International Journal of Multidisciplinary Research and Growth Evaluation.

Energy Transition and the Dynamics of Carbon Capture, Storage, and Usage Technology

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Article Info

ISSN (Online): 2582-7138
Impact Factor (RSIF): 7.98
Volume: 03
Issue: 04
July - August 2022
Received: 09-05-2022
Accepted: 10-06-2022
Published: 25-06-2022
Page No: 724-738

Abstract

In the face of accelerating climate imperatives and intensifying decarbonization goals, this study offers a comprehensive examination of carbon mitigation systems, with a focus on their evolving roles within global energy transitions and sustainable industrial strategies. The inquiry is structured around a critical analysis of technological development, sectoral readiness, policy frameworks, lifecycle sustainability, and integration into circular economic models. Anchored in a multidisciplinary methodology, the study synthesizes insights from engineering, environmental policy, innovation systems, and socio-economic governance to assess the viability and long-term contribution of these systems to net-zero trajectories.

The research highlights that while considerable advancements have been made in capture, storage, and utilization technologies, large-scale deployment remains hindered by infrastructural, financial, and institutional constraints. Notable progress is evident in the digital transformation of monitoring systems, the valorization of carbon into marketable commodities, and the alignment of emission reduction strategies with nationally determined contributions (NDCs). Additionally, life cycle assessments reveal mixed outcomes, reinforcing the need for context-specific evaluations and long-term sustainability planning.

Conclusions drawn from this study affirm that the strategic implementation of these technologies must be accompanied by coherent policy instruments, transparent risk governance, and enhanced public engagement. Their success depends on cross-sector collaboration and the ability to embed carbon management within a broader innovation and sustainability framework. Recommendations emphasize the urgency of investment in research and infrastructure, regulatory harmonization, and the development of integrated industrial systems that treat carbon not as waste, but as a resource.

This study thus offers a compelling case for the repositioning of carbon control technologies as central components of resilient, forward-looking economies. By bridging technological capacity with policy design and industrial transformation, it charts a critical pathway for meeting both environmental and economic imperatives in a carbon-constrained future.

DOI: https://doi.org/10.54660/.IJMRGE.2022.3.4.724-738

Keywords: Carbon Management, Sustainability, Energy Transition, Circular Economy, Policy Frameworks, Technological Advancement

1. Introduction

The global urgency to combat climate change has intensified the transition from fossil-fuel-based energy systems to cleaner, low-carbon alternatives. At the heart of this transformation is the challenge of decarbonizing sectors where electrification or renewables alone are insufficient. Carbon Capture, Storage, and Usage (CCSU) technologies have emerged as a key pillar of global decarbonization strategies, especially in hard-to-abate industries such as cement, steel, chemicals, and fossil-based energy systems (English & English, 2022). CCSU refers to a suite of technologies that capture carbon dioxide emissions from industrial processes or directly from the atmosphere, store them in geological formations, or repurpose them for productive uses such as enhanced oil recovery or synthetic fuels.

The increasing role of CCSU in energy policy stems from its potential to address legacy emissions and stabilize atmospheric CO_2 levels. Lau *et al*. (2021) assert that CCSU is indispensable for achieving net-zero targets, particularly because it offers both transitional and long-term pathways for emission mitigation. While renewable energy and energy efficiency form the core of sustainable energy strategies, they are often insufficient alone to eliminate emissions from high-temperature industrial processes or to compensate for emissions already in the atmosphere. In this regard, CCSU serves both as a complementary and enabling technology in the decarbonization ecosystem.

The relevance of CCSU is not limited to its technical capabilities—it is increasingly shaped by geopolitical, regulatory, and market dynamics. Countries with abundant fossil fuel resources or high industrial emissions are particularly inclined to explore CCSU as a tool for emissions reduction while maintaining energy security and economic growth. For instance, Dalei and Joshi (2022) explored the application of CCSU in Indian oil refineries, revealing that matching capture sources with storage and usage potential can significantly reduce operational carbon footprints and enhance energy system efficiency. Similarly, Dike (2020) emphasized that Nigeria, rich in hydrocarbon resources, could leverage CCSU technologies to align fossil fuel use with global climate targets, provided it adopts a legal and regulatory framework that supports deployment.

