS) using oxy-fuel. Policies supporting hydrogen–CCS integration could accelerate TRL advancement.

3.2. Post-Combustion Capture

Post-combustion capture remains the most established and widely deployed carbon capture approach because of its ability to be retrofitted to existing fossil-fuel-based infrastructure [49, 169, 42]. It involves the removal of CO_2 from flue gases produced after the combustion of coal, natural gas, or industrial feedstocks. This technology has been extensively tested in both pilot and large-scale demonstration projects, making it one of the cornerstones of carbon capture and storage (CCS) deployment strategies [8]. Two primary methods, solvent-based capture and sorbent-based capture, are leading the technological advances in this area [50].

Table 3 Post-Combustion CO_2 Capture Technologies [42, 51, 50, 57, 58, 169]

Solvent-Based Capture	**Sorbent-Based Capture**
Conventional Amines (MEA, DEA, MDEA, AMP, Piperazine blends)	Activated carbon
Sterically hindered amines	Zeolites
Advanced amine blends	Silica and alumina sorbents
Aqueous ammonia process	Amine-functionalized sorbents
Carbonate-based solvents (e.g., potassium carbonate – Benfield process)	Metal–Organic Frameworks (MOFs)
Amino acid salts	Covalent Organic Frameworks (COFs) / Porous Organic Polymers (POPs)
Ionic liquids (ILs)	Hydrotalcites / Layered Double Hydroxides (LDHs)
Deep eutectic solvents (DES)	Carbon nanomaterials (CNTs, graphene, porous carbons)
Water-lean / biphasic solvents	Hybrid structured sorbents (monoliths, foams, pellets)
Enzyme-enhanced solvents (carbonic anhydrase)	Electro-swing sorbents

3.2.1. Solvent-Based Capture

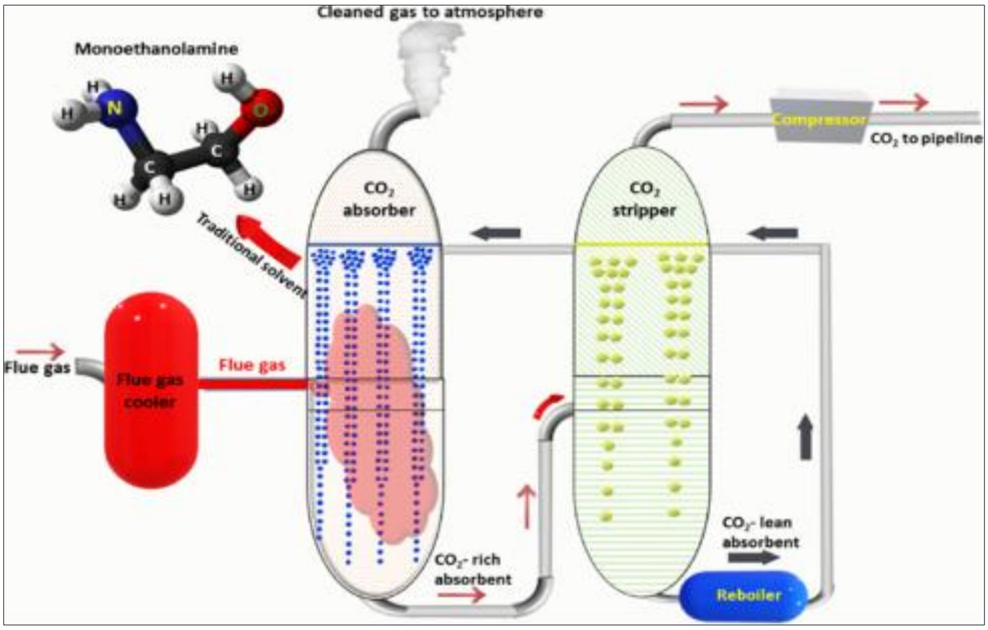

Figure 3 Post Combustion Carbon Capture Method [169]

Chemical absorption using liquid solvents has long been regarded as the benchmark technology for post-combustion CO_2 capture [50]. Among these, monoethanolamine (MEA) has historically dominated due to its relatively fast reaction kinetics with CO_2, wide availability, and technical maturity. Nevertheless, its application faces significant operational drawbacks, including high regeneration energy demand (typically 3.5–4.0 GJ per tonne of CO_2), oxidative and thermal degradation under flue gas conditions, and corrosive interactions with equipment materials [51]**.** These shortcomings have necessitated the exploration of more efficient and durable solvent systems.

Advanced Amines and Emerging Formulations

To address the limitations of monoethanolamine (MEA), researchers and industry have developed advanced amine-based solvents with higher CO_2 absorption capacity and lower regeneration energy requirements [52]. Piperazine-promoted solvents have demonstrated significant reductions in regeneration energy, with pilot studies showing up to 30 percent savings compared to conventional MEA systems [53]. Alternatives such as 2-amino-2-methyl-1-propanol and sterically hindered amines provide greater CO_2 loading capacity and improved oxidative stability, making them more robust under real flue gas conditions [54]. In addition, hybrid solvent systems, including aqueous ammonia blends and biphasic formulations, are being explored to further reduce energy penalties and limit solvent degradation [55, 169]. These advancements represent an important step toward overcoming the economic and operational barriers that have restricted large-scale deployment of solvent-based carbon capture.

Demonstration Projects and Industrial Applications

Large-scale demonstration projects have highlighted both the promise and the challenges of solvent-based CO_2 capture technologies. The Boundary Dam CCS Project in Canada, launched in 2014, became the world's first commercial-scale post-combustion capture facility. Using an MEA-based system, it captures about one million tonnes of CO_2 annually from a coal-fired power plant, with the gas used in enhanced oil recovery [56]. Despite occasional maintenance interruptions, the project has proven the long-term technical feasibility of solvent-based capture while providing valuable operational experience. This project underline the technical viability of solvent-based CCS while also revealing the financial, operational, and market-related challenges that must be addressed for large-scale deployment.

Critical Assessment and Research Gaps

Case studies show that solvent-based CO_2 capture is both technically feasible and scalable, yet its broader application is hindered by high energy demands, solvent degradation, corrosion issues, and cost challenges. The International Energy Agency has identified solvent regeneration as the dominant cost driver, accounting for as much as 70 percent of total capture expenses [26]. Research efforts are now focused on developing low-energy solvent systems such as phase-change solvents and ionic liquids, alongside strategies to improve solvent stability through additives that reduce oxidative and thermal breakdown. Integration with renewable energy sources and waste-heat recovery is also being explored as a way to offset energy penalties, while life-cycle assessments are being used to evaluate the broader environmental implications of large-scale deployment. Continued innovation in solvent design and system integration will be essential to enhance competitiveness and ensure that solvent-based capture can play a stronger role in achieving net-zero targets.

3.2.2. Sorbent-Based Capture

Solid sorbents are increasingly recognized as promising alternatives to conventional liquid solvent systems for post-combustion CO_2 capture. Their appeal lies in lower regeneration energy requirements, high selectivity, and potential for cyclic operation with minimal solvent loss [170, 26]. Unlike liquid solvents, sorbents generally allow for modular system design, enabling integration with existing industrial processes at various scales. However, challenges such as material stability under humid flue gas conditions, cost of large-scale synthesis, and reduced performance in real-world environments remain active research frontiers [170].

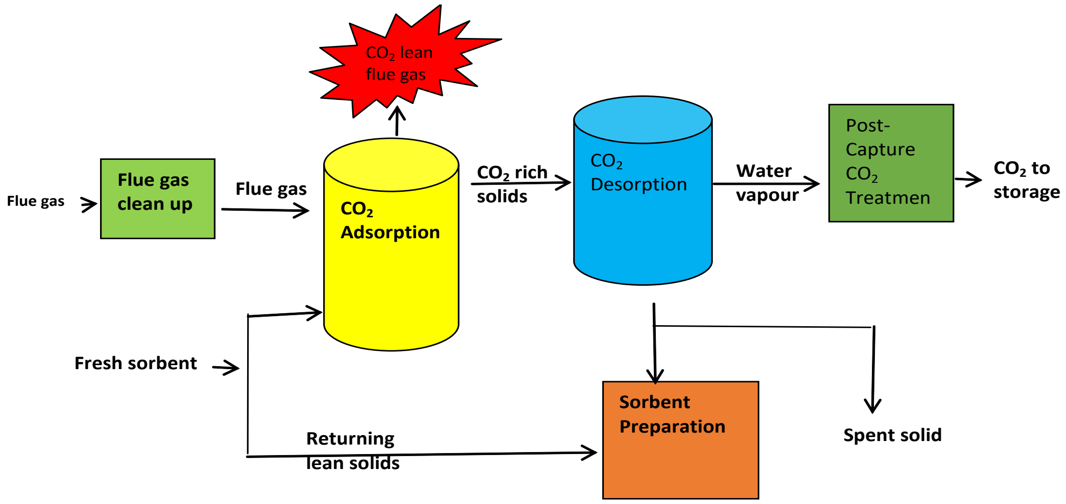

Figure 4 Solid sorbent-based carbon capture process [170]

Metal–Organic Frameworks (MOFs)

Metal-Organic Frameworks (MOFs) have emerged as one of the most promising classes of sorbents for CO_2 capture, offering ultrahigh surface areas, tunable pore structures, and significant chemical versatility [57]. Compounds such as MOF-74 and HKUST-1 have demonstrated CO_2 uptake capacities surpassing many conventional sorbents and have shown strong selectivity for CO_2 over nitrogen, a crucial advantage for flue gas separation [58]. Despite this potential, their stability under humid and high-temperature conditions remains a major challenge, with HKUST-1 in particular prone to degradation in the presence of water vapor. Research is increasingly focused on overcoming these limitations through functionalization approaches like amine grafting and the development of more resilient structures, including ZIF-8 and UiO-66 [59]. While pilot-scale testing of MOFs is still at an early stage, small-scale demonstrations in Europe and Asia indicate promising opportunities for integration into adsorption-based systems such as pressure swing and temperature swing units for power plant applications.

Zeolites

Zeolite 13X is regarded as one of the most effective commercial sorbents for CO_2 capture, owing to its crystalline aluminosilicate framework that provides uniform micropores with strong affinity for CO_2 [60]. It has shown high adsorption capacities under simulated flue gas conditions, and pilot-scale demonstrations in Europe and the United States have confirmed its suitability for post-combustion applications. A key limitation, however, lies in its sensitivity to water vapor, which competes for adsorption sites and reduces CO_2 selectivity. Current research efforts are addressing this challenge through the development of hydrophobic zeolite variants and optimized process designs aimed at minimizing the effects of moisture [61].

