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Carbon Capture, Utilization, And Storage (CCUS) For Climate Mitigation

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Abstract*—The rapid increase in atmospheric carbon dioxide concentrations due to anthropogenic activities has intensified global concerns regarding climate change and environmental sustainability [2], [3]. Fossil fuel combustion, particularly in coal-based power plants and energy- intensive industries, contributes significantly to greenhouse gas emissions, accounting for a major portion of global CO_2 output [1], [3]. Carbon Capture, Utilization, and Storage (CCUS) has emerged as a crucial technological approach to mitigate emissions by capturing CO_2 from industrial sources, transporting it, and either utilizing it in value- added processes or storing it in geological formations [1], [5]. The integration of CCUS into existing industrial systems provides an opportunity to reduce emissions without completely phasing out fossil fuels, thereby supporting a gradual transition to a low-carbon economy [16], [19]. Despite its potential, CCUS faces several technical, economic, and policy-related challenges, including high capital costs, increased energy demand, and limited large-scale implementation [4], [18]. Furthermore, uncertainties related to long-term storage safety and monitoring remain critical concerns [14], [15]. This report presents an in-depth analysis of CCUS technologies, including capture mechanisms, transport systems, utilization pathways, and storage strategies, while also identifying research gaps and future directions. The study highlights that CCUS is an essential component of global climate mitigation strategies but requires significant advancements and policy support for widespread adoption [2], [19].

I. INTRODUCTION

Climate change has become a defining issue of the modern era, driven primarily by the accumulation of greenhouse gases in the atmosphere, particularly carbon dioxide resulting from fossil fuel combustion [2]. The increasing demand for energy due to population growth, urbanization, and industrialization has led to a significant rise in fossil fuel consumption, thereby exacerbating carbon emissions [3]. Coal- based power generation alone contributes more than forty percent of global energy-related CO_2 emissions, making it the largest single source of anthropogenic emissions [3]. Major economies such as China, the United States, and India dominate global coal consumption, further intensifying the challenge of emission reduction [3], [4].

Although renewable energy sources such as solar, wind, and hydropower are being rapidly developed, their integration into existing energy systems faces limitations due to intermittency, storage challenges, and infrastructure constraints [3], [19]. As a result, there is a pressing need for transitional technologies that can reduce emissions while maintaining reliable energy supply. Carbon Capture, Utilization, and Storage (CCUS) has been identified as one such technology that can significantly reduce emissions from existing fossil fuel-based systems [1], [16].

The concept of CCUS originated in the 1970s with its application in enhanced oil recovery (EOR), where injected carbon dioxide increased oil extraction efficiency [14]. Over time, technological advancements have expanded its scope to include large-scale carbon sequestration in geological formations. The Sleipner project in Norway, initiated in 1996, demonstrated the feasibility of long-term CO_2 storage in deep saline aquifers, marking a milestone in CCUS development [14], [15]. The importance of CCUS has further increased following international agreements such as the Paris Agreement, which emphasize the need to limit global temperature rise to well below 2°C [2], [3].

In recent years, CCUS has gained global recognition as a key component of climate mitigation strategies, particularly for industries that are difficult to decarbonize, such as cement, steel, and chemical production [16]. The integration of CCUS with renewable energy systems and emerging technologies such as hydrogen production further enhances its potential to contribute to a sustainable energy future [19]. However, its widespread adoption requires overcoming significant challenges related to cost, efficiency, and policy support [4], [18].

II. OBJECTIVES OF THE STUDY

The primary objective of this study is to provide a comprehensive evaluation of Carbon Capture, Utilization, and Storage technologies and their role in reducing carbon dioxide emissions from industrial and energy sectors [1], [16]. The study aims to analyze the technical principles underlying different carbon capture methods and assess their efficiency, feasibility, and environmental impact [9], [10].

Another important objective is to compare various capture technologies, including post-combustion, pre-combustion, and oxy- fuel combustion, in terms of their operational mechanisms, energy requirements, and suitability for different industrial applications [9], [18]. The study also seeks to examine the economic aspects of CCUS implementation, including capital investment, operational costs, and potential revenue from CO_2 utilization [4], [18].

Furthermore, the study aims to identify key research gaps and challenges that hinder the large-scale deployment of CCUS technologies, such as policy limitations, infrastructure requirements, and long-term storage concerns [3], [19]. The evaluation of real-world case studies is included to provide practical insights into the performance and scalability of CCUS systems [4]. Overall, the study is intended to contribute to a deeper understanding of CCUS as a critical tool for achieving climate mitigation goals and transitioning toward a low-carbon economy [2].

