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Carbon Capture, Utilisation and Storage (CCUS) as a Tool for Climate Change Mitigation: Challenges and Opportunities with Sustainable Fuzzy Model

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Abstract:
Anthropogenic climate change, primarily driven by rising atmospheric carbon dioxide (CO_2) concentrations, poses a critical global challenge in the twenty-first century. Although renewable energy expansion and energy efficiency measures have progressed substantially, fossil fuels continue to dominate global energy and industrial systems. Emissions from hard-to-abate sectors such as cement, steel, chemicals, and oil refining remain significant due to both combustion processes and intrinsic industrial reactions. In this context, Carbon Capture, Utilisation and Storage (CCUS) has gained prominence as a strategic technological pathway for achieving deep decarbonisation while supporting a gradual transition to a low-carbon economy. CCUS comprises a range of technologies that capture CO_2 from industrial sources or directly from the atmosphere, transport it via pipelines or other means, and either utilise it in value-added applications or store it securely in geological formations. This study presents a comprehensive and critical assessment of CCUS, examining its technological foundations, mitigation potential, economic feasibility, environmental implications, and governance mechanisms. It identifies key barriers to large-scale deployment, including high capital and operational costs, energy penalties, infrastructure limitations, long-term storage concerns, and issues related to social acceptance. At the same time, the paper highlights emerging opportunities driven by innovation, supportive policy frameworks, industrial decarbonisation imperatives, and global net-zero commitments. The study concludes that while CCUS cannot address climate change independently, it is an essential component of an integrated mitigation strategy. Furthermore, a sustainable fuzzy logic model is proposed to evaluate CCUS across environmental, economic, technological, social, and policy dimensions, facilitating informed decision-making under uncertainty.

Keywords: *Carbon capture, carbon utilisation, geological storage, climate change mitigation, industrial decarbonisation, net-zero emissions, Fuzzy Logic, CCUS Sustainability*

1. INTRODUCTION

Climate change has emerged as a central challenge affecting global sustainability, economic progress, and overall human welfare. The persistent rise in atmospheric greenhouse gases (GHGs), particularly carbon dioxide (CO_2), has contributed to increasing global temperatures, altered rainfall patterns, rising sea levels, and a greater occurrence of extreme climatic events (IPCC, 2022). Scientific evidence strongly emphasizes that keeping global warming well below 2°C—and ideally limiting it to 1.5°C above pre-industrial levels—demands immediate, substantial, and sustained reductions in CO_2 emissions across all sectors of the global economy (IPCC, 2018).

Over the last twenty years, climate mitigation efforts have largely concentrated on scaling up renewable energy sources, enhancing energy efficiency, and accelerating electrification. Although these approaches are fundamental to reducing greenhouse gas emissions, they alone cannot deliver the level of decarbonisation required, particularly in sectors where emissions arise from inherent industrial processes or where low-carbon alternatives are not yet technologically mature or economically viable. For instance, cement manufacturing emits CO_2 through unavoidable calcination reactions, while conventional steel production depends on carbon-intensive reducing agents. Moreover, fossil-fuel-based power generation continues to underpin energy security and grid reliability across many regions, particularly in developing economies, where transitioning away from conventional fuels presents significant structural and financial challenges (IEA, 2020).

Carbon Capture, Utilisation and Storage (CCUS) has emerged as an increasingly important complementary mitigation approach, particularly for reducing emissions that cannot be effectively addressed through conventional decarbonisation strategies. The CCUS process entails capturing carbon dioxide (CO_2) from major industrial point sources or directly from ambient air, transporting it to designated utilisation or storage locations, and securely isolating it to prevent atmospheric release over extended periods. Integrated assessment models indicate that excluding CCUS from mitigation pathways would significantly escalate overall climate mitigation costs and could render stringent temperature targets difficult, if not impossible, to achieve (Rogelj et al., 2018).

However, despite its recognised strategic value, the global deployment of CCUS technologies has advanced at a comparatively slow pace. The number of operational large-scale facilities remains limited, and the current global CO_2 capture capacity falls substantially short of what is necessary to align with net-zero emission trajectories. This discrepancy underscores the urgency for a thorough and systematic evaluation of CCUS technologies, including their technical, economic, environmental, and policy-related dimensions. In response, this article presents a comprehensive review and critical assessment of CCUS, examining its mitigation potential, key barriers, and the enabling conditions required to accelerate its large-scale implementation as an effective climate change mitigation tool.

Carbon Capture, Utilisation and Storage (CCUS) is widely acknowledged as a crucial pathway for mitigating climate change; however, its large-scale implementation is constrained by technological limitations, economic viability concerns, social acceptance issues, and policy uncertainties. Addressing these multidimensional challenges requires decision-support frameworks capable of managing ambiguity and incomplete information. In this regard, integrating sustainability dimensions within a fuzzy logic–based model offers a systematic, transparent, and adaptive approach to decision-making under complex real-world conditions.

Li et al. (2025) strengthened CCUS evaluation methodologies by proposing a fuzzy optimization framework tailored for industrial parks, demonstrating that fuzzy logic effectively accommodates uncertainties related to costs, emission reductions, and system integration. Their findings underscore the applicability of fuzzy-based approaches in CCUS planning, particularly in contexts where data are imprecise, dynamic, or heterogeneous. Likewise, Mazhar et al. (2026) examined the integration of advanced materials and artificial intelligence in CCUS technologies, emphasizing the growing need for intelligent and flexible optimization models to enhance capture performance, reduce energy penalties, and improve scalability. They highlighted that adaptive decision-support tools, including fuzzy inference systems, can significantly improve model interpretability and robustness in uncertain environments.

2. CONCEPTUAL AND TECHNOLOGICAL FRAMEWORK OF CCUS

2.1 Carbon Capture Technologies

Carbon capture constitutes the most technologically demanding and financially intensive stage of the CCUS value chain. Capture technologies are broadly classified into post-combustion, pre-combustion, oxy-fuel combustion, and emerging direct air capture (DAC) systems (Bui et al., 2018). Post-combustion capture separates CO_2 from flue gases generated after fuel combustion, commonly using chemical solvents such as monoethanolamine (MEA). This method is particularly suitable for retrofitting existing power plants and industrial facilities because it requires minimal modification to core operations. However, the relatively low CO_2 concentration in flue gases and the substantial energy demand for solvent regeneration lead to significant energy penalties and elevated operational costs (Figueroa et al., 2008).