Activated Carbons

Activated carbons are widely studied for CO_2 capture because they are inexpensive, chemically stable, readily available, and structurally adaptable [62]. While their natural adsorption capacities are lower than those of MOFs and zeolites, performance can be significantly enhanced through modifications such as amine impregnation, which improves CO_2 selectivity by introducing chemisorption, and metal oxide doping, which strengthens CO_2 binding without creating excessive regeneration energy demands. Bench-scale tests in Asia and North America have shown that activated carbons provide robust cyclic stability and are less affected by moisture compared to zeolites, making them a practical and durable option for adsorption-based capture systems.

Critical Assessment

Sorbent-based systems offer significant advantages over solvent-based capture, particularly in reducing regeneration energy requirements, making them promising for future deployment. Nonetheless, key challenges remain, including the moisture sensitivity of some zeolites and MOFs, the high cost of producing advanced sorbents, and process integration issues such as pressure drops and material attrition in fluidized systems [32]. Research efforts are increasingly directed toward developing water-tolerant and cost-effective sorbents with strong cyclic stability, exploring hybrid approaches that combine sorbents with other capture methods, and conducting techno-economic assessments of pilot projects to inform large-scale investments. Although these technologies are still at the pilot and demonstration stage, progress in MOFs, zeolites, and activated carbons, validated by real-world trials at the NCCC and other international sites, demonstrates their growing potential as a viable alternative or complement to solvent-based systems in decarbonizing power generation and industrial processes [60, 61 62].

Table 4 Comparative Analysis of Solvent-Based vs. Sorbent-Based Capture Systems [42, 51, 58, 169,170]

Aspect	**Solvent-Based Capture**	**Sorbent-Based Capture**
Mechanism	Chemical absorption of CO_2 into liquid solvents (e.g., amines); CO_2 released during solvent regeneration via heating.	Physical/chemical adsorption of CO_2 onto solid porous materials; regeneration typically via pressure/temperature swing.
Examples	Monoethanolamine (MEA), piperazine-promoted blends, AMP, proprietary solvents (e.g., KS-1, KS-21).	Metal–Organic Frameworks (MOFs: MOF-74, HKUST-1, CALF-20), Zeolite 13X, activated carbons (amine-impregnated, metal oxide-doped).
Advantages	- Technologically mature and widely deployed. - High CO_2 capture efficiency (>90% demonstrated at scale). - Compatible with existing power and industrial infrastructure.	- Lower regeneration energy demand (up to 20–30% less than solvents). - Tunable selectivity through functionalization. - Potential for modular, cyclic operation. - Lower solvent loss/corrosion issues.
Limitations	- High energy penalty (3.5–4.0 GJ/tonne CO_2 for MEA). - Solvent degradation (oxidative/thermal). - Corrosion of equipment. - High operating costs.	- Limited large-scale deployment. - Sensitivity to moisture (especially zeolites, MOFs). - High synthesis cost for advanced sorbents. - Stability challenges under real flue gas conditions.
Scale of Deployment	Commercial-scale (e.g., Boundary Dam, Canada: 1 $MtCO_2$/year; Petra Nova, USA: 1.4 $MtCO_2$/year).	Pilot/demonstration scale (e.g., NCCC Alabama, USA; CALF-20 pilot in Canada; European zeolite and carbon pilot plants).

3.3. Direct Air Capture (DAC)

Direct air capture (DAC) represents a fundamentally different carbon capture pathway by targeting CO_2 directly from ambient air rather than from concentrated point sources such as power plants or industrial stacks [63]. With atmospheric CO_2 concentrations currently at 420 ppm, DAC technologies provide the unique capability of delivering negative emissions, making them a crucial complement to other carbon management strategies in scenarios that require net-zero and beyond-net-zero transitions [64]. While still at an early-stage relative to post-combustion and pre-combustion capture, DAC is advancing rapidly through private-sector innovation, government investment, and demonstration projects [65].

3.3.1. Emerging DAC Technologies and Materials

DAC technologies can be broadly divided into liquid solvent-based systems and solid sorbent-based systems:

- **Liquid Solvent Systems:** These typically use alkaline solutions such as sodium hydroxide (NaOH) or potassium hydroxide (KOH) to chemically bind CO_2 into carbonate salts, which are then processed to release pure CO_2 [66].
- **Solid Sorbent Systems:** These employ amine-functionalized solid materials, resins, or advanced frameworks (e.g., MOFs) to adsorb CO_2 directly from the air, which is then desorbed using heat or vacuum swing cycles. Meanwhile, emerging research on MOF-based DAC materials is showing promise for improving adsorption capacity and stability under humid air conditions [67].

3.3.2. Energy and Cost Considerations

One of the primary challenges for DAC is the high energy demand, which stems from the low concentration of CO_2 in the atmosphere [68]. Separating CO_2 from such a dilute stream requires more work than from concentrated flue gases. Current DAC systems consume both electricity (for fans, pumps, and vacuum systems) and heat (for solvent regeneration or sorbent desorption).

- **Cost Estimates:** Present DAC costs are estimated at \$250–600 per tonne of CO_2, depending on the capture pathway, plant scale, and energy source. These costs remain substantially higher than point-source capture (\$50–100/tonne) [69].
- **Energy Source Integration:** Climeworks' plants are powered by geothermal electricity and heat, while Carbon Engineering has proposed integrating DAC with natural gas (with CCS) or renewable energy. Such integration is critical to ensuring that DAC delivers true negative emissions without creating additional carbon debt [69].
- **Policy and Innovation Targets:** The U.S. Department of Energy's (DOE) Carbon Negative Shot Initiative (2021) set an ambitious target of reducing DAC costs to below \$100 per tonne by 2032. To support this, DOE announced funding exceeding \$3.5 billion for Regional DAC Hubs under the Infrastructure Investment and Jobs Act (IIJA), with projects planned in Texas, Louisiana, and California [69].

3.3.3. Critical Assessment

Direct air capture holds exceptional promise for delivering negative emissions but is constrained by significant hurdles, including high energy requirements, elevated costs, material durability under varying atmospheric conditions, and the challenge of scaling from pilot projects to the massive levels demanded by climate goals [69]. Progress is expected through advances in materials such as MOFs and hybrid systems, as well as by linking DAC with renewable energy, nuclear power, and waste heat to reduce its carbon footprint. Integrating captured CO_2 into the production of synthetic fuels and chemicals can create valuable revenue streams, while supportive policies and growing carbon markets, driven by purchases from companies like Microsoft, Stripe, and Shopify, are helping to finance early deployment [69]. Despite current obstacles, DAC is emerging as a vital technology for tackling hard-to-abate emissions and ensuring long-term atmospheric CO_2 removal, with innovation, investment, and policy alignment paving the way toward its role in global net-zero and net-negative strategies [69].

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4. Carbon Storage: Geological and Novel Approaches

Carbon storage represents a crucial component of the carbon capture, utilization, and storage (CCUS) chain. While capture technologies are advancing rapidly, their effectiveness depends largely on the ability to permanently store or stabilize CO_2. Storage strategies are typically classified into geological, mineral-based, and novel biological or ocean-related approaches. Each pathway presents unique advantages, limitations, and technological readiness levels [73].

4.1. Geological Storage

Geological storage refers to the permanent sequestration of captured CO_2 in deep subsurface formations, where it is securely trapped through multiple mechanisms, including structural trapping (retention beneath impermeable caprocks), residual trapping (CO_2 immobilized in pore spaces), solubility trapping (dissolution of CO_2 into formation fluids), and mineral trapping (precipitation of stable carbonate minerals) [71]. This approach represents the most mature and technically feasible long-term solution for carbon storage, with several large-scale demonstration projects providing critical validation [171, 72].

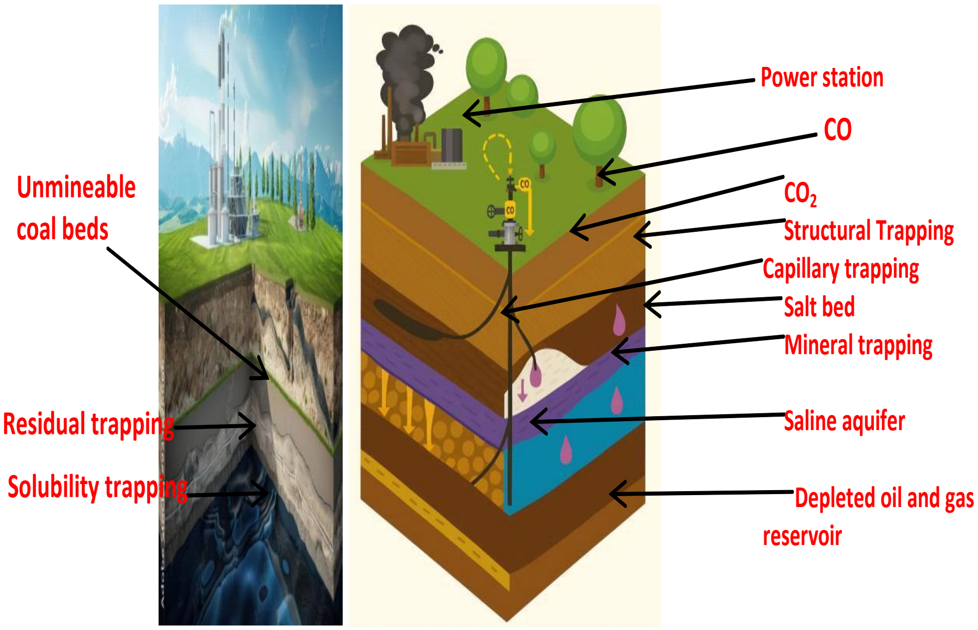

Figure 5 Geological Carbon Storage [171]

4.1.1. Saline Aquifers

Deep saline aquifers are considered the most significant global CO_2 storage resource, with theoretical capacities estimated at several thousand gigatonnes worldwide [73]. Unlike hydrocarbon reservoirs, they are widely distributed and not limited to specific oil- or gas-bearing regions. A pioneering example is the Sleipner Project in the North Sea (Norway), initiated in 1996, where about 1 Mt of CO_2 per year has been continuously injected into the Utsira Formation [74]. Over nearly three decades, extensive seismic monitoring has confirmed stable containment, making Sleipner the world's longest-running dedicated CO_2 storage project [171, 75].