III. PROBLEM STATEMENT

The continuous increase in global carbon dioxide emissions poses a significant threat to environmental sustainability, leading to rising global temperatures, extreme weather events, and ecological imbalances [2]. Industrial activities, particularly those involving fossil fuel combustion, are major contributors to greenhouse gas emissions, making it challenging to achieve meaningful emission reductions without disrupting economic growth [3], [16].

While renewable energy technologies offer a promising long-term solution, their current adoption rate and technological limitations make it difficult to completely replace fossil fuels in the near future [3], [19]. This creates a critical need for alternative solutions that can reduce emissions from existing infrastructure. Carbon Capture, Utilization, and Storage provides a viable option by capturing CO_2 emissions at the source and preventing their release into the atmosphere [1].

However, the implementation of CCUS technologies is hindered by several challenges, including high capital and operational costs, energy-intensive processes, and lack of supportive policies [4], [18]. Additionally, concerns regarding the safety and reliability of long-term CO_2 storage raise questions about its feasibility as a sustainable solution [14], [15]. Therefore, the key problem lies in developing efficient, cost-effective, and scalable CCUS technologies that can be widely adopted across industries to achieve significant emission reductions while maintaining economic stability [1], [16].

IV. LITERATURE REVIEW

The literature on CCUS technologies reflects a growing interest in their potential to mitigate climate change by reducing industrial emissions [1], [18]. Post-combustion capture is one of the most widely researched methods due to its ability to be retrofitted into existing power plants, making it a practical solution for emission reduction [10], [17]. This method typically uses chemical absorption techniques, such as amine- based solvents, to capture CO_2 from flue gases. However, the regeneration of these solvents requires significant thermal energy, which increases operational costs and reduces overall efficiency [10].

Pre-combustion capture involves the gasification of fossil fuels to produce a mixture of hydrogen and carbon dioxide, allowing for easier separation of CO_2 before combustion [9]. This method is considered more efficient than post-combustion capture but requires significant changes to existing infrastructure, making it less suitable for retrofitting [9], [18]. Oxy-fuel combustion, another advanced technique, involves burning fuel in pure oxygen, resulting in a concentrated CO_2 stream that simplifies the capture process [18]. However, the production of pure oxygen is energy-intensive and adds to the overall cost of the system [18].

Recent advancements in Direct Air Capture technologies have introduced the possibility of removing CO_2 directly from the atmosphere, offering a potential solution for achieving negative emissions [12], [13]. However, these technologies are still in the early stages of development and face challenges related to scalability and cost. Geological storage of CO_2 has been extensively studied and is considered a reliable method for long-term sequestration, although continuous monitoring is required to ensure safety and prevent leakage [14], [15].

Overall, the literature suggests that while CCUS technologies are technically feasible and effective in reducing emissions, their economic viability and large-scale implementation remain significant challenges [4], [16].

V. DETAILED OVERVIEW OF CCUS TECHNOLOGY

Carbon Capture, Utilization, and Storage represents a complex and integrated system designed to manage carbon dioxide emissions through a sequence of interdependent stages, including capture, compression, transportation, utilization, and storage [5], [16]. Each stage involves specific technologies and engineering considerations that collectively determine the overall efficiency and feasibility of the system. The capture stage is particularly critical, as it directly influences the purity, pressure, and volume of CO_2 that can be processed in subsequent stages [10], [17].

The compression of captured carbon dioxide is necessary to convert it into a supercritical state, which significantly reduces its volume and facilitates efficient transportation [5]. In this state, CO_2 exhibits properties of both liquids and gases, allowing it to be transported through pipelines with reduced energy losses. Pipeline transportation is the most commonly used method due to its reliability and cost- effectiveness for large-scale operations, although alternative methods such as shipping and trucking may be used in specific scenarios [5], [14].

The utilization of captured CO_2 has gained increasing attention as it provides an opportunity to offset some of the costs associated with CCUS implementation. Carbon dioxide can be used in enhanced oil recovery, where it is injected into oil reservoirs to increase extraction efficiency, as well as in the production of chemicals, fuels, and construction materials [16]. However, the scale of CO_2 utilization is currently limited compared to the volume of emissions, making geological storage the primary option for long-term mitigation [14], [15].