Despite these prospects, the implementation of CCSU faces significant hurdles, particularly regarding economic viability, infrastructure readiness, and social acceptance. The capital-intensive nature of CCSU infrastructure—especially pipelines, injection wells, and long-term monitoring systems—presents major financial and logistical challenges (Ibrahim, Ghazali & Rahman, 2015). However, the increasing alignment between CCSU and green financing models has begun to shift this narrative. Recent climate finance mechanisms and carbon pricing schemes, such as those developed under Article 6 of the Paris Agreement, offer economic incentives for CCSU adoption.

The scientific and technical community has been instrumental in advancing CCSU technologies, with innovations in absorbents, membranes, and storage techniques significantly enhancing the efficiency and applicability of carbon capture systems. As Dalei and Joshi (2022) observe, aligning CCSU with practical applications such as enhanced oil recovery demonstrates the potential for refining these technologies to deliver both environmental and economic benefits. Moreover, machine learning and AI-driven modeling have improved forecasting. Advancements in reservoir simulation and monitoring techniques have strengthened the credibility and transparency of CCSU operations. However, significant knowledge gaps persist, particularly regarding the long-term integrity of storage sites and the comprehensive assessment of lifecycle environmental impacts. As Burk and Miner (2020) suggest in the broader context of data-driven innovation, continuous research, coupled with large-scale demonstration projects, is essential to bridge the gap between experimental advances and practical field deployment, ensuring that CCSU evolves into a robust and trusted climate solution.

A transformative aspect of CCSU lies in its contribution to circular carbon economies. Unlike traditional models centred solely on storage, the integration of carbon utilisation (CCU) enables captured carbon to be repurposed into commercially valuable products, thereby creating new value chains. This approach not only mitigates emissions but also fosters industrial sustainability and competitiveness. Captured carbon can, for example, be converted into low-carbon materials, synthetic fuels, or polymers, advancing innovation in sustainable manufacturing. Nevertheless, as Ramakrishna *et al*. (2022) emphasise, rigorous life cycle assessments and strong regulatory oversight are essential to ensure that such pathways deliver genuine and lasting environmental benefits.

The geopolitical dimensions of CCSU deployment merit careful consideration. While technologically advanced economies currently lead in CCSU research and innovation, developing nations could benefit substantially from early adoption if supported with appropriate financial and technological assistance. As Wyns, Khandekar, and Groen (2019) note in the broader context of international climate governance, cross-border cooperation, capacity building, and knowledge sharing are vital to scaling such technologies globally. Moreover, multilateral institutions play a central role in establishing governance structures, standards, and best practices that can guide the equitable and effective integration of CCSU into future low-emission pathways.

It is important to note that public perception and societal acceptance play critical roles in CCSU deployment. Resistance from local communities over perceived risks—such as groundwater contamination or induced seismicity—can hinder projects, despite their technical soundness. Thus, transparent communication, community engagement, and participatory decision-making are critical to ensuring that CCSU projects gain legitimacy and public trust (English & English, 2022).

This study aims to examine the interplay between global energy transitions and the evolution of Carbon Capture, Storage, and Usage (CCSU) technologies. Specifically, it seeks to understand how CCSU can support deep decarbonization pathways while addressing technical, policy, and economic constraints. The objective is to provide a comprehensive review of CCSU's historical development, current applications, innovation trends, and governance mechanisms, framed within the broader context of a just and sustainable energy transition. The scope of this review includes CCSU applications in power generation, industry, and negative emissions technologies, as well as the policy instruments, risk considerations, and life-cycle assessments that shape their long-term viability.

2. The Dynamics of CCSU in the Context of Energy Transition

As global energy systems face increasing pressure to decarbonize, Carbon Capture, Storage, and Usage (CCSU) technologies have emerged as an indispensable component of climate mitigation strategies. Their appeal lies not only in their ability to reduce point-source carbon emissions from fossil-fuel-based facilities but also in their potential to serve as a transitional bridge to a net-zero future. In this context, the dynamics of CCSU are being shaped by evolving scientific advancements, energy policy landscapes, economic feasibility considerations, and geopolitical realities (Lau *et* *al*., 2021).