4.1.2. Depleted Oil and Gas Reservoirs

Depleted oil and gas fields provide ideal candidates for CO_2 storage due to their proven geological integrity (demonstrated by their ability to trap hydrocarbons for millions of years), availability of existing infrastructure, and opportunities for Enhanced Oil Recovery (EOR) [71]**.** The Weyburn-Midale CO_2 Monitoring and Storage Project in Saskatchewan, Canada, is one of the most extensively studied cases [76, 171].

4.1.3. Basalt Formations

Basaltic formations, rich in calcium, magnesium, and iron, provide a unique advantage due to their potential for rapid mineral trapping of CO_2 into stable carbonate minerals [77, 171].

Site Selection, Risk Management, and Monitoring

The effectiveness of geological storage is closely tied to careful site selection and strong risk management [78]. Suitable reservoirs require sufficient depth to keep CO_2 in a supercritical state, high porosity and permeability for injectivity, and an impermeable caprock to prevent leakage. Key risks include leakage through abandoned wells or faults, seismic activity triggered by pressure build-up, and possible groundwater contamination, with U.S. cases of wastewater injection illustrating the importance of managing subsurface pressures [78]. To address these concerns, advanced monitoring is employed, such as 4D seismic surveys at Sleipner to track plume migration, down hole sensors and soil gas sampling at the Illinois Basin–Decatur Project for detailed subsurface insights, and satellite-based InSAR to detect surface deformation. These technologies not only improve safety and performance but also build public trust by providing transparent verification of CO_2 storage integrity [78].

4.2. Mineral Carbonation

Mineral carbonation exploits the natural geochemical tendency of silicate and alkaline minerals to react with CO_2 and form stable carbonate minerals (e.g., calcite, magnesite) [77].Unlike some other storage approaches, mineral carbonation ensures permanent CO_2 immobilization through thermodynamically stable products, thereby eliminating the risk of long-term leakage [77]. This process can occur either in situ (direct injection into reactive rock formations) or ex situ (reaction with mined minerals or industrial waste streams).

4.2.1. Natural vs. Accelerated Mineralization

In nature, mineral carbonation occurs over geological timescales through the weathering of silicate minerals such as olivine and serpentine [77]. These processes play a critical role in Earth's long-term carbon cycle but are far too slow to mitigate anthropogenic CO_2 emissions. Engineered or accelerated mineralization aims to overcome kinetic limitations by applying elevated temperatures, pressures, or chemical/physical pretreatment (e.g., acid leaching, grinding). For example, research by the U.S. Department of Energy's National Energy Technology Laboratory (NETL) has demonstrated that olivine and serpentine can be carbonated within hours under optimized conditions, compared to thousands of years in nature [78]. Similarly, pilot studies in Oman's peridotite formations have shown the potential for in situ carbonation at depth, where injected CO_2-bearing fluids accelerate natural weathering reactions [78].

4.2.2. Rock Types and Industrial Wastes

Ultramafic and mafic rocks (such as peridotite, basalt, and dunite) are the most promising natural candidates for in situ carbonation because of their abundance of divalent cations (Mg^{2+}, Ca^{2+}, Fe^{2+}) [79]. Large outcrops of ultramafic rocks in regions like Oman, Papua New Guinea, and parts of the United States are being actively studied as potential sites for large-scale mineralization [80]. The CarbFix project in Iceland, which initially focused on basalt formations, has already demonstrated rapid in situ mineral trapping of CO_2, with over 95% of injected CO_2 mineralized within two years [81]. This success provides a proof-of-concept for scalable mineral carbonation in reactive rock systems. In parallel, ex situ mineralization approaches make use of industrial by-products that are rich in alkaline oxides. These include steel slag, cement kiln dust, coal fly ash, and red mud (a by-product of alumina refining). By carbonating such waste materials, two environmental challenges are simultaneously addressed: CO_2 sequestration and hazardous waste management [82]. For example, the steel industry produces approximately 400 Mt of slag annually, which, if fully carbonated, could theoretically store significant quantities of CO_2 [83].

4.3. Ocean Storage and Bio-Sequestration

The ocean represents the largest natural carbon sink on Earth, absorbing approximately one-quarter of anthropogenic CO_2 emissions annually [84]. Engineered approaches seek to enhance this natural function through deliberate interventions, either by stimulating marine primary productivity or by cultivating algae for biomass-based carbon utilization. However, these strategies remain at an exploratory stage, constrained by ecological uncertainties, governance challenges, and ethical considerations [84].

4.3.1. Ocean Fertilization and Marine Biomass

Ocean fertilization aims to enhance carbon sequestration by adding nutrients like iron, nitrogen, or phosphorus to nutrient-poor ocean regions, stimulating phytoplankton growth that captures CO_2 through photosynthesis [85]. Some of this organic matter may sink to the deep ocean, theoretically locking away carbon for centuries. Early experiments such as IronEx I and II in the Equatorial Pacific showed that iron addition could trigger large blooms and boost carbon fixation, though much of the biomass remained in surface waters. LOHAFEX in the Southern Ocean demonstrated increased phytoplankton growth, but grazing by zooplankton limited deep-ocean carbon export. EIFEX indicated that under certain ecological conditions, iron fertilization could promote measurable carbon sinking [85]. Despite these insights, the long-term effectiveness of sequestration is uncertain, and potential ecological impacts, including harmful algal blooms, oxygen depletion, and disruption of marine ecosystems, have prompted international regulations, restricting large-scale experiments until environmental safeguards are better understood [85].

4.3.2. Algae-Based Sequestration

Microalgae cultivation is gaining attention as a bio-sequestration strategy that combines CO_2 capture with the production of valuable biomass for energy and materials [86]. Microalgae are highly efficient at photosynthesis, can thrive in saline or wastewater environments, and generate products such as biofuels, bioplastics, pigments, and animal feed [86]. Initiatives like Seambiotic in Israel have integrated flue gas CO_2 with open algal ponds to produce biomass for biofuel and feed applications, while Algenol in the U.S. has developed photobioreactors with genetically enhanced algae that directly produce ethanol, though scaling remains challenging. European projects such as BIOFAT and All-Gas have explored combining wastewater treatment with algal cultivation, achieving CO_2 capture, nutrient recycling, and bioenergy production [86]. Research into offshore farms and closed photobioreactors continues, offering solutions that avoid land competition, yet high capital costs and the energy demands of mixing, harvesting, and processing biomass remain significant barriers to large-scale deployment [86].

4.3.3. Challenges and Outlook

Both ocean fertilization and algae-based bio-sequestration illustrate the potential and risks of ocean-based carbon management [85]. While fertilization demonstrates the possibility of enhancing natural sinks, its ecological risks and uncertain permanence hinder deployment. Conversely, algae-based approaches hold promise for integrated carbon capture and resource recovery, but require breakthroughs in cost reduction, energy efficiency, and large-scale cultivation systems to compete with land-based solutions [86].

5. Carbon Utilization: From Waste to Resource

Carbon utilization represents a transformative approach to climate mitigation by re-imagining CO_2 not merely as a waste product but as a valuable feedstock for new industries [87]. Instead of releasing captured carbon back into the atmosphere, utilization pathways convert it into fuels, chemicals, construction materials, and even food and polymers [88, 172]. This shift supports a circular carbon economy, where emissions are redirected into productive use, reducing dependence on fossil resources while opening opportunities for innovation and economic growth [87]. By turning waste into resource, carbon utilization bridges climate action with industrial sustainability, offering a dual benefit of emissions reduction and value creation [88, 172].

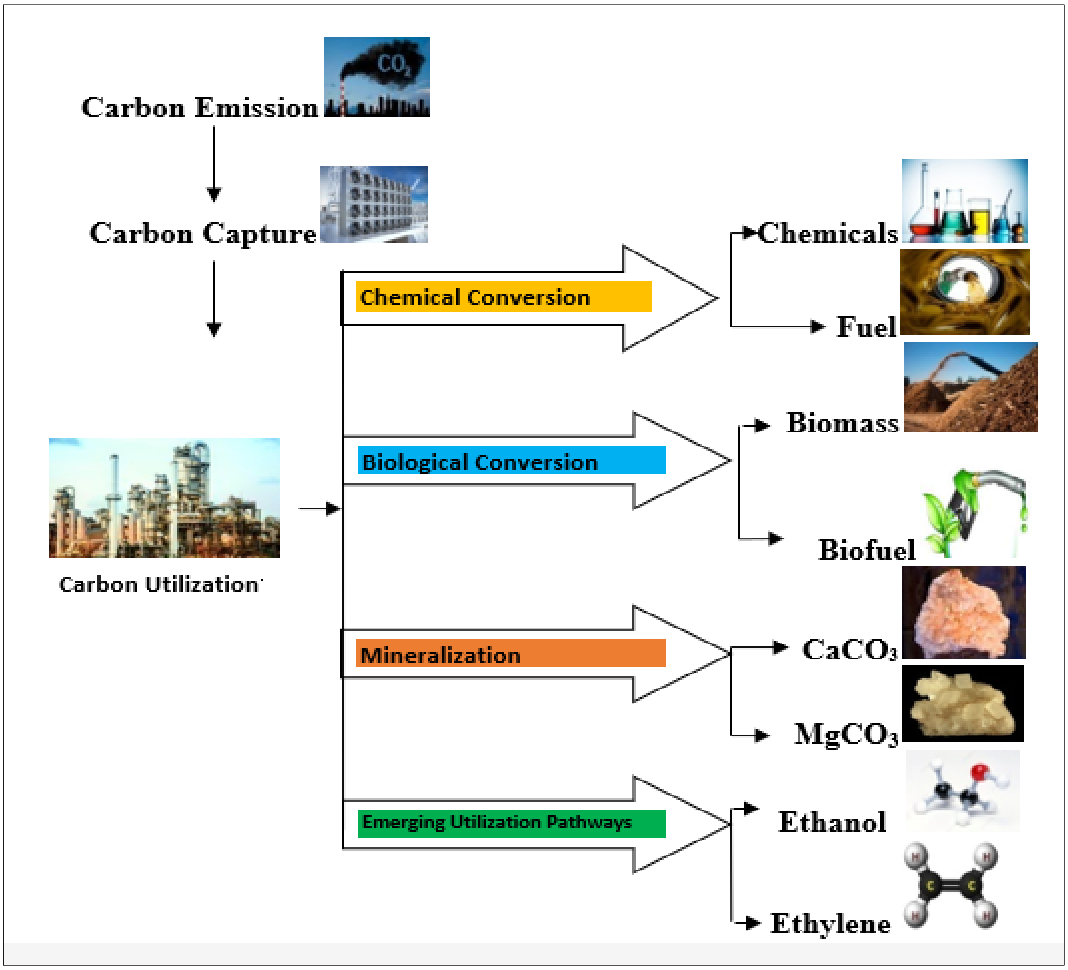

Figure 6 Carbon Utilization Pathways [172]

5.1. Chemical Conversion

Chemical conversion pathways involve the transformation of captured CO_2 into fuels and value-added chemicals through thermal, catalytic, photochemical, or electrochemical processes [89]. These approaches not only reduce atmospheric CO_2 concentrations but also create economic value by displacing fossil-derived raw materials, thereby contributing to the development of a circular carbon economy [90, 172]. Importantly, the success of chemical conversion depends on integrating renewable energy sources to ensure overall carbon neutrality and economic competitiveness [90].

