U.P.B. Sci. Bull., Series B, Vol. 87, Iss. 1, 2025 ISSN 1454-2331

CO_2 SOLUTIONS: INNOVATIONS IN CARBON CAPTURE, UTILIZATION AND STORAGE

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This paper explores innovative approaches and provides a comprehensive analysis of Carbon Capture, Utilization and Storage - CCUS technologies. It examines current methods, including post-combustion, pre-combustion and oxy-combustion, as well as emerging techniques such as direct air capture and advanced solvent applications. The study also includes the economic and political challenges associated with CCUS, offering insights into future perspectives for overcoming these obstacles through technological advancements and policy support. The findings contribute to a deeper understanding of CCUS's influence in achieving global CO_2 emissions reduction goals.

Keywords: greenhouse gas, climate change, decarbonization, carbon neutrality

1. Introduction

CCUS (Carbon Capture, Utilization, and Storage) is a critical set of technologies designed to capture CO_2 emissions from sources such as power plants and industrial processes, preventing them from entering the atmosphere [1]. The captured CO_2 can either be stored underground in geological formations or utilized in various industrial applications, including enhanced oil recovery and the production of chemicals and materials. The importance of CCUS lies in its potential to significantly reduce greenhouse gas emissions, thus playing a pivotal role in mitigating climate change. As global efforts intensify to achieve net-zero emissions targets [2], CCUS technologies are increasingly seen as indispensable tools in the transition to a sustainable and low-carbon energy future.

The deployment of CCUS technologies is gaining momentum globally, driven by the urgent need to reduce CO_2 emissions and combat climate change [3, 4]. Currently, there are approximately 26 commercial CCUS facilities in operation worldwide [5], with several more in development. These projects capture and store millions of tons of CO_2 annually, demonstrating the technical viability of these technologies. Despite this progress, the scale of deployment remains insufficient relative to the volume of emissions that need to be abated to meet international climate goals, such as those outlined in the Paris Agreement. Regions like North

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America, Europe, and Asia are leading the charge, with significant investments and policy frameworks supporting CCUS. However, the high costs, technological challenges, and limited infrastructure continue to hinder widespread adoption. To accelerate the deployment of CCUS, there is a growing call for enhanced policy support, international cooperation, and investments in research and development.

This review aims to provide a comprehensive analysis of the technologies and strategies involved in CCUS. It will cover key aspects including the various methods of CO_2 capture, such as post-combustion, pre-combustion and oxy-combustion, as well as emerging technologies like direct air capture. The review will also explore the utilization of captured CO_2 in industrial processes and its potential for storage in geological formations. Additionally, it will address the economic and policy frameworks supporting CCUS, highlighting the current challenges and potential future advancements. By examining both technical and socio-economic perspectives, the review seeks to offer a holistic understanding of the role of CCUS in achieving global carbon reduction targets.

2. Technologies for CO_2 Capture

2.1 Post-Combustion Capture

Post-combustion capture involves removing CO_2 from flue gases after the combustion of fossil fuels. This method is particularly suitable for retrofitting existing power plants and industrial facilities. The primary techniques for CO_2 separation include absorption, adsorption, membrane separation and cryogenic separation.

2.1.1. Absorption: CO_2 is absorbed into a liquid solvent, which can be an amine solution or other chemical solvents such as ammonia [6]. The CO_2 chemically reacts with the solvent, forming a compound that can be heated to release pure CO_2, thereby regenerating the solvent. This method is well-established and capable of achieving high capture rates [7, 8], making it effective for separating CO_2 from gas streams with lower concentrations. However, the process is energy-intensive, primarily due to the heat required for solvent regeneration. Additionally, the solvent can degrade over time, leading to increased costs and operational challenges [7].