Pre-combustion capture is typically implemented in integrated gasification combined cycle (IGCC) plants and selected industrial applications. In this process, fuel is converted into synthesis gas composed primarily of hydrogen and carbon monoxide. The carbon monoxide is then shifted to produce CO_2 and additional hydrogen, allowing CO_2 to be separated prior to combustion. The resulting hydrogen serves as a low-carbon fuel. While pre-combustion systems can achieve higher capture efficiencies, they involve complex configurations and high capital investment.

Oxy-fuel combustion technology burns fuel in nearly pure oxygen rather than air, generating a flue gas composed mainly of CO_2 and water vapour, thereby simplifying CO_2 separation. Nevertheless, the need for energy-intensive air separation units increases overall system costs and energy consumption. Direct Air Capture (DAC) technologies remove CO_2 directly from ambient air and offer potential for negative emissions and flexible deployment. However, their economic viability remains constrained by high costs associated with the low atmospheric CO_2 concentration (Haszeldine, 2009).

2.2 CO_2 Transport Infrastructure

After carbon dioxide (CO_2) is captured and compressed, it must be conveyed to designated utilisation facilities or long-term storage locations. Transportation infrastructure therefore constitutes a vital link within the Carbon Capture, Utilisation and Storage (CCUS) value chain, ensuring that captured emissions are moved safely, efficiently, and economically—often across considerable distances. Pipelines remain the most established and widely deployed transport option, particularly for large-scale and continuous CO_2 flows. Decades of operational experience from enhanced oil recovery (EOR) projects, especially in North America, demonstrate that well-designed and properly regulated pipeline systems can function safely and reliably (Metz et al., 2005; Bui et al., 2018). In addition to pipelines, alternative modes such as shipping, rail, and road transport are gaining importance, particularly for smaller volumes, pilot-scale initiatives, offshore storage projects, or regions where pipeline infrastructure is limited. Shipping offers notable flexibility and scalability, making it especially attractive for cross-border CO_2 transport and emerging hub-and-cluster CCUS configurations (IEA, 2020).

However, the development of CO_2 transport systems requires substantial upfront capital investment and long-term strategic coordination, especially when integrating multiple emission sources with diverse storage sites. Shared pipeline networks and cluster-based infrastructure models are increasingly recognised as cost-effective approaches that enable economies of scale, reduce financial risk, and accelerate deployment (GCCSI, 2023). Overall, robust and well-planned CO_2 transport infrastructure is indispensable for scaling up

CCUS technologies and achieving sustained climate mitigation objectives.

2.3 Carbon Utilisation Pathways

Carbon utilisation refers to the conversion of captured carbon dioxide (CO_2) into value-added products such as fuels, chemicals, polymers, and construction materials, thereby reframing CO_2 as a resource rather than a waste stream. Within the broader Carbon Capture, Utilisation and Storage (CCUS) framework, utilisation pathways can help offset capture costs and enhance public acceptance of carbon management strategies. CO_2 is already commercially applied in beverage carbonation, urea production, and enhanced oil recovery (EOR), where injected CO_2 improves hydrocarbon extraction while enabling partial geological storage.

Emerging technological pathways focus on converting CO_2 into synthetic fuels, methanol, and other chemicals through catalytic, thermochemical, or electrochemical processes. However, these conversion routes typically require substantial energy inputs, and meaningful emission reductions depend on the use of low-carbon or renewable energy sources. Mineral carbonation represents a more permanent utilisation option, as CO_2 reacts with alkaline materials to form stable carbonates suitable for construction applications. Biological approaches, including algae-based CO_2 fixation, are also under investigation, though their large-scale deployment remains technically and economically constrained.

Despite its economic and technological promise, the climate mitigation potential of carbon utilisation depends heavily on the permanence of storage and the life-cycle emissions associated with production and end use. In many cases, utilisation leads to delayed rather than permanent CO_2 storage. Therefore, rigorous life-cycle assessment (LCA) is essential to determine net environmental benefits. Overall, carbon utilisation should be regarded as a complementary strategy that supports, but does not replace, long-term geological storage in comprehensive climate mitigation efforts.

2.4 Geological Storage of CO_2

Geological storage refers to the injection of compressed carbon dioxide (CO_2) into deep underground formations to prevent its release into the atmosphere. Typical storage sites include depleted oil and gas reservoirs, deep saline aquifers, and unmineable coal seams. These formations are chosen based on their storage capacity, porosity, permeability, caprock integrity, and overall ability to securely confine CO_2 through physical and geochemical trapping mechanisms (IPCC, 2005).

As a core element of Carbon Capture and Storage (CCS) strategies, geological storage plays a vital role in mitigating climate change by reducing large-scale industrial emissions. Once injected, CO_2 is retained through several complementary mechanisms: structural and stratigraphic trapping beneath impermeable caprocks, residual trapping within pore spaces, solubility trapping through dissolution in formation fluids, and mineral trapping via long-term geochemical reactions (Benson & Cole, 2008). These processes collectively enhance the permanence and security of storage over geological timescales.

Extensive research, field demonstrations, and operational projects—such as the Sleipner project in the North Sea—have shown that properly selected and managed storage sites can safely contain CO_2 for thousands of years (Metz et al., 2005). Effective Monitoring, Reporting, and Verification (MRV) systems are essential to ensure storage integrity, detect potential leakage, and maintain regulatory compliance and public confidence.

Although challenges remain, including uncertainties regarding long-term liability, leakage risks, and societal acceptance, current scientific assessments conclude that well-regulated geological storage provides a reliable, scalable, and long-term solution for CO_2 sequestration. Consequently, it is widely recognized as a critical pillar of global climate change mitigation efforts (IPCC, 2022).

