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## Carbon Capture and Storage: A Pathway to Climate Change Mitigation

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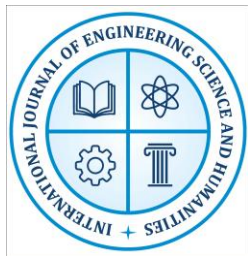
### Abstract

Carbon Capture and Storage (CCS) has emerged as a vital technological pathway in addressing the global challenge of climate change by reducing carbon dioxide (CO<sub>2</sub>) emissions from major industrial and energy sectors. As CO<sub>2</sub> remains the most significant contributor to global warming, CCS provides a mechanism to capture emissions at their source, transport them safely, and store them in deep geological formations, thereby preventing their release into the atmosphere. Unlike renewable energy expansion or afforestation, CCS specifically targets hard-to-abate sectors such as cement, steel, and chemical industries, where decarbonization options are limited. International assessments, including those of the Intergovernmental Panel on Climate Change (IPCC) and International Energy Agency (IEA), underscore that achieving net-zero targets by mid-century is unlikely without CCS integration. Despite concerns over cost, infrastructure, and public acceptance, advancements in technology and supportive policies highlight CCS as an essential complement to other mitigation strategies for a sustainable, low-carbon future.

**Keywords:** Carbon Capture and Storage (CCS); Climate Change Mitigation; Greenhouse Gas Emissions; Sustainable Energy Transition; Net-Zero Targets

### Introduction

Climate change, driven primarily by anthropogenic greenhouse gas emissions, represents one of the greatest challenges of the twenty-first century, threatening ecosystems, economies, and human well-being on a global scale. Carbon dioxide (CO<sub>2</sub>), as the most dominant long-lived greenhouse gas, accounts for the majority of emissions, largely stemming from fossil fuel combustion, industrial activities, and deforestation. Despite rapid advancements in renewable energy technologies, energy efficiency measures, and afforestation initiatives, these strategies alone remain insufficient to meet the ambitious targets of the Paris Agreement, which calls for limiting global temperature rise to well below 2°C above pre-industrial levels. In this context, Carbon Capture and Storage (CCS) has emerged as a critical pathway to complement existing mitigation strategies. CCS involves capturing CO<sub>2</sub> emissions from large point sources such as power plants and industrial facilities, transporting it through pipelines, and securely storing it in deep geological formations, thereby preventing its release into the atmosphere. Distinguished from related approaches like Carbon Capture and Utilization (CCU) or Direct Air Capture



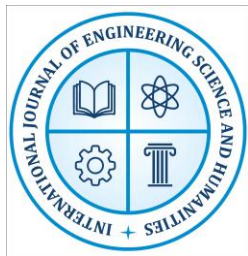
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(DAC), CCS plays a particularly important role in decarbonizing hard-to-abate sectors including steel, cement, and chemical production, where alternatives are technologically or economically limited. Reports from the Intergovernmental Panel on Climate Change (IPCC) and the International Energy Agency (IEA) emphasize that achieving net-zero emissions by mid-century will be nearly impossible without widespread deployment of CCS technologies. However, the pathway is not without challenges: high operational costs, infrastructure demands, risks of leakage, and public skepticism pose significant barriers to large-scale adoption. Nonetheless, ongoing innovations in capture techniques, supportive policies, and investments in pilot projects indicate growing global recognition of CCS as an indispensable climate mitigation tool. Therefore, analyzing the potential, limitations, and future trajectory of CCS is vital for understanding how this technology can bridge the gap between present emission realities and the urgent global imperative for a sustainable, low-carbon future.

## **Importance of CCS in Climate Mitigation**

Carbon Capture and Storage (CCS) has emerged as an indispensable strategy in the global effort to mitigate climate change, particularly because it addresses the persistent challenge of reducing carbon dioxide (CO<sub>2</sub>) emissions in hard-to-abate sectors such as steel, cement, and power generation. These industries are the backbone of modern economies but also among the largest contributors to greenhouse gas emissions, as their processes rely on high-temperature combustion and chemical reactions that inherently release CO<sub>2</sub>, making complete substitution with renewable energy or electrification extremely difficult in the near future. In this context, CCS provides a viable pathway by capturing emissions directly from industrial flue gases, transporting them via pipelines, and storing them permanently in deep geological formations, thus preventing their release into the atmosphere. Global institutions like the Intergovernmental Panel on Climate Change (IPCC) and the International Energy Agency (IEA) have repeatedly emphasized the centrality of CCS in achieving net-zero emission targets by mid-century, noting that without its deployment, the cost of mitigation would rise significantly and the 1.5–2°C temperature stabilization goal would become virtually unattainable. IPCC assessments highlight scenarios where CCS accounts for capturing billions of tons of CO<sub>2</sub> annually, while IEA's net-zero roadmap estimates that around 15% of cumulative emission reductions by 2050 will depend on CCS, especially for sectors where alternatives remain limited or prohibitively expensive. From an economic perspective, while CCS is often criticized for its high upfront costs, ongoing advancements in capture technologies, economies of scale, and integration with carbon pricing mechanisms are steadily improving its feasibility. Technological innovations, including oxy-fuel combustion, pre-combustion capture, and post-combustion solvent-based systems, are being refined to lower energy penalties and operational costs, making CCS more attractive for