2.1.1.a. Amine-based Solvents: Amine solutions, especially MEA, are commonly used in CO_2 capture due to their strong CO_2 affinity and straightforward operation. CO_2 reacts with the amine to form a carbamate complex, releasing heat and efficiently capturing CO_2 from flue gases [9]. The loaded solvent is then heated in a regeneration unit, breaking the CO_2-amine bond and releasing CO_2 gas, allowing the amine to be reused [10, 11]. This cyclical process enables continuous operation and reduces costs, but the energy-intensive regeneration process can lower overall efficiency. Additionally, amines degrade over time, forming products that reduce effectiveness, requiring periodic replacement or reconditioning.

2.1.1.b. Ionic Liquids: Ionic liquids are solvents composed entirely of ions, remaining liquid at temperatures often below 100°C [12]. Their low vapor pressure makes them non-volatile, reducing solvent losses and enhancing environmental safety [13]. The tunable nature of ionic liquids allows customization of properties like viscosity and thermal stability, making them effective for CO_2 capture due to high solubility and selectivity [14]. Their thermal stability supports CO_2 desorption and regeneration without significant degradation. However, challenges like high viscosity and potential toxicity must be addressed [15, 16]. Ongoing research aims to optimize these properties and reduce costs, positioning ionic liquids as a versatile option for CO_2 capture technologies.

2.1.1.c. Deep Eutectic Solvents (DES): DES are formed by mixing a hydrogen bond donor and acceptor, resulting in a eutectic mixture with a melting point lower than the individual components [6, 17-19]. This allows DES to stay liquid at or near room temperature. DES are environmentally friendly, non-toxic, biodegradable, and often made from renewable materials. They have high viscosity, tunable polarity, and good thermal stability. DES are highly effective in CO_2 capture due to their ability to dissolve large amounts of CO_2, minimizing solvent losses and reducing emissions [18, 20-22]. They also require less energy for regeneration, making the process more energy-efficient and cost-effective. Research is focused on optimizing DES composition to improve CO_2 capture and reduce energy needs, making them a promising alternative in sustainable CO_2 capture technologies.

2.1.2. Adsorption: The adsorption process for CO_2 capture involves the interaction of CO_2 molecules with the surface of a solid adsorbent material [23]. These materials, which include activated carbon, zeolites, calcium oxide and metal-organic frameworks (MOFs), have large surface areas and porosity, enabling them to capture significant amounts of CO_2. The captured CO_2 can be released from the adsorbent by altering the temperature or pressure conditions, a process known as regeneration. Adsorption systems are highly valued for their selectivity and ability to operate under a variety of conditions, making them particularly suitable for applications requiring high-purity CO_2. However, the technology faces challenges such as the substantial energy required for adsorbent regeneration and the potential degradation of adsorbent materials over time, which can lead to reduced efficiency and increased operational costs.

2.1.2.a. CaO-looping, or calcium looping, is a CO_2 capture technology that uses the reversible reaction between calcium oxide (CaO) and CO_2 to form calcium carbonate ($CaCO_3$) [24-26]. CO_2-laden flue gas reacts with CaO, forming $CaCO_3$, which is then heated in a calciner to release pure CO_2 and regenerate CaO for reuse. This process is efficient and can be integrated into existing power plants. The advantages include the abundance and low cost of calcium-based sorbents [27-29] and lower energy penalties compared to amine-based systems. However, challenges like sorbent deactivation and the need for high-temperature calcination must be addressed to enhance economic viability.

2.1.3. Membranes: Membrane technology captures CO_2 by using selective barriers that allow CO_2 to pass through while blocking other gases based on partial pressure differences [30]. Membranes, made from materials like polymers and ceramics, offer continuous operation with low energy consumption and modular scalability for different facility needs [6, 31-34]. However, successful implementation requires membranes that are highly selective, permeable, and resistant to fouling, which are critical for maintaining efficiency and cost-effectiveness [35].