3. ROLE OF CCUS IN CLIMATE CHANGE MITIGATION

3.1 Industrial Decarbonisation

Industrial activities contribute nearly one-quarter of global CO_2 emissions, with a considerable proportion stemming from process-related sources that cannot be mitigated solely through switching to cleaner energy (IEA, 2020). Carbon Capture, Utilisation and Storage (CCUS) represents one of the limited but practical solutions for achieving deep decarbonisation in hard-to-abate sectors such as cement, steel, and chemicals. In cement manufacturing, approximately 60% of total emissions arise from the calcination of limestone—a chemical reaction intrinsic to clinker production. CCUS technologies enable the capture of these emissions directly at their source, allowing significant emission reductions without requiring fundamental changes to existing production systems. Comparable opportunities are evident in steel manufacturing, particularly when CCUS is integrated with hydrogen-based production pathways.

Industrial decarbonisation involves the systematic reduction of greenhouse gas emissions from energy-intensive industries—including cement, steel, chemicals, and oil refining—which together account for nearly one-quarter of global CO_2 emissions (IEA, 2020). Unlike emissions from the power sector, industrial emissions result from both fossil fuel combustion and unavoidable chemical processes, making mitigation more complex. Major strategies for reducing industrial emissions include enhancing energy efficiency, electrifying processes with renewable power, switching to low-carbon fuels such as hydrogen and biomass, and deploying CCUS technologies (IPCC, 2022).
Among these approaches, CCUS is particularly vital for managing process emissions that cannot otherwise be eliminated, especially in cement and steel production. Emerging solutions, including green hydrogen-based steelmaking and circular economy models, offer additional decarbonisation potential but demand significant infrastructure investment and supportive policy frameworks. Integrated assessment modelling indicates that postponing industrial decarbonisation would substantially raise the overall cost of meeting global climate goals (Rogelj et al., 2018). Therefore, comprehensive policy alignment, technological advancement, and international collaboration are crucial to accelerating industrial transformation while preserving economic competitiveness and advancing sustainable development objectives.

3.2 Power Sector Applications

Despite the rapid growth of renewable energy, fossil-fuel-based power generation remains a major component of electricity systems in many parts of the world. Power plants equipped with Carbon Capture, Utilisation and Storage (CCUS) technologies can deliver dispatchable, low-carbon electricity, thereby complementing intermittent renewable sources and strengthening grid stability (Bui et al., 2018). The power sector continues to be one of the largest contributors to global carbon dioxide (CO_2) emissions because of its sustained dependence on coal and natural gas. In this context, CCUS provides a practical and scalable solution for substantially reducing emissions from coal- and gas-fired power plants while preserving energy security and system reliability. By capturing CO_2 from flue gases before they are released into the atmosphere, CCUS systems can reduce emissions by up to 90%, aligning fossil-based electricity generation with long-term climate mitigation objectives (Bui et al., 2018).

CCUS becomes particularly significant in electricity systems with high shares of variable renewable energy sources such as wind and solar. Fossil-fuel plants fitted with CCUS can operate flexibly, supplying reliable backup power to manage fluctuations in renewable output (IEA, 2020). Additionally, retrofitting existing facilities with post-combustion capture technologies extends the lifespan of current infrastructure while significantly lowering its carbon intensity. Integrated assessment models further suggest that excluding CCUS from decarbonization pathways in the power sector would markedly increase the overall cost of achieving net-zero emissions, underscoring its strategic relevance (IPCC, 2022). Consequently, CCUS in the power sector functions as an essential transitional and complementary strategy within a diversified, low-carbon energy framework.

3.3 Negative Emissions and Net-Zero Pathways

Most net-zero emission pathways depend on negative emission technologies (NETs) to counterbalance residual emissions from hard-to-abate sectors such as agriculture, aviation, and certain industrial activities. While rapid and deep emission reductions remain essential, integrated assessment models indicate that mitigation efforts alone are insufficient to eliminate all greenhouse gas emissions by mid-century. Residual emissions from sectors with limited decarbonization options necessitate large-scale carbon dioxide (CO_2) removal from the atmosphere, making NETs a critical pillar of credible net-zero strategies (IPCC, 2018).

NETs encompass a range of approaches, including bioenergy with carbon capture and storage (BECCS), direct air capture with carbon storage (DACCS), afforestation and reforestation, and enhanced weathering. Among these, BECCS and DACCS feature prominently in climate mitigation scenarios because they offer the potential for substantial and durable CO_2 removal when integrated with secure geological storage systems (Rogelj et al., 2018). As a result, carbon capture, utilization, and storage (CCUS) technologies play a dual role—not only reducing emissions at source but also enabling long-term carbon removal.

However, large-scale deployment of NETs presents considerable challenges. High capital and operational costs, significant energy demands, land and water resource constraints, and uncertainties surrounding long-term sustainability, environmental impacts, and governance frameworks all limit their immediate scalability. Therefore, most policy analyses stress that negative emissions should supplement—not substitute—ambitious near-term emission reductions (IEA, 2021). Achieving global net-zero greenhouse gas emissions by mid-century will thus require a balanced and integrated approach that combines aggressive mitigation efforts with carefully governed and strategically deployed carbon removal technologies to ensure an equitable and sustainable climate transition.

4. CHALLENGES IN CCUS DEPLOYMENT

4.1 Economic and Financial Barriers

High capital and operating expenditures continue to represent the primary obstacles to the large-scale deployment of Carbon Capture, Utilisation, and Storage (CCUS). Among the various components, carbon capture technologies are the most costly, often determining the overall feasibility of projects. In the absence of strong carbon pricing mechanisms or targeted financial incentives, many CCUS initiatives struggle to attain commercial viability (IEA, 2020). The substantial upfront investments required for capture systems, transportation networks, and secure long-term storage facilities create significant financial barriers. Notably, capture units alone may constitute nearly 70% of total project costs, largely due to energy-intensive separation processes and the requirement for advanced materials and specialised equipment (Bui et al., 2018).