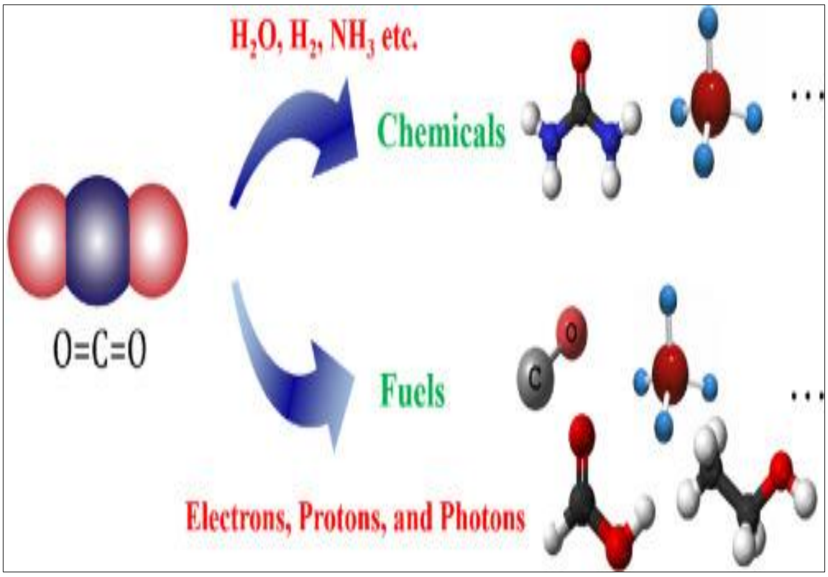

Figure 7 Chemical Conversion of CO_2 [173]

5.1.1. CO_2 to Fuels

One of the most intensively researched and industrialized conversion pathways is the hydrogenation of CO_2 to methanol [91]. Methanol is a highly versatile product: it can be used directly as a fuel, blended with gasoline, reformed to hydrogen for fuel cells, or employed as a chemical feedstock in plastics and solvents [92]. The catalytic hydrogenation reaction ($CO_2 + 3H_2 \rightarrow CH_3OH + H_2O$) requires a renewable hydrogen supply, typically obtained via water electrolysis powered by renewable energy [93, 172]. Syngas, a mixture of carbon monoxide (CO) and hydrogen (H_2), can also be derived from CO_2 through the reverse water-gas shift (RWGS) reaction. Syngas serves as a crucial intermediate for producing Fischer–Tropsch hydrocarbons, including synthetic diesel, jet fuels, and waxes. This pathway is particularly relevant for the aviation and shipping industries, which are difficult to decarbonize through electrification [94]. Another emerging pathway involves electrochemical reduction of CO_2 into fuels such as carbon monoxide, ethanol, and formic acid using renewable electricity [95].

5.1.2. CO_2 to Chemicals

Beyond fuels, CO_2 is gaining traction as a sustainable feedstock for the chemical industry. One of the most established examples is urea production, where CO_2 reacts with ammonia to produce fertilizers [96]. Globally, the urea industry consumes more than 130 million tonnes of CO_2 annually, making it one of the largest industrial sinks for anthropogenic CO_2 [97]. Although most of this CO_2 originates from fossil fuel-based ammonia production, ongoing efforts to decarbonize ammonia synthesis (through renewable hydrogen) could make urea production a genuinely carbon-neutral process. High-value polymers are also being synthesized from CO_2. Polycarbonates, produced by reacting CO_2 with epoxides in the presence of catalysts, represent an important class of lightweight, durable plastics with reduced fossil feedstock dependency [98]. Another important pathway is the synthesis of salicylic acid from CO_2 and phenol, which can be used in pharmaceuticals (e.g., aspirin), preservatives, and dyes. This reaction, although industrially less significant in terms of CO_2 consumption, underscores the versatility of CO_2 as a chemical precursor for fine chemicals. Similarly, formic acid and dimethyl carbonate production from CO_2 are being developed for applications in solvents, fuel cells, and lithium-ion batteries [99].

5.1.3. Case Examples and Industrial Implications

Industrial deployment of CO_2 utilization is already evident across diverse sectors. In Iceland, the George Olah Renewable Methanol Plant produces thousands of tonnes of methanol each year from CO_2 and renewable hydrogen, while in Germany, Sunfire GmbH is developing CO_2-derived syngas for Fischer–Tropsch fuels aimed at aviation and maritime transport [92]. Covestro AG has achieved commercial-scale production of CO_2-based polyols for foams, marking significant progress in CO_2-derived plastics [98]. On a global scale, the urea industry consumes more than 130 million tonnes of CO_2 annually, making it one of the largest and most established utilization pathways [96]. In the U.S., Twelve is advancing electrochemical reduction of CO_2 into carbon monoxide, opening pathways for modular and scalable CO_2-to-chemical systems [95].

5.1.4. Outlook and Challenges

While chemical conversion of CO_2 is transitioning from laboratory-scale research to commercial deployment, several challenges remain. These include high energy requirements, reliance on cost-effective renewable hydrogen, catalyst efficiency, and scalability of electrochemical and catalytic systems [94]. Nevertheless, the examples above show rapid progress in bridging the gap between technology demonstration and market-ready deployment [93]. By integrating renewable energy sources, advancing catalyst development, and creating supportive policy frameworks, chemical conversion of CO_2 could emerge as a cornerstone technology in global decarbonization strategies [97].

5.2. Biological Conversion

Biological conversion leverages the natural and engineered metabolic processes of organisms such as microalgae, cyanobacteria, and specialized microbes to capture and transform CO_2 into biomass, biofuels, and bio-based materials [91]. Compared to thermochemical or catalytic methods, biological pathways operate under relatively mild conditions, often at atmospheric pressure and ambient temperatures, and can be scaled using cultivation or fermentation systems [96]. Importantly, these processes offer the dual benefit of mitigating CO_2 emissions while producing renewable resources that displace fossil-derived products [99]. Furthermore, durable bio-based products, such as biochar or bioplastics, can provide long-term carbon storage, contributing to negative emission strategies [98].

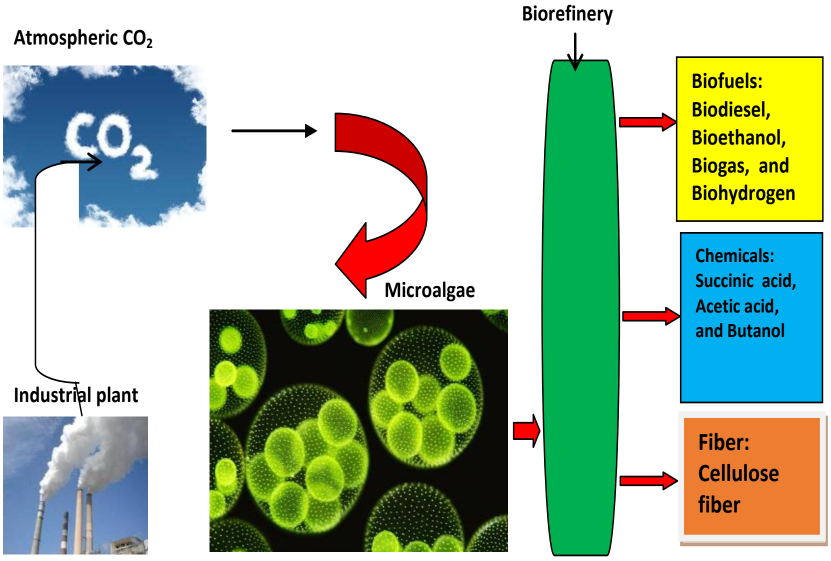

Figure 8 Biological Capture and Conversion of CO_2 [174]

5.2.1. Algae and Microbial Pathways

Microalgae cultivation has emerged as a leading biological pathway for CO_2 utilization, converting emissions into biomass rich in lipids, proteins, and carbohydrates that can be processed into fuels, animal feed, fertilizers, and high-value nutraceuticals like omega-3 fatty acids [100]. Real-world applications include projects such as the Eni Green Refinery in Italy, which integrates flue gas CO_2 into algal biomass production for biofuels, and large algae farms in the U.S. and Australia that channel power plant emissions into photobioreactors and open ponds [101]. Beyond algae, advances in synthetic biology and metabolic engineering are enabling microbes such as bacteria, yeast, and cyanobacteria to fix CO_2 with renewable energy inputs and redirect metabolism toward fuels and chemicals [102]. LanzaTech has already commercialized this approach by converting steel mill emissions in China into ethanol at industrial scale, while laboratory research has demonstrated microbial production of building block chemicals like succinic acid, acetic acid, and butanol from CO_2 [103]. Companies such as Solar Foods are also pioneering microbial protein production, using CO_2 and hydrogen to create sustainable food products like Solein with minimal resource demands [104]. Together, these innovations show how biological systems can both capture carbon and expand the bio-economy, turning waste emissions into energy, chemicals, and food.

5.2.2. Biochar and Bioplastics

Biochar, created through the pyrolysis of biomass in oxygen-limited conditions, provides a durable means of sequestering CO_2 while improving soil health [105]. Its stability over centuries, combined with benefits such as enhanced nutrient retention and water-holding capacity, makes it valuable for climate-smart agriculture. Large-scale initiatives under the International Biochar Initiative have validated its role as both a carbon sink and a soil amendment, with field trials in Kenya and India reporting increased crop yields alongside measurable sequestration gains [106]. Alongside biochar, bioplastics represent another important CO_2 utilization pathway. Certain microorganisms can convert CO_2 or methane into polymers like polyhydroxyalkanoates, offering biodegradable alternatives to conventional plastics [107].