2.1.4. Cryogenic Separation: Cryogenic separation cools flue gases to very low temperatures, causing CO_2 to condense as a liquid or solid [36, 37]. This process exploits the different boiling points of gases, allowing selective CO_2 separation. It is particularly effective for high CO_2 concentrations and when CO_2 needs to be in liquid form for transport or storage [38]. However, the high energy required for such low temperatures and the technical challenges of maintaining equipment at these temperatures make the process costly and complex, requiring robust insulation and system integrity solutions.

Each of these methods —absorption, adsorption, membrane separation, and cryogenic separation— has specific applications and suitability depending on the characteristics of the flue gas, the required CO_2 purity and economic factors. The choice of technology for CO_2 capture in post-combustion processes depends on a balance between efficiency, cost and the specific needs of the application. As technologies advance, there is potential for more efficient and cost-effective solutions to be developed.

2.2 Pre-Combustion Capture

In pre-combustion capture, fossil fuels are partially oxidized to produce a mixture of hydrogen and carbon monoxide [1, 7]. The CO is then converted to CO_2 via the water-gas shift reaction, and the CO_2 is separated before combustion. This method is commonly used in integrated gasification combined cycle (IGCC) plants. Pre-combustion capture is efficient for CO_2 separation and can produce hydrogen as a clean energy source. However, it is more complex and expensive than post-combustion systems.

2.3 Oxy-Combustion Capture

Oxy-combustion involves burning fuel using a mixture of oxygen and recycled exhaust gases instead of air [23, 39]. This results in a flue gas that is mainly CO_2 and water vapor, making CO_2 separation easier. The primary challenge is the high cost of oxygen production [40]. Ongoing research aims to develop more efficient oxygen generation technologies to make oxy-combustion more economically viable.

2.4 Direct Air Capture (DAC)

Direct Air Capture is a technology designed to capture CO_2 directly from the ambient air [41]. This process typically involves the use of chemical sorbents or filters that absorb CO_2 from the air [7]. The captured CO_2 is then released from the sorbents through heating or chemical reactions, allowing it to be collected for storage or utilization [42]. DAC can be used to produce carbon-neutral fuels, enhance oil recovery, or even directly remove CO_2 from the atmosphere as a negative emissions technology. Although currently expensive and energy-intensive, DAC has significant potential in the fight against climate change, particularly as costs decrease with technological advancements [43]. Companies such as Climeworks, Carbon Engineering, and Global Thermostat are leading the development of DAC technologies, each employing different methods and materials to capture CO_2.

3. Utilization of Captured CO_2

Captured CO_2 can be used in various industrial applications, contributing to a circular economy and reducing net carbon emissions [44].

3.1. Industrial Applications: Captured CO_2 is used in the production of urea, a widely used fertilizer, making the process more sustainable by reducing reliance on naturally occurring CO_2 [45]. Another key application is methanol production, where CO_2 is converted through hydrogenation, especially using renewable hydrogen, enhancing sustainability [46]. CO_2 is also utilized in producing building materials like concrete, where it reacts with calcium silicates to form calcium carbonate, improving concrete's strength and durability while sequestering CO_2 [47]. Additionally, CO_2 is used in making polymers and other chemical intermediates, offering a sustainable alternative to fossil-based feedstocks [48].

3.2. Enhanced Oil Recovery (EOR): One of the largest uses of captured CO_2 is in EOR [3]. In this process, CO_2 is injected into depleted oil fields to increase the pressure and reduce the viscosity of the remaining oil, thereby enhancing its recovery [49]. This not only helps in extracting additional oil from existing fields but also sequesters CO_2 underground, effectively reducing atmospheric CO_2 levels. EOR has been widely adopted in the oil industry and represents a significant opportunity for the utilization of captured CO_2 [50].