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industrial deployment. Furthermore, the development of transport and storage infrastructure, coupled with supportive regulatory frameworks and incentives, is creating an enabling environment for large-scale implementation. Beyond emissions reduction, CCS also opens avenues for negative emissions when combined with bioenergy (BECCS), offering the possibility to actively remove CO<sub>2</sub> from the atmosphere. Therefore, despite challenges of cost, infrastructure, and public acceptance, CCS stands as a critical pillar in the climate mitigation portfolio, bridging the gap between current emission trajectories and the urgent necessity of reaching net-zero, while ensuring that essential industrial processes can continue to support global development in a sustainable, low-carbon future.

## **Role of Carbon Dioxide in Climate Change**

Carbon dioxide (CO<sub>2</sub>) is widely recognized as the most dominant long-lived greenhouse gas and plays a central role in driving anthropogenic climate change because of its unique capacity to remain in the atmosphere for centuries, thereby accumulating over time and intensifying the greenhouse effect. Unlike other greenhouse gases such as methane, which although more potent has a relatively short atmospheric lifespan, CO<sub>2</sub> persists, creating a lasting warming influence that steadily disrupts the Earth's climate system. Historically, the concentration of CO<sub>2</sub> in the atmosphere remained stable for thousands of years, averaging around 280 parts per million (ppm) before the onset of industrialization, sustaining a climate balance conducive to human civilization and natural ecosystems. However, the Industrial Revolution of the late 18th century marked a turning point as widespread use of coal, followed by oil and natural gas, began to power rapid industrial growth, transportation, and electricity generation, resulting in unprecedented CO<sub>2</sub> emissions. Over time, deforestation, land-use change, and industrial processes such as cement production further contributed to rising levels of atmospheric carbon dioxide. By the mid-20th century, with post-war economic expansion and energy-intensive industrialization, emissions accelerated sharply, and today atmospheric CO<sub>2</sub> levels exceed 420 ppm—levels not experienced for at least three million years. This relentless rise has been directly linked to increasing global average temperatures, melting glaciers and ice caps, ocean acidification, sea-level rise, and more frequent extreme weather events. Projections for the future indicate that without significant and immediate interventions, CO<sub>2</sub> emissions will continue to rise in tandem with population growth, urbanization, and industrial demand, potentially surpassing 600 ppm by the end of this century. Such an outcome would correspond with global temperature increases well beyond 2°C above pre-industrial levels, a threshold identified by the Paris Agreement as critical to preventing catastrophic climate impacts. Continued emissions could also trigger feedback loops such as large-scale permafrost thaw, diminished carbon uptake by oceans and forests, and the collapse of polar ice sheets, all of which would further accelerate warming in ways that may become irreversible. Thus, the role of carbon dioxide in climate change is both



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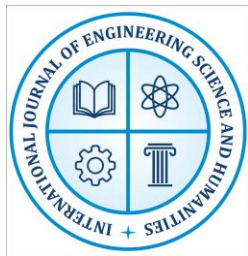
historic and predictive, underscoring not only its centrality in shaping the current climate crisis but also the urgent necessity of aggressive mitigation strategies to stabilize atmospheric concentrations and avert the most dangerous consequences of unchecked global warming.

## Literature Review

**Anderson, S., & Newell, R. (2004).** In this early and influential review, Anderson and Newell (2004) evaluate the technical, economic, and policy prospects for Carbon Capture and Storage (CCS) technologies, positioning CCS as a potentially transformative tool for reducing greenhouse gas emissions. They highlight that while CCS is technically feasible, its widespread adoption hinges on reducing high costs, developing infrastructure for capture and storage, and establishing regulatory and legal frameworks for safe long-term storage. The authors stress that CCS should not be seen as a silver bullet but as a complementary measure to renewable energy, efficiency improvements, and carbon pricing mechanisms. Importantly, they argue that successful deployment requires strong policy support, including incentives, subsidies, and emissions trading systems, to stimulate industry investment. This paper laid the groundwork for subsequent CCS research by emphasizing the integration of technological progress with political and economic structures, making it one of the foundational works on the subject.