In addition to high capital expenditure, CCUS projects face limited and uncertain revenue streams. The economic value of captured CO_2 depends heavily on utilisation markets, which remain relatively small and underdeveloped. Consequently, insufficient demand for CO_2-derived products generates uncertainty regarding long-term financial returns (Boot-Handford et al., 2014). Operational challenges further compound these issues, as carbon capture processes impose energy penalties that reduce plant efficiency and increase ongoing fuel and maintenance costs (Figueroa et al., 2008).

Financial risks are amplified by policy instability and the absence of consistent carbon pricing frameworks across many regions. Without predictable support mechanisms—such as carbon credits, tax incentives, or direct subsidies—private investors are often hesitant to commit to large-scale CCUS projects (GCCSI, 2023). These economic and financial constraints highlight the urgent need for coherent policy support, stable regulatory environments, and strengthened market mechanisms to enhance the commercial viability and scalability of CCUS technologies.

4.2 Energy Penalties

The additional energy required for CO_2 capture and compression lowers the overall efficiency of power plants and industrial installations. This so-called energy penalty increases fuel consumption and operating costs and may partially offset the emissions reductions achieved. The large-scale deployment of Carbon Capture, Utilisation and Storage (CCUS) is therefore constrained by substantial economic and efficiency-related challenges. A major barrier is the high capital and operational expenditure associated with capture technologies, which often renders CCUS financially unattractive in the absence of carbon pricing mechanisms or government subsidies (Bui et al., 2018). Capture systems—particularly solvent-based technologies such as amine scrubbing—demand significant upfront investment, continuous solvent regeneration, and intensive maintenance, all of which elevate total project costs compared to conventional energy systems (Figueroa et al., 2008).

Beyond financial constraints, the energy required to capture, compress, and transport CO_2 further reduces net plant performance. In post-combustion systems, the capture process alone can consume approximately 20–30% of a power plant's generated output, thereby lowering efficiency and increasing the levelised cost of electricity (Haszeldine, 2009). Additional energy is also needed for CO_2 compression and pipeline transport, adding to the overall system burden and potentially generating indirect upstream emissions (Boot-Handford et al., 2014). These intertwined cost and energy penalties underscore the necessity for technological advancements, improved process integration, and robust policy support to enhance the commercial and environmental viability of CCUS as a long-term climate mitigation solution.

4.3 Storage Risks and Liability

Concerns regarding potential CO_2 leakage and long-term liability present significant technical, environmental, and regulatory challenges for Carbon Capture, Utilisation and Storage (CCUS) systems. Ensuring the long-term security of stored CO_2 and clearly defining responsibility over extended timescales remain central issues in the large-scale deployment of CCUS (Metz et al., 2005). Geological storage typically involves injecting captured CO_2 into deep saline aquifers, depleted oil and gas reservoirs, or other suitable subsurface formations. Although these formations are selected for their capacity and containment properties, the risk of CO_2 migration through faults, fractures, or improperly sealed abandoned wells raises concerns about groundwater contamination, ecosystem impacts, and induced seismicity (Metz et al., 2005; Haszeldine, 2009). The inherent complexity and heterogeneity of subsurface geology further increase uncertainty regarding storage integrity over decades to centuries.

In addition to technical risks, regulatory and legal uncertainties complicate CCUS implementation. In many jurisdictions, existing frameworks do not adequately clarify long-term liability once a storage site is decommissioned. Ambiguities persist regarding whether responsibility for post-closure leakage rests with the project operator, the state, or another designated authority. Such uncertainty can discourage private investment, delay permitting processes, and increase financial risk for project developers (IEA, 2020).

To address these challenges, governments must establish comprehensive monitoring, reporting, and verification (MRV) systems alongside clear liability-transfer mechanisms that ensure environmental protection while maintaining commercial viability. Transparent governance structures and well-defined legal frameworks are essential to reduce risk perceptions, build public trust, and facilitate the broader adoption of CCUS technologies—particularly in regions where subsurface resource governance systems are still evolving.

4.4 Infrastructure and Scale Constraints

The absence of integrated transport and storage infrastructure remains a major constraint on the large-scale deployment of Carbon Capture, Utilisation, and Storage (CCUS) technologies. Effective implementation of CCUS requires coordinated networks that connect multiple industrial CO_2 sources to appropriate geological storage reservoirs or utilisation facilities. However, establishing such interconnected systems demands substantial capital investment, strategic long-term planning, and consistent policy support (Metz et al., 2005). In many regions, transport and storage infrastructure is either fragmented or entirely lacking, limiting the practical feasibility of deploying CCUS across industrial hubs. Moreover, the development of CO_2 pipelines frequently faces technical, environmental, and regulatory challenges, including land acquisition issues, safety compliance requirements, and concerns about ecological impacts (Bui et al., 2018).

Scale-related constraints further hinder CCUS expansion. Major CO_2 emission sources are often geographically dispersed, necessitating distributed capture facilities supported by extensive transport networks. Early-stage CCUS projects typically operate at limited capacities, restricting the economies of scale required to reduce overall capture and transport costs (IEA, 2020). Additionally, geological storage sites have finite capacities, and their uneven spatial distribution may create regional bottlenecks, preventing optimal utilisation of capture infrastructure. Addressing these challenges requires coordinated policy frameworks, shared or hub-based infrastructure models, and comprehensive regional planning to facilitate cost-effective, large-scale CCUS integration within existing industrial and energy systems (GCCSI, 2023).

4.5 Social Acceptance

Public resistance to CO_2 storage initiatives has led to the postponement or cancellation of several projects. Establishing public trust through transparent communication, meaningful stakeholder involvement, and strong regulatory oversight is therefore crucial for achieving social acceptance (Haszeldine, 2009). The large-scale implementation of Carbon Capture, Utilisation, and Storage (CCUS) depends not only on technological readiness but also on the development of comprehensive infrastructure and public support. A functional CCUS system includes CO_2 capture facilities, compression technologies, transportation networks—primarily pipelines—and secure geological storage sites. The establishment of such infrastructure demands substantial capital investment and coordinated collaboration among industries, policymakers, and financial stakeholders to optimise network design and reduce overall costs (Bui et al., 2018). In this context, shared pipeline systems and hub-and-cluster configurations are increasingly viewed as practical strategies to lower expenses and enable multiple emission sources to connect efficiently to common storage facilities (GCCSI, 2023).