3.3. Conversion into Biomass Products: Conversion into biomass is a sustainable way to utilize captured CO_2 [51]. This process uses CO_2 to cultivate microalgae and other biomass-producing organisms, which efficiently convert CO_2 into biomass through photosynthesis [52-55]. Microalgae, with their rapid growth and high lipid content, are ideal for producing biofuels, animal feed, and bioplastics [56, 57]. The biomass can also serve as a renewable energy source, reducing fossil fuel dependence [58]. This approach enhances industrial sustainability by recycling waste CO_2 into valuable products. Ongoing research focuses on optimizing algal strains, growth conditions, and cost-effective harvesting techniques [53, 54, 59-62], creating a circular carbon economy where CO_2 emissions are recycled into renewable raw materials [52].

3.4 CCUS in the Transport Sector: The transport sector is a major contributor to global greenhouse gas (GHG) emissions, accounting for approximately one-quarter of total emissions. Road, air and maritime transport each present unique challenges in reducing CO_2 emissions due to their reliance on fossil fuels [30, 41]. In this context, CCUS technologies can play a significant role in decarbonizing transportation through multiple pathways. Direct Air Capture (DAC) can be leveraged for the production of synthetic fuels that are carbon-neutral, providing an alternative to conventional petroleum-based fuels [42, 43]. Additionally, integrating CCUS into industrial processes for green hydrogen production or alternative fuels can substantially lower the carbon footprint of the transport sector. Captured CO_2 can also be used to produce *e-fuels* through the combination of CO_2 and renewable hydrogen, offering a scalable solution for aviation and shipping, where electrification remains challenging [43, 46]. In the long term, integrating CCUS with policies like carbon pricing and low-carbon fuel incentives can accelerate transport decarbonization. Further research and investment in CCUS-based fuel production are crucial for enhancing efficiency and economic viability.

4. CO_2 Storage

4.1 Geological Storage: Geological storage involves injecting captured CO_2 into underground formations like depleted oil, gas reservoirs or deep saline aquifers, where it can be securely stored for long periods [63, 64]. These reservoirs are ideal due to their proven ability to contain hydrocarbons, and their existing infrastructure can be repurposed for CO_2 storage. Ensuring safety and integrity is crucial, requiring thorough site characterization, including capacity and permeability assessments, and the presence of a secure cap rock [65]. Continuous monitoring through seismic surveys, tracers, and advanced modeling techniques is essential to prevent leaks and ensure the CO_2 remains securely contained [66].

4.2 Ocean Storage: Ocean storage involves injecting CO_2 into deep ocean waters, where it can dissolve and be sequestered [67]. Two main methods are considered: direct injection into the deep ocean and the formation of CO_2 hydrates on the ocean floor. While the deep ocean can hold large amounts of CO_2, the environmental impacts of ocean storage are a significant concern. CO_2 injection can lower the pH of seawater [63, 68], leading to ocean acidification, which can harm marine life, particularly organisms with calcium carbonate shells. Thorough environmental impact assessments and the development of mitigation, strategies are crucial to address these concerns.

4.3 Mineral Storage: Mineral storage, or mineral carbonation, involves reacting CO_2 with naturally occurring minerals like olivine and serpentine to form stable carbonates such as magnesite and calcite [69, 70]. This process accelerates natural weathering and is exothermic, providing additional energy [71]. Mineral storage offers a stable, permanent form of CO_2 sequestration, as the carbonates are stable over geological timescales [72]. It has the potential to store vast amounts of CO_2, but the natural reaction rates are slow. Research is focused on enhancing reaction kinetics through methods like increasing mineral surface area or using catalysts, though scalability and economic feasibility remain challenges [73].

5. Economic and Political Aspects

5.1. Costs Associated with CCUS: Implementing CCUS technologies incurs significant costs, primarily in capture, transportation, and storage. The capture phase is the most expensive, often comprising up to 70% of the total cost due to advanced separation technologies. Transportation costs vary by distance and method, such as pipelines or shipping. Storage costs include site preparation, injection, and long-term monitoring. However, technological advances and economies of scale are expected to reduce these expenses over time [74, 75]. Additionally, avoiding carbon taxes and generating revenue from CO_2 utilization can help offset some of these costs.