Storage involves injecting carbon dioxide into deep underground formations, where it can be trapped through a combination of physical and chemical mechanisms. These include structural trapping, residual trapping, solubility trapping, and mineral trapping, each contributing to the long-term stability of stored CO_2 [14], [15]. The effectiveness of storage depends on factors such as geological conditions, reservoir characteristics, and monitoring systems, which are essential to ensure environmental safety and prevent leakage [14].

VI. CARBON CAPTURE TECHNOLOGIES

Carbon capture technologies form the foundation of CCUS systems and are broadly classified into post-combustion, pre-combustion, and oxy- fuel combustion methods, each with distinct operational principles and applications [9], [18]. Post-combustion capture is the most widely implemented approach, particularly in existing power plants, due to its ability to be retrofitted without major modifications to infrastructure [10]. This method typically involves chemical absorption processes, where solvents such as monoethanolamine selectively capture CO_2 from flue gases [10], [17]. Despite its effectiveness, the process requires significant energy for solvent regeneration, leading to increased operational costs and reduced plant efficiency [10].

Pre-combustion capture involves the gasification of fossil fuels to produce a synthesis gas composed primarily of hydrogen and carbon monoxide, which is subsequently converted into carbon dioxide and hydrogen through a water-gas shift reaction [9]. The carbon dioxide is then separated, and the hydrogen is used as a clean fuel for energy generation. This method offers higher efficiency compared to post-combustion capture but requires advanced infrastructure and is therefore more suitable for new installations rather than retrofitting existing plants [9], [18].

Oxy-fuel combustion represents another advanced capture technology, where fuel is burned in pure oxygen instead of air, resulting in a flue gas stream that consists mainly of carbon dioxide and water vapor

[18]. This simplifies the capture process, as CO_2 can be easily separated after condensation of water vapor. However, the production of pure oxygen requires energy-intensive air separation units, which increases the overall cost and complexity of the system [18].

In addition to these conventional methods, emerging technologies such as membrane separation, adsorption techniques, and cryogenic separation are being explored to improve capture efficiency and reduce costs [11], [17]. Direct Air Capture technologies, which remove CO_2 directly from ambient air, have also gained attention as a potential solution for achieving negative emissions, although they are currently limited by high energy requirements and costs [12], [13].

VII. CO_2 TRANSPORTATION SYSTEMS

The transportation of captured carbon dioxide is a critical component of CCUS systems, as it connects capture facilities with utilization or storage sites [5]. Pipelines are the most widely used method for CO_2 transportation due to their ability to handle large volumes over long distances with relatively low operational costs [5], [14]. The design of CO_2 pipelines requires careful consideration of factors such as pressure, temperature, and material compatibility to ensure safe and efficient operation [5].

In regions where pipeline infrastructure is not feasible, alternative transportation methods such as shipping, rail, and road transport may be used [5]. Shipping is particularly suitable for offshore storage projects, where CO_2 can be transported in liquefied form to injection sites [14]. However, these methods are generally more expensive and less efficient compared to pipelines, making them suitable only for specific applications.

The development of extensive CO_2 transportation networks is essential for the large-scale deployment of CCUS technologies, as it enables the integration of multiple capture sources with centralized storage facilities [4], [5]. However, the establishment of such infrastructure requires significant investment and coordination among stakeholders, which remains a major challenge for widespread implementation [4].

VIII. CO_2 UTILIZATION PATHWAYS

The utilization of captured carbon dioxide offers an opportunity to convert waste emissions into valuable products, thereby enhancing the economic viability of CCUS systems [16]. One of the most established applications of CO_2 utilization is enhanced oil recovery, where injected CO_2 increases reservoir pressure and improves oil extraction efficiency [14]. This approach not only reduces emissions but also generates economic returns, making it attractive for industries [16].

In addition to EOR, CO_2 can be used in the production of chemicals such as methanol, urea, and polymers, as well as in the synthesis of fuels through processes such as Fischer-Tropsch synthesis [16]. The use of CO_2 in the production of building materials, such as carbonated concrete, is another promising application that can contribute to emission reduction in the construction sector [16].

Despite these opportunities, the overall capacity for CO_2 utilization remains limited compared to the volume of emissions generated globally, which restricts its impact on climate mitigation [16]. Furthermore, many utilization processes require additional energy input, which may offset some of the environmental benefits [18]. Therefore, while CO_2 utilization can complement storage, it cannot fully replace it as a primary mitigation strategy [14].