Equally important is the societal dimension of CCUS deployment. Public apprehensions typically revolve around safety concerns, the possibility of CO_2 leakage, and the environmental implications of long-term storage (Haszeldine, 2009). Research indicates that early engagement with local communities, transparent dissemination of information, and inclusive decision-making processes significantly strengthen public confidence and minimise resistance (Dowd et al., 2014). Emphasising potential local economic advantages—such as employment generation and regional industrial development—can further enhance acceptance. Additionally, well-defined regulatory frameworks that address liability, ensure continuous monitoring, and incorporate effective risk management mechanisms are essential to align technical feasibility with societal approval (IPCC, 2022). In summary, the successful advancement of CCUS requires a balanced strategy that combines efficient infrastructure development with proactive measures to secure long-term public trust and legitimacy.

5. OPPORTUNITIES AND EMERGING TRENDS

Carbon Capture, Utilisation, and Storage (CCUS) technologies are increasingly recognized as an essential strategy for reducing anthropogenic CO_2 emissions, particularly in hard-to-abate industries such as cement, steel, chemicals, and power generation (Bui et al., 2018). Although renewable energy capacity has expanded significantly, fossil fuels continue to dominate the global energy mix, underscoring the need for complementary decarbonisation approaches. In this context, CCUS offers a viable pathway to achieve substantial emission reductions while ensuring energy reliability and industrial continuity (IEA, 2020).

Recent progress in advanced materials, process optimization, and digital monitoring systems has improved the technical and economic viability of CCUS technologies. These developments have opened new avenues for large-scale industrial decarbonisation, the generation of negative emissions, and alignment with circular carbon economy frameworks (Boot-Handford et al., 2014; Haszeldine, 2009). This section therefore examines emerging opportunities for CCUS implementation, reviews current technological innovation trends, and evaluates their broader implications for climate change mitigation.

5.1 Technological Innovation

Advances in capture materials, process integration, and digital monitoring are reducing costs and improving performance. Novel solvents, solid sorbents, and membrane technologies show promise for next-generation capture systems (Boot-Handford et al., 2014).

5.2 Advanced Capture Materials

A major limitation of Carbon Capture, Utilisation and Storage (CCUS) has been the substantial energy demand and high operational costs associated with conventional post-combustion capture systems (Figueroa et al., 2008). In response, advanced materials such as solid sorbents, metal–organic frameworks (MOFs), and ionic liquids have emerged as promising alternatives for enhancing CO_2 capture efficiency while lowering energy penalties (Samanta et al., 2012). Solid sorbents, particularly amine-functionalised silica materials, exhibit strong CO_2 selectivity and require less energy for regeneration than traditional aqueous amine solutions. MOFs, characterized by tunable pore structures and exceptionally high surface areas, enable efficient gas adsorption and improved capture performance at relatively lower temperatures (Li et al., 2021). Similarly, ionic liquids demonstrate high chemical stability and negligible volatility, contributing to improved separation efficiency and operational safety. Collectively, these material innovations create new opportunities to retrofit existing power plants and industrial facilities with more energy-efficient CCUS technologies, thereby reducing overall system costs and enhancing economic feasibility.

5.3 Membrane and Hybrid Systems

Membrane-based CO_2 separation has gained significant attention as an efficient alternative to traditional chemical absorption techniques. Both polymeric and inorganic membranes enable selective separation of CO_2 from flue gases while generally requiring lower energy input compared to solvent-based systems (Baker et al., 2019). To improve overall performance, hybrid configurations integrating membrane technology with adsorption or solvent processes are increasingly being developed. Such integrated systems enhance capture efficiency, support large-scale deployment, and offer modular designs suitable for industrial clusters. Moreover, these hybrid approaches have the potential to lower the operational costs associated with Carbon Capture, Utilisation and Storage (CCUS) (Boot-Handford et al., 2014).

5.4 Direct Air Capture (DAC)

Direct Air Capture (DAC) technologies, designed to extract CO_2 directly from ambient air, are increasingly recognized as a promising approach for delivering negative emissions. Despite their high energy requirements, ongoing advancements in sorbent materials, system integration, and the use of renewable energy sources are enhancing both operational efficiency and economic feasibility (Keith et al., 2018). A key advantage of DAC is its location flexibility, as it can operate independently of point emission sources, thereby supporting net-zero objectives and mitigating residual emissions from hard-to-abate sectors.

6. OPPORTUNITIES FOR CCUS DEPLOYMENT

6.1 Industrial Decarbonisation

Technological advancements in Carbon Capture, Utilisation and Storage (CCUS) provide a viable route for reducing emissions in energy-intensive industries. For instance, incorporating advanced capture systems in cement manufacturing facilities can effectively mitigate process-related emissions from calcination reactions, which cannot be eliminated solely through fuel switching or energy substitution (IEA, 2020). In the steel sector, integrating CCUS with hydrogen-based reduction technologies can substantially lower CO_2 emissions while sustaining production efficiency. The deployment of next-generation CCUS solutions thus enables industries to preserve output and competitiveness while progressing toward national and global climate objectives.

6.2 Enhanced Carbon Utilisation

Recent advances in technology have significantly broadened the scope of carbon utilisation pathways. Captured CO_2 can now be transformed into synthetic fuels, value-added chemicals, and construction materials, thereby generating new revenue opportunities and lowering the overall cost burden of CCUS initiatives (Bui et al., 2018). Among these approaches, mineralisation processes—where CO_2 reacts with alkaline substances to produce stable carbonate compounds—provide durable storage solutions while simultaneously yielding commercially viable building materials. Such innovations promote the development of a circular carbon economy by re-framing CO_2 from an environmental liability into a productive resource (Samanta et al., 2012).

6.3 Integration with Renewable Energy Systems

Integrating Carbon Capture, Utilisation and Storage (CCUS) with renewable energy technologies improves overall system efficiency and long-term sustainability. For example, carbon capture operations can be driven by renewable electricity or by utilizing waste heat recovered from industrial activities, thereby lowering the emissions associated with the capture process itself (Li et al., 2021). In addition, pairing Direct Air Capture (DAC) systems with renewable energy sources enables the achievement of negative emissions without reinforcing reliance on fossil fuels, thereby contributing to climate resilience and facilitating a cleaner energy transition.