5.2. Policies and Regulations: Effective policies and regulations are essential for the widespread adoption of CCUS. Governments play a key role by setting frameworks that mandate or incentivize CO_2 emission reductions, such as emission targets, carbon taxes, and cap-and-trade systems [76, 77]. Clear guidelines for CO_2 storage site selection and monitoring are also crucial. Policies that promote research and development in CCUS and streamline permitting for new projects are vital [4, 78]. International agreements like the Paris Agreement emphasize the importance of collaborative efforts to address global carbon emissions through CCUS.

5.3. Financing and Support Initiatives: Financing CCUS projects requires significant investment, often combining public and private funding. Governments can support CCUS with grants, subsidies, and tax incentives to ease the financial burden on companies. Public-private partnerships [79, 80] also play a key role in funding, leveraging both sectors' strengths. Financial institutions and investors are increasingly focusing on sustainable investments, leading to green bonds and other instruments supporting environmental initiatives, including CCUS. Global initiatives like the Carbon Capture and Storage Association (CCSA) and the Global CCS Institute facilitate knowledge sharing and collaboration, further promoting CCUS development and deployment.

6. Challenges and Future Perspectives

The high costs of capturing and storing CO_2, due to energy-intensive methods like amine scrubbing [3, 81], make large-scale CCUS deployment economically challenging. Significant investment is required for infrastructure such as pipelines and storage facilities. Additionally, technical challenges, including the long-term stability of storage sites and the need for robust monitoring systems, further add to the complexity [82].

Despite these obstacles, ongoing research is improving the efficiency and cost-effectiveness of CCUS technologies [83, 84]. Advances in materials science, such as the development of new solvents and adsorbents like ionic liquids and MOFs, show promise in reducing costs [81, 85]. DAC technologies are also being explored to offset emissions in hard-to-decarbonize sectors. Process integration innovations, like combining CO_2 capture with waste heat recovery, are being pursued to lower the overall energy footprint.

CCUS is crucial for achieving global emission reduction targets, particularly in sectors like heavy industry and power generation. By capturing and storing CO_2 or converting it into useful products, CCUS can significantly reduce emissions [86]. This technology is essential for meeting international climate goals, such as those set by the Paris Agreement, and can serve as a transitional solution while renewable energy sources are scaled up.

7. Conclusions

The deployment of CCUS technologies is crucial in the global fight against climate change. CCUS offers a comprehensive solution to significantly reduce CO_2 emissions from various sources, including industrial processes and power generation. Technologies such as post-combustion, pre-combustion, and oxy-combustion capture, as well as direct air capture and advanced solvents like ionic liquids and deep eutectic solvents, provide versatile approaches to CO_2 capture, each with unique benefits and challenges.

Industrial applications of captured CO_2, such as in the production of urea and methanol, and its use in enhanced oil recovery, highlight the economic potential of CCUS. Additionally, converting CO_2 into valuable products like building materials and biomass supports a circular economy, transforming waste into resources. Geological storage remains the most established method for long-term

CO_2 sequestration, utilising depleted oil and gas reservoirs and deep saline aquifers. Ensuring the safety and integrity of these storage sites through robust monitoring systems is essential for public acceptance and environmental security. Ocean and mineral storage present additional options, each with specific advantages and environmental considerations.

Economically, the high costs of CCUS technologies are a significant barrier to their widespread adoption. However, technological advancements, supportive policies and innovative financing mechanisms can help overcome these obstacles. Governments and industries must work together to establish regulatory frameworks, provide financial incentives, and promote research and development to reduce costs and improve the feasibility of CCUS projects. Politically, CCUS is vital for meeting international climate targets, such as those outlined in the Paris Agreement. As nations aim for net-zero emissions, CCUS will play a pivotal role in bridging the gap between current emission levels and future sustainability goals. With continued innovation, investment and policy support, CCUS can become a cornerstone of global efforts to mitigate climate change.

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