5.2.3. Outlook and Challenges

Biological CO_2 conversion pathways offer a unique opportunity to cut emissions while producing renewable fuels, materials, and food, positioning them as a cornerstone of a sustainable bio-economy [108]. Their potential, however, is tempered by challenges that include the large land, water, and nutrient demands of algae cultivation, high production costs relative to fossil alternatives, and the need for greater efficiency in microbial and algal systems compared to thermochemical methods [109]. Progress also depends on access to continuous, low-cost renewable energy to drive microbial CO_2 fixation. Future advances are expected through genetic engineering and synthetic biology to enhance organism performance, improved cultivation systems with closed-loop recycling, and policy measures such as carbon pricing that strengthen economic viability. Growing consumer demand for sustainable products further supports adoption. Moving beyond the laboratory, these pathways are gradually reaching commercial maturity, with the potential to play a critical role in carbon management and the broader shift toward a circular carbon economy [109].

5.3. Mineral and Construction Materials

Mineralization and construction material pathways harness the natural reactivity of CO_2 with alkaline materials such as calcium, magnesium, and iron oxides. This process results in the formation of stable carbonate minerals (e.g., $CaCO_3$, $MgCO_3$, $FeCO_3$), ensuring permanent carbon sequestration while simultaneously improving the performance and durability of construction products [100]. Unlike many carbon utilization routes where the CO_2 is eventually re-released, mineralization offers near-irreversible storage, positioning it as a critical component in achieving long-term carbon neutrality. Furthermore, coupling CO_2 storage with the production of value-added construction materials creates strong economic incentives and large-scale deployment potential [101].

5.3.1. CO_2 in Concrete and Cement

The cement and concrete sector, a major contributor to global CO_2 emissions, is increasingly turning to mineralization as a way to cut its carbon footprint while improving material performance [102]. Injecting CO_2 during the curing of fresh concrete produces stable carbonates that both sequester carbon and enhance compressive strength, allowing for reduced cement use and lower lifecycle emissions. Several companies are advancing this approach at commercial scale. CarbonBuilt, developed from UCLA research, integrates flue gases directly into concrete blocks, linking industrial emissions with sustainable building materials and earning recognition through multiple innovation awards [103]. This efforts show how CO_2 utilization in cement and concrete can transform one of the most carbon-intensive industries into a driver of climate solutions [104].

5.3.2. Carbonation of Industrial Residues

Mineralization of industrial residues offers a practical pathway for both CO_2 storage and waste management, using alkaline by-products such as steel slag, fly ash, cement kiln dust, and mine tailings to capture carbon through natural or accelerated processes [105]. This not only provides permanent sequestration but also transforms waste into valuable construction materials. Demonstration projects around the world highlight its feasibility. Research initiatives such as Slag2Concrete in Norway and the Netherlands are further exploring steel slag carbonation as a replacement for natural aggregates, aligning with circular economy strategies [106]. Collectively, these efforts demonstrate how industrial residues can be repurposed into carbon-storing products that advance both decarbonization and sustainable resource use [107].

5.4. Emerging Utilization Pathways

Novel approaches to CO_2 utilization are emerging at the intersection of renewable energy, catalysis, and material science [108]. These frontier technologies hold the potential to unlock entirely new markets while complementing established chemical, biological, and mineralization pathways. Unlike conventional utilization methods, these emerging strategies emphasize direct conversion of CO_2 into fuels and high-value products using renewable inputs, thereby aligning with global strategies for deep decarbonization and advancing the circular carbon economy [109].

5.4.1. Electrochemical and Photochemical Reduction

Electrochemical reduction of CO_2 is a rapidly advancing pathway that uses electrocatalysts and renewable electricity to convert emissions into valuable products such as carbon monoxide, formic acid, ethanol, ethylene, and other hydrocarbons [100]. By coupling carbon capture with renewable energy, it offers a means of both decarbonization and energy integration [101]. Industrial demonstrations are already showing its potential [102]. Alongside these efforts, photochemical reduction of CO_2 is emerging as a complementary approach, directly using sunlight and photocatalysts to drive carbon conversion under mild conditions [103]. Though still at the research stage, work at institutions such as the University of Tokyo and the U.S. National Renewable Energy Laboratory highlights the potential of solar-driven CO_2 reduction as a low-cost, selective pathway for sustainable fuel and chemical production [104].

5.4.2. Artificial Photosynthesis

Artificial photosynthesis is designed to mimic and improve upon natural photosynthesis by using carbon dioxide, water, and sunlight to generate fuels and chemicals [110]. Unlike biological systems, it targets greater efficiency and long-term stability, offering a promising route for renewable energy storage and carbon recycling. Major initiatives illustrate the global push in this field. In the United States, the Joint Center for Artificial Photosynthesis has made advances in photoelectrochemical cells that convert carbon dioxide into fuels, with research progressing from laboratory to pilot scale [111]. At the global level, the Solar Fuels Institute is driving collaborations between academia and industry to accelerate the scale-up of solar-to-fuel technologies [112].

5.4.3. Other Emerging Pathways

Beyond electrochemical and photochemical approaches, emerging CO_2 utilization pathways are opening new frontiers of innovation. Plasma-assisted conversion employs high-energy reactors to activate CO_2 and transform it into syngas and chemicals, with pilot projects in countries like the Netherlands and China showing promise when powered by renewable electricity [110]. Another avenue is CO_2-to-protein technology, where companies such as Solar Foods in Finland and Deep Branch Biotechnology in the UK use hydrogen-oxidizing microbes to produce single-cell proteins for food and animal feed, offering a sustainable alternative with low land and water requirements [111]. Advances in nanostructured catalysts, including metal–organic frameworks, single-atom catalysts, and perovskite systems, are further enhancing efficiency and selectivity, enabling CO_2 to be converted into valuable specialty chemicals [112].

6. Integration of CCUS with Renewable Energy and Industry

Carbon Capture, Utilization and Storage (CCUS) technologies cannot be viewed in isolation but must be integrated into broader energy and industrial systems to maximize climate, economic, and social benefits. The coupling of CCUS with renewable energy, alongside its integration into heavy industries, offers a pathway toward large-scale decarbonization while creating synergies that improve system efficiency and sustainability [113].

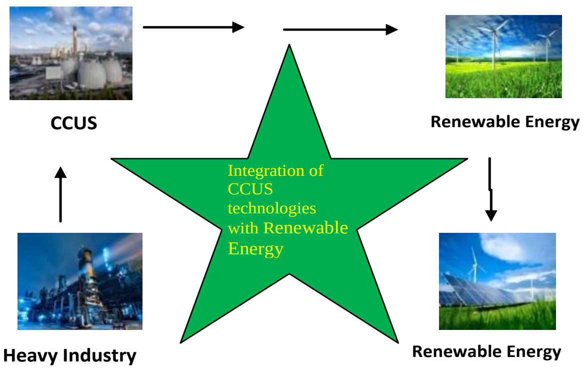

Figure 9 Integration of CCUS with renewable energy and industry [9]

6.1. Coupling CCUS with Renewable Power

The integration of Carbon Capture, Utilization and Storage (CCUS) technologies with renewable energy systems represents a transformative approach for enabling deep decarbonization while simultaneously creating new carbon-neutral energy carriers. By aligning CO_2 capture and utilization with intermittent renewable power sources such as solar, wind, and hydro, it becomes possible to establish a circular carbon economy in which atmospheric or point-source CO_2 is recycled into fuels, chemicals, and materials without dependence on fossil energy inputs. This synergy not only advances emissions mitigation but also contributes to renewable energy reliability, storage, and sector coupling across industries [114].

6.1.1. Solar-Powered DAC and Electrochemical CCU

Direct Air Capture (DAC) powered by renewable electricity is gaining traction as a means of extracting CO_2 directly from the atmosphere with minimal life-cycle emissions. Solar photovoltaic (PV) or concentrated solar power (CSP) systems can supply the substantial energy demand of DAC units while simultaneously driving electrochemical carbon conversion processes. When coupled with renewable hydrogen from electrolysis, these systems can produce synthetic hydrocarbons, methanol, and other liquid fuels suitable for aviation, shipping, and heavy transport [115]. This syngas can be further processed into kerosene or methanol, providing a fully renewable aviation fuel pathway [116].

6.1.2. Role in Grid Balancing and Energy Storage

One of the most compelling advantages of coupling CCUS with renewable power lies in addressing the intermittency challenge of renewables. Solar and wind energy are inherently variable, often producing excess electricity during peak conditions that cannot be directly absorbed by the grid. CCUS technologies, especially electrochemical CO_2 reduction and power-to-fuels systems, can serve as flexible energy sinks that consume surplus renewable electricity and store it in the form of chemical bonds [117].

6.1.3. Outlook and Challenges

Coupling CCUS with renewable energy offers significant potential to decarbonize power, transportation, and industry, while simultaneously addressing renewable intermittency and storage. However, challenges remain in terms of system efficiency, cost competitiveness, and scalability. DAC processes are currently energy-intensive, requiring advances in sorbent and process design to reduce costs. Electrochemical CO_2 reduction and fuel synthesis pathways face barriers related to catalyst stability, product selectivity, and integration with variable renewable inputs [118]. Policy frameworks, such as carbon pricing, renewable fuel standards, and green procurement, will play a crucial role in creating market demand for carbon-neutral fuels and products. Nonetheless, as demonstrated by pilot and commercial projects across Europe, Asia, and North America, renewable-powered CCUS represents a cornerstone technology for achieving net-zero emissions and building a resilient, circular carbon economy [119].

6.2. Industrial Symbiosis and CCU Hubs

Heavy industries such as cement, steel, and fertilizers are among the largest point-source emitters of carbon dioxide, collectively accounting for a significant share of global greenhouse gas emissions. These sectors are considered “hard-to-abate” because CO_2 emissions originate not only from the combustion of fossil fuels for heat but also from intrinsic process reactions, such as the calcination of limestone in cement kilns or the reduction of iron ore in blast furnaces [120]. Nevertheless, the scale and concentration of emissions from these industries create favorable conditions for the deployment of Carbon Capture, Utilization and Storage (CCUS) technologies. By integrating CCUS with industrial operations, not only can emissions be mitigated, but new value chains for carbon-based products can also be established, advancing the concept of a circular carbon economy [121].