6.4 Negative Emissions and Climate Targets

Technological advancements in Carbon Capture, Utilisation and Storage (CCUS) play a vital role in enabling negative emission pathways that are essential for meeting ambitious climate goals, including limiting global warming to 1.5°C and achieving net-zero emissions, as emphasized by the Intergovernmental Panel on Climate Change (2018). Approaches such as Bioenergy with Carbon Capture and Storage (BECCS) and Direct Air Capture (DAC) are increasingly recognized as promising methods for actively removing CO_2 from the atmosphere. Continued innovation aimed at enhancing capture efficiency, minimizing energy requirements, and reducing operational costs is critical to scaling up these technologies and facilitating their widespread deployment.

7. DIGITALISATION AND MONITORING INNOVATIONS

Technological advancements in CCUS are increasingly centered on digitalization, automation, and process optimization. The integration of IoT-enabled sensors, AI-based predictive maintenance systems, and real-time data analytics significantly improves operational efficiency, safety, and the integrity of CO_2 storage (Haszeldine, 2009). The development of digital twins for CCUS facilities enables virtual simulation and performance optimization of capture, transportation, and storage operations, thereby enhancing energy efficiency and lowering operational costs. Robust monitoring and verification systems are particularly vital for geological storage to ensure the long-term containment of CO_2 and adherence to regulatory standards. Techniques such as advanced seismic imaging, pressure monitoring systems, and satellite-based surveillance provide continuous assessment and long-term assurance of storage security and environmental safety (Boot-Handford et al., 2014).

8. SUSTAINABLE FUZZY MODEL: CARBON CAPTURE, UTILISATION AND STORAGE (CCUS)

Recent scholarship increasingly recognizes Carbon Capture, Utilisation and Storage (CCUS) as a pivotal strategy for achieving global climate mitigation goals, particularly within net-zero emission frameworks. Nevertheless, the large-scale deployment of CCUS remains constrained by economic volatility, technological maturity gaps, inconsistent policy environments, and challenges related to public acceptance. These complexities highlight the need for integrated decision-support systems capable of addressing uncertainty and multi-criteria evaluation simultaneously.

From a socio-economic and governance standpoint, Sovacool et al. (2024) investigated CCUS within European industrial decarbonization pathways and identified critical barriers such as fragmented governance structures, limited public trust, and uneven policy incentives. Their findings stress the necessity of embedding social legitimacy and policy coherence as core components of sustainability assessment models. Similarly, Eze et al. (2024) examined CCUS adoption across African energy systems and concluded that regional diversity in institutional capacity and market structures requires adaptable and context-sensitive evaluation frameworks.

El-Meligi and Nabawy (2025) further noted that atmospheric CO_2 removal and storage technologies involve inherent trade-offs among efficiency, economic cost, and potential environmental risks. This reinforces the limitation of deterministic assessment approaches and supports the application of soft computing techniques. In this regard, fuzzy logic-based models offer a practical mechanism for converting qualitative expert judgments and uncertain data into quantifiable sustainability indicators.

Despite these contributions, much of the existing literature remains fragmented, concentrating separately on technological optimization, regulatory analysis, or material advancements. There is a clear lack of a comprehensive sustainability framework that synthesizes these dimensions. Addressing this gap, the proposed Sustainable Fuzzy CCUS Model integrates environmental performance, economic viability, technological readiness, social acceptance, and policy support within a unified fuzzy inference system. By consolidating multidisciplinary insights, the model delivers a transparent, flexible, and decision-oriented approach for evaluating CCUS pathways under uncertainty, thereby advancing and operationalizing prior research in a holistic manner.

8. 1. Conceptual Framework of the Sustainable Fuzzy CCUS Model

The proposed Sustainable Fuzzy CCUS Model (SF-CCUS) integrates environmental, economic, technological, and social dimensions under uncertainty using fuzzy logic. CCUS performance is evaluated by converting qualitative expert judgments and quantitative indicators into fuzzy linguistic variables, enabling realistic sustainability assessment where crisp data are insufficient.

Model Structure

- Inputs (Fuzzy Variables): Sustainability dimensions of CCUS
- Fuzzy Inference System (FIS): Rule-based evaluation
- Output: Overall CCUS Sustainability Index (CCUS-SI)

8. 2. Input Variables and Linguistic Terms

A. Environmental Sustainability (E)

Indicators:

- CO_2 capture efficiency
- Net emission reduction
- Storage leakage risk

Linguistic terms:

- {Low, Medium, High}

B. Economic Feasibility (EC)

Indicators:

- Capital cost
- Operational cost
- Cost per tonne CO_2 captured

Linguistic terms:

- {Poor, Moderate, Good}

C. Technological Maturity (T)

Indicators:

- Technology Readiness Level (TRL)
- Energy penalty
- Scalability

Linguistic terms:

- {Emerging, Developing, Mature}

D. Social Acceptance (S)

Indicators:

- Public perception
- Regulatory support
- Community risk perception

Linguistic terms:

- {Low, Medium, High}

E. Policy & Institutional Support (P)

Indicators:

- Carbon pricing
- Incentives/subsidies
- Legal framework

Linguistic terms:

- {Weak, Moderate, Strong}

8. 3. Fuzzy Membership Functions

Triangular membership functions are used for simplicity and transparency.

For any variable x:

$$\mu(x;a,b,c)=\begin{cases}0, & x\leq a\\ x\text{-}a/\ b\text{-}a, & a<x\leq b\\ c\text{-}x/\ c\text{-}b, & b<x<c\\ 0, & x\geq c\end{cases}$$

Where:

- a = lower bound
- b = peak value
- c = upper bound

8.4. Fuzzy Rule Base (Examples)

The sustainability of CCUS is inferred using IF–THEN rules derived from expert knowledge.