IX. CO_2 STORAGE MECHANISMS

Geological storage of carbon dioxide is considered the most viable option for long-term emission reduction, as it allows large volumes of CO_2 to be securely stored underground [14], [15]. Storage sites typically include depleted oil and gas reservoirs, deep saline aquifers, and unmineable coal seams, each offering different advantages in terms of capacity and stability [14].

The trapping of CO_2 in geological formations occurs through multiple mechanisms, including structural trapping, where CO_2 is confined beneath impermeable rock layers, and residual trapping, where it is immobilized in pore spaces [14]. Solubility trapping involves the dissolution of CO_2 in formation water, while mineral trapping results in the formation of stable carbonate minerals over long periods [15].

The effectiveness of geological storage depends on site selection, reservoir characteristics, and monitoring systems to ensure long-term stability and prevent leakage [14], [15]. Advanced monitoring techniques, such as seismic imaging and pressure analysis, are used to track the movement of CO_2 and detect any potential risks [15]. Despite these measures, concerns regarding long-term safety and environmental impact remain important areas of research [14].

X. EXPANDED RESEARCH GAPS AND CHALLENGES

The implementation of CCUS technologies is hindered by several interconnected challenges that must be addressed to enable large-scale deployment [4], [18]. Economic barriers remain one of the most significant obstacles, as the high cost of capture, transportation, and storage limits the attractiveness of CCUS for industries [4]. The energy penalty associated with capture processes further exacerbates this issue by reducing overall system efficiency [1], [18].

Policy and regulatory frameworks play a crucial role in supporting CCUS deployment, but many countries lack comprehensive policies and financial incentives to encourage investment in these technologies [3], [19]. Additionally, public perception and acceptance of CO_2 storage projects can influence their implementation, highlighting the need for effective communication and stakeholder engagement [3].

Technical challenges, such as improving capture efficiency, reducing energy consumption, and ensuring safe storage, also require ongoing research and innovation [18]. The limited number of large-scale CCUS projects demonstrates the need for further demonstration and commercialization efforts to validate the technology and build confidence among stakeholders [4].

XI. SUSTAINABLE DEVELOPMENT GOALS

Carbon Capture, Utilization, and Storage contributes significantly to multiple Sustainable Development Goals by addressing environmental, economic, and social challenges associated with climate change [2], [19]. By reducing emissions from industrial sources, CCUS supports the transition to cleaner energy systems and contributes to sustainable industrial development [16].

The technology also plays a role in promoting innovation and infrastructure development, as it requires advanced engineering solutions and large-scale implementation [19]. In urban areas, CCUS can help reduce air pollution and improve environmental quality, contributing to sustainable cities and communities [3]. Most importantly, it directly supports climate action by reducing greenhouse gas emissions and enabling countries to meet their emission reduction targets [2].

XII. DISCUSSION

The role of CCUS in climate mitigation is both significant and complex, as it offers a practical solution for reducing emissions while maintaining energy security [1], [16]. However, its effectiveness depends on several factors, including technological advancements, economic feasibility, and policy support [4], [18]. While CCUS can significantly reduce emissions from industrial sources, it should be viewed as part of a broader strategy that includes renewable energy, energy efficiency, and behavioral changes [2], [19].

The integration of CCUS with emerging technologies, such as hydrogen production and renewable energy systems, presents new opportunities for enhancing its effectiveness and sustainability [19]. However, achieving large-scale deployment requires overcoming challenges related to cost, infrastructure, and public acceptance [4]. Collaborative efforts among governments, industries, and research institutions are essential to address these challenges and accelerate the adoption of CCUS technologies [2].

XIII. CONCLUSION

Carbon Capture, Utilization, and Storage represents a critical technological solution for mitigating climate change by reducing carbon dioxide emissions from industrial and energy sectors [1], [16]. While the technology has demonstrated significant potential, its widespread adoption is limited by economic, technical, and policy- related challenges [4], [18]. Addressing these challenges requires continued research, innovation, and strong policy support to improve efficiency, reduce costs, and ensure safe storage [2], [19].

In conclusion, CCUS is not a standalone solution but an essential component of a comprehensive climate mitigation strategy that includes renewable energy and sustainable practices [3]. With proper implementation and support, CCUS can play a vital role in achieving global climate goals and transitioning toward a low-carbon future [2].

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