6.2.1. Cement, Steel, and Fertilizer Industries as Anchor Points for CCUS

- **Cement Industry:** Cement production is responsible for nearly 8% of global CO_2 emissions, primarily due to the calcination of limestone ($CaCO_3 \rightarrow CaO + CO_2$). Capturing CO_2 from cement kilns is particularly attractive because of its high concentration and steady output. Once captured, this CO_2 can be reused in concrete curing processes to form stable calcium carbonates, thereby enhancing compressive strength while permanently sequestering carbon. Companies such in Canada and USA have successfully commercialized CO_2 curing technologies, with deployment across North America, Europe, and Asia [122]. The Heidelberg Materials "Brevik Project" in Norway, set to become the world's first full-scale carbon capture facility at a cement plant, aims to capture 400,000 tons of CO_2 annually for offshore storage, providing a replicable model for global cement decarbonization [123].
- **Steel Industry:** Steelmaking contributes roughly 7–9% of global CO_2 emissions, arising from blast furnaces and direct reduced iron processes. Integrating CCUS into steel plants offers dual benefits: capturing CO_2 emissions and supplying carbon streams to adjacent chemical or fuel production facilities. These initiatives highlight the steel industry's potential to act not only as a CO_2 emitter but also as a supplier of captured carbon for industrial symbiosis [124].
- **Fertilizer Industry:** Fertilizer plants, particularly ammonia and urea production facilities, already consume significant volumes of CO_2. Urea synthesis involves reacting ammonia with CO_2, providing a natural pathway for integrating CCU. Fertilizer companies in countries such as India and China have long utilized captured CO_2 streams, though the opportunity exists to expand these practices through low-carbon hydrogen integration and large-scale carbon hubs [125]. This integration demonstrates how existing CO_2-consuming industries can serve as anchor points for broader industrial CCU ecosystems.

6.2.2. Integrated Carbon Capture and Reuse Networks

Beyond individual industrial plants, the development of carbon capture and utilization hubs is emerging as a strategic approach to leverage economies of scale and maximize cross-sectoral synergies. These hubs bring together multiple emitters within an industrial cluster, refineries, chemical plants, power stations, cement kilns, and steelworks, connected by shared CO_2 transport and storage infrastructure. Captured CO_2 can be distributed either to utilization facilities (e.g., for fuel, chemical, or material synthesis) or directed toward secure geological storage [113].

6.2.3. Advantages of Industrial Symbiosis and CCU Hubs

The establishment of CCU hubs creates multiple benefits beyond emissions reduction. First, shared infrastructure such as pipelines and storage sites lowers the capital and operational costs of carbon management, compared to stand-alone projects. Second, industrial symbiosis facilitates the exchange of resources and byproducts, for instance, using steel mill off-gases as feedstock for ethanol or fertilizers, thereby improving resource efficiency. Third, hubs provide a platform for innovation and investment, attracting both private sector stakeholders and public funding under net-zero strategies [126].

6.2.4. Outlook

Industrial symbiosis and CCU hubs are critical to accelerating industrial decarbonization in hard-to-abate sectors. While technical and economic challenges remain, including high capital costs, CO_2 transport logistics, and the need for supportive regulatory frameworks, the growing number of demonstration projects worldwide signals momentum toward commercialization. Coupling CCUS with industrial clusters not only reduces emissions but also creates new industrial ecosystems where waste CO_2 becomes a resource. By linking cement, steel, and fertilizer plants with shared utilization and storage facilities, these hubs lay the foundation for a sustainable, carbon-circular industrial future [127].

6.3. Techno-Economic and Life-cycle Analysis

Evaluating the integration of Carbon Capture, Utilization and Storage (CCUS) into industrial and energy systems requires rigorous techno-economic assessments and life cycle analyses to determine feasibility, profitability, and environmental performance. While CCUS holds strong potential for supporting net-zero transitions, its large-scale deployment hinges on balancing costs, policy frameworks, and verified climate benefits [18].

6.3.1. Cost-Benefit Analysis of CCUS Pathways

The economic viability of CCUS projects depends on several factors: the cost of CO_2 capture, energy requirements, product value, and enabling policy mechanisms such as carbon pricing, subsidies, or tax credits. Capture costs vary widely depending on the CO_2 source. Direct Air Capture (DAC) remains among the most expensive options, with current estimates ranging from \$200–\$600 per ton of CO_2. However, DAC costs are projected to decline with technological improvements, economies of scale, and integration with renewable energy [128]. In contrast, point-source capture from concentrated industrial emissions is more cost-competitive. Cement plants and fertilizer facilities, where CO_2 streams are purer, can achieve capture costs below \$40–\$80 per ton [41]. The profitability of CCUS projects also hinges on the value of products derived from CO_2. High-value applications such as specialty chemicals, polymers, or advanced fuels offer stronger returns than bulk markets like aggregates. Policy support remains a decisive enabler of CCUS economics. In the United States, the 45Q tax credit provides up to \$85 per ton of CO_2 captured and stored, significantly improving project feasibility. Similarly, the European Union's Innovation Fund has financed several CCUS demonstration projects, reducing the financial risk of early deployment [129].

6.3.2. Life Cycle Assessment (LCA) and Carbon Footprint

Beyond economics, assessing whether CCUS technologies achieve real and verifiable emission reductions requires a holistic life cycle perspective. Life Cycle Assessment (LCA) considers all stages of CCUS systems, upstream energy supply, raw materials, capture and conversion processes, and downstream product use. For example, producing methanol from captured CO_2 and renewable hydrogen can reduce emissions by up to 90% compared to fossil-derived methanol [130]**.** However, if hydrogen is sourced from natural gas without CCS, the emissions advantage is largely negated, highlighting the importance of renewable integration. In construction materials, CO_2 mineralization pathways exhibit strong long-term climate benefits. By converting CO_2 into stable carbonates within concrete or aggregates, the captured carbon remains locked for decades to centuries [131]. A study by CarbonCure Technologies demonstrated that injecting CO_2 during concrete curing not only improved compressive strength but also achieved net-negative emissions when coupled with renewable-powered capture. Synthetic fuels, while valuable for decarbonizing hard-to-abate sectors like aviation and shipping, offer a different emissions profile. Since these fuels re-release CO_2 upon combustion, their climate benefit depends on renewable energy inputs and the recycling efficiency of the carbon [132]. Demonstration projects such as Sunfire's Power-to-Liquids plant in Germany, which combines captured CO_2 with renewable hydrogen to produce kerosene, illustrate how synthetic fuels can close the carbon loop. However, LCAs reveal that without 100% renewable power, synthetic fuels risk shifting rather than reducing emissions.

6.3.3. Balancing Trade-offs: Insights from TEA and LCA

Techno-economic and life-cycle studies highlight the trade-offs that shape the viability of different CCUS pathways. Direct air capture provides large-scale carbon removal but remains highly cost-intensive, while industrial point-source capture is more affordable yet risks prolonging fossil fuel dependence unless powered by clean energy [133]. Mineralization and CO_2-to-materials routes secure permanent storage but face limited market demand, whereas synthetic fuels integrate well with energy systems but only recycle carbon temporarily. These dynamics show that the value of each pathway depends heavily on regional conditions. In places rich in renewable resources, such as Iceland and Norway, CO_2-to-fuel technologies become more appealing, while industrial hubs like Rotterdam and Teesside gain advantages from shared infrastructure that supports mineralization and CCU hubs. In fertilizer-producing economies such as India, coupling capture with urea production provides immediate and practical opportunities. Most importantly, CCUS should be seen as a portfolio of complementary strategies rather than a single solution. Its success relies on supportive policies, access to renewable energy, and product market demand, with life-cycle assessments essential for distinguishing between temporary recycling options and those that lock carbon away permanently. A balanced and region-specific mix of technologies, guided by transparent metrics, will be critical to ensure both cost-effectiveness and meaningful climate mitigation [133].

7. Policy, Market, and Societal Dimensions

The large-scale deployment of Carbon Capture, Utilization and Storage (CCUS) technologies is not solely dependent on technical feasibility but is strongly shaped by policy frameworks, market dynamics, and societal acceptance. The interplay of these dimensions will determine whether CCUS transitions from pilot-scale projects to becoming a cornerstone of global decarbonization strategies [134].

7.1. Global and Regional CCUS Policies

The widespread adoption of Carbon Capture, Utilization and Storage (CCUS) technologies depends heavily on policy frameworks that create economic signals, reduce investor risk, and accelerate technology learning curves. Since CCUS Soften entails higher upfront costs than conventional industrial or energy processes, well-designed policies are essential for internalizing the external costs of carbon emissions and providing incentives for low-carbon innovation [135]**.** Globally, governments and regional bodies have established diverse instruments including carbon pricing, subsidies, tax incentives, and regulatory mandates that are shaping the trajectory of CCUS deployment.

7.1.1. Carbon Credits and Emissions Trading

Emissions trading schemes (ETS) are among the most influential mechanisms for promoting CCUS adoption. By assigning a financial value to avoid or captured CO_2, these markets allow CCUS projects to generate tradable credits, thereby enhancing their commercial viability [136].

- **European Union Emissions Trading System (EU ETS):** As the world's largest carbon market, the EU ETS covers power plants, industrial facilities, and airlines within Europe. The rising carbon price, which exceeded €90 per ton CO_2 in 2023, has created a strong incentive for industrial sectors to explore CCUS integration. For instance, the Porthos Project in Rotterdam, a shared CO_2 transport and storage hub, relies partly on EU ETS revenues to finance the capture of emissions from refineries and chemical plants [137].
- **California Cap-and-Trade Programme:** California's ETS allows CCUS projects to earn credits under the state's Low Carbon Fuel Standard (LCFS). CarbonCure, a Canadian company injecting CO_2 into concrete, has successfully registered projects under the LCFS, demonstrating how CO_2 utilization in durable products can be monetized [138].
- **China's National Carbon Market:** Launched in 2021, this market initially covers the power sector, with plans to expand to cement, steel, and petrochemicals industries where CCUS integration is highly relevant. Although carbon prices in China remain lower (around \$8–\$12 per ton CO_2), the program establishes an important policy foundation for scaling CCSU in the world's largest emitter [139].