Sample Rules

1. **IF** Environmental Sustainability is *High*
   AND Economic Feasibility is *Good*
   AND Technology is *Mature*
   THEN CCUS Sustainability is *Very High*
2. **IF** Economic Feasibility is *Poor*
   AND Energy Penalty is *High*
   THEN CCUS Sustainability is *Low*
3. **IF** Social Acceptance is *Low*
   AND Policy Support is *Weak*
   THEN CCUS Sustainability is *Very Low*

8.5. Fuzzy Inference Mechanism

- **Inference Method:** Mamdani-type FIS
- **AND Operator:** Minimum (min)
- **OR Operator:** Maximum (max)

$\mu_{rule}=\min(\mu_E,\mu_{EC},\mu_T,\mu_S,\mu_P)$

8.6. Defuzzification

The Centroid method is used to obtain a crisp sustainability score:

CCUS-SI = $\int z.\ \mu(z)\ dz\ /\ \int \mu(z)\ dz$

Where:

CCUS-SI € [0, 1]

8.7. Interpretation of CCUS Sustainability Index

CCUS-SI Value	Sustainability Level
0.00–0.20	Very Low
0.21–0.40	Low
0.41–0.60	Moderate
0.61–0.80	High
0.81–1.00	Very High

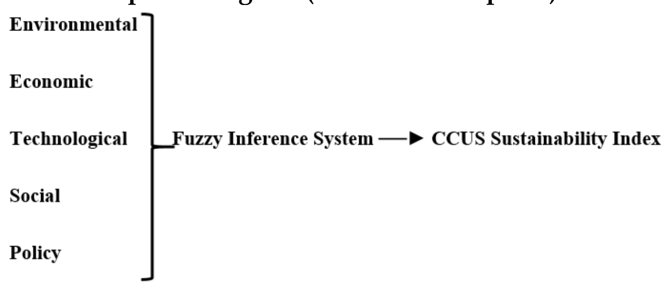
8.8. Model Applications

- Comparative evaluation of post-combustion, pre-combustion, DAC, and BECCS
- Policy prioritization under uncertainty
- Regional CCUS feasibility assessment (India, EU, Global South)
- Integration with net-zero pathway modelling

8.9. Advantages of the Sustainable Fuzzy CCUS Model

- Handles uncertainty and subjectivity
- Integrates multi-dimensional sustainability
- Supports transparent decision-making
- Adaptable to regional and sectoral contexts

8.10. Conceptual Diagram (Textual Description)



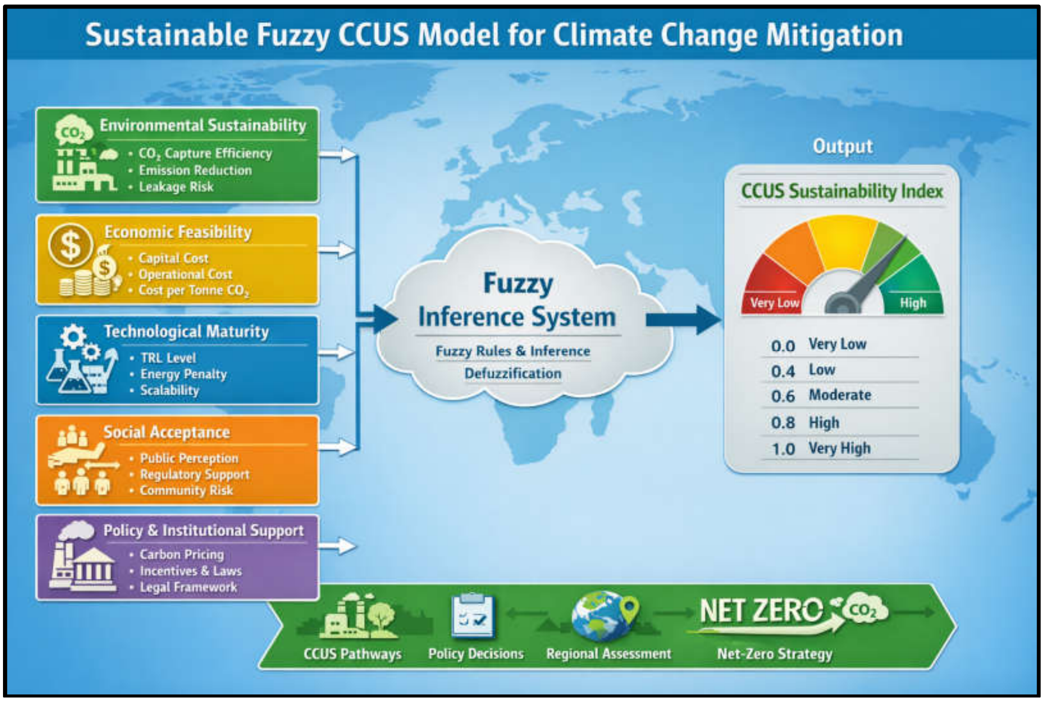


Figure 2: Sustainable Fuzzy CCUS Model for Climate Change Mitigation

8.11 Previous published work

Year	Authors	Title	Source / Journal	Key Focus
2025	Zhiwei Li, Chao Wang, Ziting Ge, et al.	*A fuzzy optimization approach to carbon capture and utilization in industrial parks*	*Energy*	Introduces fuzzy MINLP model to optimize CO_2 integration balancing cost and emissions in industrial CCUS systems.
2025	A. A. El-Meligi & B. S. Nabawy	*Challenges of CO_2 removal from the atmosphere by capturing, storage, and utilization…*	*J. Umm Al-Qura Univ. Appl. Sci.*	Reviews atmospheric CO_2 capture, utilisation, storage challenges for climate change.
2026	S. Mazhar, M. W. Mumtaz, M. El Oirdi, et al.	*Synergizing advanced materials and artificial intelligence for next-generation CCUS*	*RSC Advances*	Reviews advanced materials and AI/ML integration to enhance CCUS efficiency and sustainability.
2024	Benjamin K. Sovacool, Dylan F. Del Rio, et al.	*Reconfiguring European industry for net-zero: hydrogen and CCUS benefits & challenges*	*Energy & Environmental Science*	Qualitative review on CCUS deployment, barriers, and socio-economic impacts in industrial contexts.
2024	Val Hyginus Udoka Eze, Wisdom O. Okafor, Foday H. Bawor	*Integration of carbon capture utilization and storage into sustainable energy policies in Africa*	*Oxford Open Energy*	Analyses CCUS within energy policy frameworks in Liberia, linking mitigation and policy support.