**Plasynski et al. (2009)** provide a comprehensive overview of the progress and emerging developments in CCS, with a focus on pilot projects and research initiatives under the U.S. Department of Energy. The authors review advances in capture technologies—such as post-combustion solvent-based methods and pre-combustion gasification—while also highlighting breakthroughs in transport and geological storage. They underscore the role of regional partnerships in testing storage capacity and monitoring CO<sub>2</sub> behavior in saline aquifers and depleted oil and gas reservoirs. Importantly, the paper addresses the challenges of scaling up CCS, including energy penalties, costs, and public acceptance of underground storage safety. The authors conclude that while CCS shows promise, significant research, development, and demonstration projects are needed to build confidence in its technical viability and environmental integrity. Their work contributes by bridging scientific progress with real-world implementation, highlighting the importance of early-stage projects in advancing CCS readiness.

**Pires et al. (2011)** present a detailed overview of recent developments in CCS, emphasizing technological advances, environmental implications, and policy frameworks. They systematically discuss capture techniques—including absorption, adsorption, membranes, and cryogenic separation—evaluating their efficiency, costs, and applicability to different industrial sectors. The authors also explore storage options, such as geological formations, deep ocean



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injection, and mineral carbonation, highlighting both opportunities and environmental risks. A key strength of this work is its balanced view, recognizing CCS as a crucial tool for reducing emissions while also stressing uncertainties surrounding leakage risks, monitoring requirements, and long-term storage security. The paper also examines the role of CCS in policy frameworks, particularly in relation to carbon markets and emission reduction targets. By synthesizing technological, environmental, and political dimensions, this article provides a valuable state-of-the-art perspective on CCS at the time, serving as a reference for researchers and policymakers alike.

**Gibbins and Chalmers (2008)** provide an in-depth examination of CCS within the broader energy policy landscape, situating the technology as a necessary component of long-term climate change mitigation strategies. They focus on the integration of CCS into existing fossil-fuel-based energy systems, particularly coal-fired power plants, which represent some of the largest global sources of CO<sub>2</sub> emissions. The article discusses capture methods, transport infrastructure, and geological storage, while also analyzing cost implications and the potential for retrofitting existing plants. Importantly, the authors argue that CCS can play a transitional role in decarbonizing energy systems until renewable energy and efficiency measures become more widespread. They also highlight the policy requirements needed for CCS adoption, such as carbon pricing mechanisms and government support for pilot projects. This paper is notable for linking technological insights with policy considerations, showing how CCS can be realistically embedded in national and international energy strategies.

**Szulczewski et al. (2012)** provide a forward-looking analysis of the longevity and climate impact of CCS as a mitigation strategy. Using quantitative modeling, they assess how long CCS can remain effective given the constraints of storage capacity, leakage risks, and the global scale of emissions reduction needed. Their findings suggest that while CCS could play a crucial role in bridging the gap toward sustainable energy transitions, its lifetime as a dominant mitigation strategy is limited, making it insufficient as a standalone solution. The paper emphasizes that CCS must be deployed in conjunction with renewable energy expansion, energy efficiency, and behavioral changes to achieve meaningful long-term climate stabilization. Importantly, the authors also analyze the potential of CCS to delay climate action if over-relied upon, warning against its use as an excuse for continued fossil fuel dependency. This study adds nuance by critically evaluating CCS not just as a technology but as a temporal strategy within broader mitigation portfolios.

## Conclusion

Carbon Capture and Storage (CCS) represents a critical pathway in the global response to climate change, offering a practical solution to curb rising carbon dioxide emissions, particularly





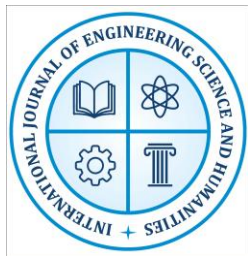
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in hard-to-abate sectors such as steel, cement, and power generation, where alternatives remain limited or technologically unfeasible. As the most dominant long-lived greenhouse gas, CO<sub>2</sub> poses an immense threat to ecological and human systems, and without urgent mitigation measures, future projections indicate catastrophic warming beyond safe thresholds. In this context, CCS complements renewable energy, energy efficiency, and afforestation by directly targeting emissions at their source and preventing their release into the atmosphere through secure geological storage. Both the Intergovernmental Panel on Climate Change (IPCC) and the International Energy Agency (IEA) underscore that achieving net-zero emissions by mid-century will be nearly impossible without large-scale CCS deployment, highlighting its indispensable role in meeting global climate goals. While challenges remain, including high implementation costs, infrastructure requirements, and public acceptance, continuous technological advancements, supportive policies, and growing investments are steadily enhancing the feasibility and scalability of CCS. Furthermore, innovations such as Bioenergy with CCS (BECCS) and integration with carbon utilization technologies expand its potential beyond mitigation to active carbon removal, strengthening its role in long-term sustainability strategies. Therefore, CCS should not be viewed in isolation but as part of a holistic climate solution portfolio, bridging the gap between current emission realities and the urgent need for decarbonization. By addressing industrial emissions that cannot be easily eliminated, CCS provides a strategic opportunity to balance development with environmental responsibility, ensuring that societies can progress toward a resilient, low-carbon future while safeguarding the planet for generations to come.

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