7.1.2. Incentives and Financial Support Mechanisms

Incentives and financial support mechanisms are crucial in reducing the high costs of CCUS and encouraging large-scale deployment. In the United States, the Section 45Q tax credit has positioned the country as a leader by offering significant payments per ton of CO_2 stored or utilized, which has spurred projects such as ADM's Illinois Industrial CCS initiative and Heidelberg Materials' cement capture project in Indiana [140]. Europe's Innovation Fund provides substantial funding from emissions trading revenues to support early-stage demonstration projects, including the Brevik Cement Project in Norway, set to be the first full-scale cement plant with CCS, and Orsted's bioenergy with CCS projects in Denmark. Canada has introduced a CCS investment tax credit covering a large share of project capital costs, complementing its Emissions Reduction Plan and supporting infrastructure like the Alberta Carbon Trunk Line, which links captured CO_2 from refineries and fertilizer plants to storage sites and enhanced oil recovery projects. Collectively, these measures strengthen the financial case for CCUS by lowering investment risks, sharing costs between public and private sectors, and enabling projects that would otherwise remain unfeasible [129].

7.1.3. Regulatory Mandates and Standards

Regulatory frameworks are playing an increasingly important role in driving CCUS adoption alongside financial incentives. In Europe, industrial decarbonization mandates under the Fit-for-55 package require heavy industries like cement and steel to cut emissions, positioning CCSU as a necessary compliance option where alternatives are limited. Clean fuel standards in regions such as California, Canada, and soon the EU are expanding markets for CO_2-derived fuels by granting compliance credits, with technologies like LanzaTech's gas fermentation process gaining a competitive edge through these policies. At the same time, governments are beginning to set clearer distinctions between permanent storage solutions and temporary recycling. The U.S. Department of Energy's Carbon Negative Shot initiative highlights this shift by prioritizing durable storage approaches, signaling that future regulatory preferences will increasingly favor CCUS projects with long-term climate impact [141].

7.1.4. Regional Comparisons and Policy Lessons

Different regions are taking distinct approaches to advancing CCUS, shaped by their policy framework sand industrial contexts. The United States has emerged as a leader through strong fiscal incentives such as the 45Q tax credit and Department of Energy funding, enabling deployment at scale. Europe relies more on carbon pricing and innovation grants, with a particular emphasis on industrial hubs and cross-border CO_2 infrastructure. Canada combines tax credits with major infrastructure investments, focusing on sectors like oil sands, fertilizer, and industrial clusters in Alberta. China remains at an early stage but is laying the groundwork by extending carbon pricing to heavy industries, signaling long-term integration of CCUS. In developing regions, growing interest is evident in countries such as India and in the Middle East, where fertilizer and steel industries are exploring CCUS to meet international decarbonization standards. Saudi Aramco's Jubail CCUS hub exemplifies this trend, aiming to provide capture and utilization solutions for regional industries. Collectively, these varied approaches show that supportive policies are indispensable for enabling CCUS by reducing risks, creating markets, and building infrastructure [119]. While strategies differ, common features include carbon pricing, incentives, and mandates for industrial decarbonization. Aligning these efforts across regions, recognizing durable utilization in carbon markets, and linking CCUS with broader net-zero strategies will be essential for maximizing its contribution to climate goals.

7.2. Market Potential and Investment Trends

The commercial viability of Carbon Capture, Utilization and Storage (CCUS) depends on the ability of industries to turn captured CO_2 into marketable products and on the willingness of investors to finance the scaling of these technologies. While policy incentives provide an enabling environment, the long-term sustainability of CCUS hinges on the economic value of CO_2-derived products and the strength of investment trends shaping the sector [142].

7.2.1. Economic Feasibility of CCU Products

The economics of CO_2 utilization vary widely across products, reflecting differences in technological maturity, production costs, and market demand.

- **Established Products -Urea and Fertilizers:** Urea production remains the largest commercial use of captured CO_2, consuming more than 130 million tonnes annually in fertilizer manufacturing. This represents a mature and cost-effective utilization pathway, but its climate benefits are limited since the CO_2 is re-released when fertilizers degrade [143]. Nevertheless, it illustrates that large-scale markets exist for CO_2-derived commodities.
- **Synthetic Fuels and Methanol:** Producing synthetic fuels from CO_2 and green hydrogen is significantly more expensive than fossil alternatives, with production costs often ranging between $800–1,200 per tonne of methanol compared to $300–400 for fossil-based methanol. However, demand for sustainable aviation fuel (SAF) is creating new market opportunities [144].
- **Carbonated Concrete and Building Materials:** CO_2 use in concrete curing and aggregate production is commercially available and cost-competitive in certain markets. In the U.S., Solidia Technologies produces precast concrete cured with CO_2 instead of water, reducing emissions by up to 70%. Analysts project that the market for CO_2-cured concrete could exceed $400 billion by 2030, making it one of the most promising utilization pathways [145].
- **Polymers and Plastics:** Companies like Covestro (Germany) are producing polycarbonate polyols using up to 20% CO_2 as a feedstock, lowering fossil input while creating sustainable plastics for furniture, textiles, and automotive sectors. While cost competitiveness remains a barrier, consumer preference for green products and the rise of circular economy frameworks are driving niche adoption [146].

Premium Products and Carbon Branding: The marketing value of "carbon-negative" or "carbon-neutral" products also contributes to economic feasibility. For example, Air Company (USA) sells vodka, perfume, and cleaning products made from CO_2, leveraging consumer interest in climate-conscious branding [147]. Though small in scale, these premium markets illustrate how non-traditional value creation can support early commercialization.

7.2.2. Scaling Innovations through Private/Public Funding

Commercial viability also depends on access to capital, particularly given the high upfront costs and risks of CCUS projects. Both private and public financing play essential roles in scaling innovations [148].

Venture Capital and Startups: In recent years, venture capital investment in carbontech startups has surged, with companies like Climeworks (Switzerland) and CarbonClean (UK) raising hundreds of millions of dollars to advance direct air capture and industrial capture technologies. Startups focusing on electrochemical conversion (e.g., Twelve in the U.S., which converts CO_2 into carbon-neutral fuels and chemicals) are attracting increasing investor interest, reflecting confidence in the scalability of CO_2-to-products platforms [149].

- **Corporate Net-Zero Commitments:** Major corporations are investing directly in CCUS as part of their net-zero strategies. For example, Microsoft and Shopify have signed long-term purchase agreements with carbon removal companies, providing guaranteed demand. Exxon Mobil and Shell are developing large CCUS hubs, while Air Liquide and BASF are collaborating on CO_2-to-chemicals projects in Europe [150]. These initiatives highlight how private sector demand is catalyzing innovation.
- **Public–Private Partnerships:** Large-scale CCUS deployment requires coordinated funding mechanisms. The Norwegian Longship Project exemplifies this model, with the government funding approximately two-thirds of the $2.7 billion cost to establish a full-chain CCS network including capture at industrial sites, transport, and offshore storage [151].
- **Green Bonds and Multilateral Financing:** Financing CCUS in emerging economies is increasingly supported through climate finance mechanisms. For example, the Asian Development Bank (ADB) and the World Bank are investing in industrial decarbonization projects that incorporate CCUS. Green bonds issued by companies and municipalities are also being used to raise capital for CO_2 utilization facilities, ensuring alignment with environmental, social, and governance (ESG) investment criteria [152].

7.2.3. Market Outlook

While CCUS products currently account for less than 0.1% of annual CO_2 emissions, the market potential is significant. Reports by the International Energy Agency (IEA) and McKinsey estimate that global CO_2 utilization could reach 7–10 gigatonnes annually by 2050, with an economic market size of over $1 trillion, particularly in fuels, building materials, and polymers [153]. The success of this market transition depends on continuous innovation, falling renewable energy costs, and the maturation of carbon markets that reward low-carbon products.

7.3. Public Perception and Ethical Considerations

The successful deployment of Carbon Capture, Utilization and Storage (CCUS) is not determined by technical feasibility or cost alone but also by the degree to which society perceives the technology as safe, fair, and beneficial. Public perception and ethical considerations therefore play a central role in shaping CCUS's future trajectory [154]. These factors encompass risk communication, environmental justice, and consumer acceptance of CO_2-derived products.

7.3.1. Risk Communication and Environmental Justice

Public skepticism regarding CCUS is often rooted in fears of environmental and safety risks, particularly with respect to storage. Concerns include the possibility of CO_2 leakage from geological reservoirs, induced seismicity, or long-term liability for stored carbon. High-profile debates, such as the Barendrecht CCS project in the Netherlands, illustrate how public opposition can derail projects even after significant investment. Despite strong technical evidence supporting the safety of geological storage, the project was cancelled in 2010 due to intense local resistance and lack of transparent engagement with the community [155]. To overcome such barriers, clear and open communication is critical. Successful cases demonstrate that when communities are engaged early, risks are explained transparently, and benefits are shared, acceptance improves. Environmental justice is another key ethical consideration. There is a risk that CCUS facilities may be disproportionately sited in already disadvantaged or marginalized communities, reinforcing social inequities. For instance, U.S. environmental groups have raised concerns about locating CCUS projects near low-income and minority communities that already face high pollution burdens from refineries and heavy industry [156]. To address this, policy frameworks must incorporate equity safeguards, ensuring that vulnerable populations are not disproportionately exposed to risks while also sharing in the economic benefits [156]. Job creation, skills development, and local reinvestment are essential for equitable deployment.

7.3.2. Acceptance of CO_2-Derived Products

Public acceptance extends beyond infrastructure siting to the end-use of CO_2-derived products. Studies show that consumer attitudes toward CCUS products vary depending on their application and perceived environmental benefits.

- **High Acceptance Products – Fuels, Concrete, and Chemicals:** Surveys conducted in Europe and North America suggest strong support for CO_2-derived fuels and building materials, particularly when framed as reducing dependence on fossil resources and lowering carbon footprints [157]. For example, CO_2-to-methanol products, such as those from Carbon Recycling International in Iceland, benefit from positive branding as "renewable methanol."
- **Mixed Acceptance – Consumer Goods and Food Applications:** Acceptance is more complex for products perceived as directly linked to health or personal consumption. While bioplastics and consumer goods made from CO_2 are gradually gaining traction, surveys indicate hesitation regarding CO_2-derived food or beverages.

For instance, when Coca-Cola experimented with CO_2-derived plastic bottles, consumers were generally supportive due to sustainability branding. However, acceptance of CO_2-derived proteins or food additives, such as those developed by Solar Foods in Finland, remains cautious, requiring extensive communication on safety and regulatory approval [158].