9. POLICY AND MARKET OPPORTUNITIES

Technological innovation by itself cannot ensure the large-scale deployment of Carbon Capture, Utilisation and Storage (CCUS) without enabling policy support. Effective policy instruments—such as carbon pricing mechanisms, tax credits, and targeted market incentives—are critical to accelerating CCUS adoption and enhancing the commercial feasibility of emerging technologies (GCCSI, 2023). Well-designed policy frameworks facilitate the development of industrial clusters where shared CO_2 transport and storage infrastructure can significantly reduce operational costs and generate economies of scale.

Simultaneously, expanding demand for low-carbon products and sustainable construction materials is creating new market opportunities. Firms that invest in CCUS technologies can strengthen their competitive position, improve corporate sustainability performance, and meet rising investor expectations related to climate accountability (Bui et al., 2018). Strengthened climate policies—including carbon pricing systems, fiscal incentives such as tax credits, and mechanisms like contracts for difference—are progressively improving the investment landscape for CCUS (GCCSI, 2023).

A comprehensive governance framework is equally essential to ensure responsible and effective deployment. This includes clear regulations governing site selection, monitoring and verification, long-term liability, and stakeholder engagement. Furthermore, international collaboration plays a vital role in facilitating knowledge exchange, lowering technology costs, and supporting implementation in developing and emerging economies (IPCC, 2022).

Overall, policy and market drivers—anchored in carbon pricing, regulatory support, fiscal incentives, and expanding low-carbon markets—collectively enhance the economic viability of CCUS. Growing global climate commitments and evolving carbon utilisation pathways further stimulate private-sector investment, thereby accelerating large-scale deployment as part of long-term sustainable climate mitigation strategies.

10. CHALLENGES TO ADOPTION OF INNOVATIVE CCUS TECHNOLOGIES

High capital investment, substantial energy demand, inadequate infrastructure, and concerns over public acceptance continue to impede the large-scale deployment of Carbon Capture, Utilisation and Storage (CCUS) technologies. Advanced capture materials, Direct Air Capture (DAC) systems, and integrated hybrid configurations involve considerable upfront expenditure, which can restrict their uptake, particularly in cost-sensitive regions (Figueroa et al., 2008). Moreover, several capture approaches—especially DAC—are highly energy-intensive and must be coupled with low-carbon energy sources to ensure both environmental integrity and economic feasibility (Keith et al., 2018). The expansion of CCUS at scale further relies on the development of extensive pipeline systems, transportation infrastructure, and secure storage facilities, which remain underdeveloped in many emerging economies (Metz et al., 2005). In addition, societal concerns related to the long-term safety of CO_2 storage and potential environmental risks may delay or obstruct project execution (Haszeldine, 2009). Consequently, overcoming these constraints through continued technological advancement, enabling policy frameworks, financial incentives, and effective stakeholder engagement is critical to unlocking the full mitigation potential of CCUS technologies.

11. FUTURE TRENDS IN CCUS INNOVATION

Most pathways aligned with climate targets anticipate a significant contribution from Carbon Capture, Utilisation and Storage (CCUS) by mid-century. Achieving large-scale deployment will depend on long-term policy support, continuous technological advancement, robust infrastructure expansion, and broad societal acceptance. Rather than replacing renewable energy, CCUS functions as a critical complement within an integrated decarbonisation framework. Recent innovations emphasize modular CCUS designs, enabling phased expansion and smoother integration with existing industrial systems. Such modular configurations help lower upfront capital risks, shorten implementation timelines, and allow customization to regional industrial and energy conditions (Bui et al., 2018).

CCUS also plays a pivotal role in advancing hydrogen as a low-carbon energy carrier. Through pre-combustion capture during hydrogen production—particularly from natural gas reforming—substantial emissions reductions can be achieved. In turn, hydrogen utilisation in electricity generation and industrial applications provides additional pathways for deep decarbonisation (IEA, 2020). Furthermore, the integration of artificial intelligence (AI) and machine learning techniques is enhancing CCUS performance by improving capture optimization, ensuring storage site integrity, and enabling predictive maintenance. These digital tools contribute to lower operational costs and strengthen the long-term safety and reliability of CCUS systems (Boot-Handford et al., 2014).

12. CONCLUSION

CCUS technologies, strengthened by advances in capture materials, process optimisation, digital monitoring systems, and innovative utilisation pathways, offer substantial potential for mitigating climate change. Ongoing technological progress is lowering operational costs, enhancing capture efficiency, and broadening applicability across industrial and power-generation sectors. In addition, CCUS developments facilitate negative emissions, support industrial decarbonisation, and contribute to the transition toward a circular carbon economy. Despite persistent challenges—such as high energy intensity, infrastructure limitations, and issues of public acceptance—robust policy frameworks, targeted market incentives, and sustained research and development efforts can significantly accelerate large-scale deployment. Continuous innovation will be pivotal in realising the full potential of CCUS as a key instrument for achieving net-zero emissions and addressing the global climate crisis.

Carbon Capture, Utilisation and Storage constitutes a vital component of global climate mitigation strategies. By tackling emissions from hard-to-abate industries and enabling pathways for negative emissions, CCUS addresses critical gaps in conventional mitigation approaches. Although barriers remain, growing technological innovation, increasing policy commitment, and the urgency of climate action are reinforcing its strategic importance. A comprehensive and integrated strategy—combining CCUS with renewable energy expansion, energy efficiency improvements, and behavioural transformation—is essential to ensure long-term climate stability and sustainable development. Furthermore, the sustainable fuzzy CCUS model offers a comprehensive decision-support framework that incorporates environmental, economic, technological, social, and policy uncertainties. By converting qualitative assessments into measurable sustainability indices, the model enhances transparency in evaluating CCUS options and facilitates evidence-based policy and investment decisions for effective climate change mitigation.

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