- **Certification and Labeling for Trust:** To address consumer concerns, certification and labeling frameworks are emerging. The Carbon Trust has piloted carbon labeling initiatives that transparently communicate emissions reductions associated with products. Similarly, the CO_2 Value Europe initiative is working on standardized methodologies to certify CO_2-derived products, aiming to build trust in both environmental and safety claims [159]. Such frameworks are critical for improving transparency and consumer confidence, especially as markets expand to everyday goods.

7.3.3. Ethical Dimensions of CCUS Deployment

Beyond acceptance, CCUS raises broader ethical debates around climate priorities. Critics argue that heavy reliance on CCUS could delay investments in renewable energy and energy efficiency, effectively locking in fossil fuel use. For example, environmental advocacy groups opposed CCUS integration with coal-fired plants in the U.S., arguing it served as a "lifeline" for the fossil industry rather than a genuine transition strategy [160]. From an ethical standpoint, CCUS deployment must be framed as complementary to, rather than competitive with, renewable energy transitions. It's most justifiable applications lie in hard-to-abate sectors (cement, steel, aviation) where direct electrification is limited. Transparent governance, equitable community participation, and strong regulatory oversight are therefore necessary to ensure CCUS deployment aligns with long-term decarbonization and social equity goals [119, 160].

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8. Challenges, Limitations, and Research Gaps

Despite the promise of Carbon Capture, Utilization and Storage (CCUS) in advancing global decarbonization efforts, a number of challenges and limitations hinder large-scale deployment. These span technological, economic, infrastructural, and societal dimensions. Addressing these barriers requires sustained research, development, and policy support [41].

8.1.1. Energy Penalty and Cost Concerns

One of the most significant challenges of CCUS is the high energy intensity of capture and conversion processes. Conventional post-combustion capture using amine-based solvents imposes an energy penalty of about 20–30% of a power plant's output, significantly reducing overall efficiency [43]. The economic feasibility of CCUS also depends on the competitiveness of CO_2-derived products. While fertilizers and certain chemicals are cost-competitive, synthetic fuels, polycarbonates, and mineralized materials remain more expensive than fossil-based alternatives [87]. This cost disparity highlights the urgent need for breakthroughs in capture efficiency, low-cost renewable hydrogen production, and integration with renewable energy to reduce lifecycle costs.

8.1.2. CO_2 Purity and Transport Infrastructure

The utilization and storage of CO_2 often require high-purity streams, which can be costly to achieve when capturing from dilute or mixed sources such as flue gases. For example, cement plants produce highly concentrated CO_2, making capture more straightforward, while natural gas processing or biomass combustion facilities may produce mixed streams requiring additional purification [49]. Another major barrier is the lack of dedicated CO_2 transport infrastructure. Unlike oil and gas, which benefit from extensive pipeline networks, CO_2 pipelines are limited to specific regions such as the United States, where approximately 8,000 km of pipelines are used primarily for Enhanced Oil Recovery (EOR). However, replicating these networks globally will require substantial investment and regulatory coordination, particularly in regions lacking prior experience with subsurface gas transport [49].

8.1.3. Storage Permanence and Monitoring

A recurring concern with CCUS is the long-term permanence of geological storage. Ensuring that captured CO_2 remains securely stored over centuries is essential to delivering genuine climate benefits [78]. Advanced monitoring technologies, including seismic imaging, tracer injection, and satellite-based measurements, are being developed to enhance confidence in storage permanence [161]. However, standardized global frameworks for long-term liability, monitoring, and verification remain limited. Without clear governance mechanisms, public trust and private sector investment in large-scale storage could be undermined [162].

8.1.4. Knowledge Gaps and Technology Readiness Levels

The maturity of CCUS technologies varies significantly across pathways, creating knowledge gaps in performance, scalability, and integration [119].

- **High Readiness:** Post-combustion capture and geological storage are relatively advanced, with several commercial-scale plants in operation worldwide.
- **Intermediate Readiness:** Mineralization and CO_2 use in concrete curing are moving toward commercial viability, with companies like CarbonCure and Solidia scaling applications [163].
- **Low Readiness:** Emerging pathways such as artificial photosynthesis, electrochemical CO_2 reduction, and CO_2-to-proteins remain at early pilot stages with high technical and cost uncertainties.

Knowledge gaps also extend to lifecycle impacts and systems integration. For example, while CO_2-derived fuels can recycle carbon, they ultimately re-release CO_2 upon combustion, raising questions about their role in long-term decarbonization compared to permanent storage pathways. Similarly, the interaction of CCUS with renewable grids, whether as a flexible load or a competing demand for low-cost electricity, requires further investigation. In essence, the deployment of CCUS faces intertwined challenges: energy penalties that raise costs, infrastructural bottlenecks in CO_2 purification and transport, uncertainties regarding long-term storage, and uneven technology readiness across utilization pathways [142]. Overcoming these barriers requires not only technical innovation but also cross-sector collaboration, international standards for monitoring and verification, and targeted funding for early-stage research.

9. Future Prospects and Roadmap to Net-Zero

The future of Carbon Capture, Utilization and Storage (CCUS) lies in its ability to evolve from a niche set of industrial pilot projects into a mainstream decarbonization pillar that complements renewable energy, efficiency measures, and circular economy practices [119]. Achieving net-zero emissions by mid-century will require accelerated innovation, cross-sector integration, and coordinated international policy frameworks [26].

Figure 10 Future of Carbon Capture, Utilization and Storage (CCUS) and Roadmap to a Net-Zero Carbon Economy. Source; Author.

9.1. Next-Generation Materials and Modular Technologies

Breakthroughs in advanced materials and modular system designs are expected to transform the scalability and efficiency of CCUS. For instance, metal-organic frameworks (MOFs) and novel solid sorbents are being developed to capture CO_2 with higher selectivity and lower regeneration energy compared to traditional amines [164]. Pilot projects in the U.S. National Carbon Capture Center have tested MOF-based capture systems under flue gas conditions, showing significant potential to reduce capture costs [165].In parallel, modular Direct Air Capture (DAC) units pioneered by some companies are demonstrating the viability of distributed carbon removal. These companies, highlight how compact, modular technologies can be scaled up in clusters near renewable energy hubs [166]. Such modularity allows flexible deployment across geographies, including hard-to-abate regions with limited storage capacity.

9.1.1. Integration with the Hydrogen Economy and Negative Emissions

The coupling of CCUS with the emerging hydrogen economy provides a powerful pathway toward deep decarbonization. CO_2 captured from industrial sources can be combined with green hydrogen to produce synthetic fuels such as e-methanol, e-kerosene, and ammonia, which are essential for decarbonizing aviation, shipping, and fertilizer production [87]. Moreover, CCUS plays a central role in delivering negative emissions, which are indispensable to achieving IPCC’s 1.5°C and 2°C scenarios.

9.1.2. Policy Alignment with UN SDGs and IPCC Goals

The roadmap for CCUS must be aligned with broader sustainability and climate goals. In the context of the UN Sustainable Development Goals (SDGs), CCSU can contribute to SDG 7 (Affordable and Clean Energy), SDG 9 (Industry, Innovation, and Infrastructure), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action) [3]. For instance, the use of CO_2 in building materials not only reduces emissions but also promotes sustainable urban infrastructure, contributing to SDG 11 (Sustainable Cities and Communities). At the international level, the IPCC’s Sixth Assessment Report (AR6) emphasizes that CCUS is essential for achieving net-zero, particularly for decarbonizing cement, steel, and aviation sectors [14].Large-scale initiatives such as Norway’s Longship and Northern Lights projects are already serving as global benchmarks by aligning industrial CCUS hubs with Europe’s Green Deal targets [167]. These examples highlight how coordinated policy and financing mechanisms can integrate CCUS into national net-zero strategies.

9.1.3. A Proposed Roadmap for CCUS Deployment by 2050

A robust roadmap toward 2050 requires phased and geographically diverse action, combining near-term deployment with long-term innovation [41].

- **2025–2030:** Scale demonstration projects to commercial hubs. Expand CO_2 transport and storage infrastructure.
- **2030–2040:** Widespread integration of CCUS with renewable hydrogen and industrial clusters. Commercial deployment of CO_2-derived fuels in aviation and shipping. Expansion of mineralization pathways and CO_2-enhanced building materials into global construction markets [120].
- **2040–2050:** Achieve global CCUS capacity in the order of 5–10 $GtCO_2$/year, with balanced deployment across storage and utilization. DAC and BECCS deliver large-scale negative emissions to offset residuals. Comprehensive global monitoring and verification frameworks ensure storage permanence and public trust [14].

By 2050, CCUS is projected to transition from a niche mitigation option to a core enabler of net-zero economies, operating synergistically with renewables, hydrogen, and circular carbon markets. The roadmap underscores the necessity of aligning research, finance, and governance structures to overcome technical and societal barriers, ensuring CCUS contributes both to climate targets and sustainable development.

10. Conclusion

Advances in the development and integration of Carbon Capture, Utilization, and Storage (CCUS) highlight its growing significance in accelerating the global transition toward a net-zero carbon economy. As demonstrated throughout this review, progress in capture technologies, expanding utilization pathways, and diversified storage options confirms that CCUS has evolved from a supplementary mitigation measure into a core component of industrial decarbonization strategies. Beyond emissions abatement, CCUS enables a circular carbon economy by transforming captured CO_2 into fuels, chemicals, construction materials, and other value-added products, thereby closing material loops and reducing reliance on fossil-derived carbon. The strategic relevance of CCUS lies in its capacity to decarbonize hard-to-abate sectors such as cement, steel, and fertilizer production, while complementing renewable energy deployment and enabling negative-emission pathways. Its dual function, simultaneously mitigating emissions and supporting the production of durable carbon-based materials, positions CCUS as a critical link between near-term climate action and long-term sustainability goals. Moreover, CCUS creates opportunities for economic diversification, industrial innovation, and job creation within a rapidly decarbonizing global economy. However, unlocking the full potential of CCUS extends beyond technological advancement alone. Widespread deployment will require sustained interdisciplinary collaboration, supportive and coherent policy frameworks, innovative business models, and accessible financing mechanisms. Equally vital is meaningful societal engagement to foster public trust and acceptance. When embedded within broader energy transition and circular economy strategies, CCUS offers a systems-level pathway for reconfiguring the global carbon cycle and advancing climate neutrality. Ultimately, the realization of a net-zero carbon future will depend on the collective ability to integrate innovation, policy, and societal commitment to fully harness the promise of CCUS.

Compliance with ethical standards

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No conflict of interest to be disclosed.

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