CCSU technologies operate at the intersection of energy production and climate stewardship. At their core, these systems capture carbon dioxide (CO_2) from large stationary sources such as power plants, industrial facilities, or directly from the atmosphere through direct air capture, then transport it to sites for storage or repurpose it for industrial applications (English & English, 2022). While CCSU was once seen as a marginal technology, the rising urgency of emissions reduction targets has brought it into the mainstream of energy policy dialogues across both developed and developing economies (Dalei & Joshi, 2022).

One of the defining features of CCSU within the energy transition framework is its versatility. Unlike renewables, which primarily displace fossil fuels, CCSU technologies complement existing energy infrastructure, enabling emissions mitigation without requiring full systemic overhauls. This feature is particularly relevant in fossil-fuel-dependent regions, where abrupt transitions could disrupt energy access and economic stability (Ibrahim, Ghazali & Rahman, 2015). For these regions, CCSU offers a pathway to decarbonize without abandoning vital domestic industries.

The deployment of CCSU is particularly significant in addressing the challenge of “residual emissions,” which remain even under scenarios of extensive renewable energy adoption. Hard-to-abate sectors such as cement, steel, fertiliser, and chemical production generate emissions that cannot be fully mitigated through electrification or fuel switching alone. As Wyns, Khandekar, and Groen (2019) emphasise, innovative governance and technological frameworks are essential to enable CCSU to act as a critical backstop, capturing and storing carbon where alternative decarbonisation measures prove insufficient.

In examining the current landscape of CCSU, policy and governance play a pivotal role. Regulatory frameworks and fiscal incentives have historically been limited or inconsistent, leading to underinvestment in CCSU infrastructure. However, several jurisdictions are now implementing comprehensive CCSU strategies. The UK's CCS Infrastructure Fund and the U.S. 45Q tax credit are prime examples of how targeted incentives can catalyze development (Dike, 2020). Furthermore, integrating CCSU into Nationally Determined Contributions (NDCs) under the Paris Agreement signals a growing global consensus on its necessity.

Technological innovation has been central to the advancement of CCSU, with breakthroughs in absorbent materials, membrane separation, and pressure swing adsorption significantly improving both cost-effectiveness and energy efficiency. At the same time, pathways for carbon utilisation are expanding, enabling captured carbon to be transformed into fuels, chemicals, and low-carbon materials. Such developments enhance the economic viability of CCSU while shifting its role from a model of carbon disposal toward one of carbon valorisation, aligning with broader efforts to foster sustainable and competitive industrial systems (Ramakrishna *et al*., 2022).

Life cycle and systems thinking perspectives have become critical in evaluating CCSU’s role within community-scale and industrial-scale energy systems. Kotagodahetti *et al*. (2021) argue that considering life cycle environmental impacts is essential in ensuring that CCSU deployment genuinely contributes to emissions mitigation without creating new ecological or social burdens. Their findings emphasize the importance of integrating CCSU into broader circular economy frameworks, where captured carbon becomes a resource rather than waste.

Despite these strengths, CCSU faces enduring criticisms, particularly concerning its economic viability and the risk of prolonging fossil fuel dependency. Critics argue that CCSU may delay the shift toward renewables by offering polluting industries a technological justification to continue operations (English & English, 2022). This perspective is particularly relevant in regions where fossil fuel interests heavily influence policy frameworks. Nevertheless, Terlouw *et al*. (2021) argue that carbon management technologies and renewable energy systems are not inherently conflicting but rather complementary components of a diversified energy strategy that must address both supply- and demand-side imperatives.

There are also significant regional disparities in CCSU development. High-income nations have led in research, demonstration, and policy frameworks, while many low- and middle-income countries face barriers in terms of financing, infrastructure, and capacity. Dalei and Joshi (2022) underscore the importance of strategic matching between CO_2 sources and sinks, particularly in resource-constrained regions. Their research on Indian oil refineries suggests that geographic clustering and integrated planning can improve CCSU project efficiency and scalability.

Socio-political dynamics further influence the adoption of CCSU. Public perception of carbon storage—particularly concerns about leakage and induced seismicity—can derail projects, even when scientifically validated. As such, community engagement and transparent communication are critical. Dike (2020) highlights that trust deficits in governance can hinder CCSU development, especially in countries where regulatory oversight is weak. Hence, building public trust must go hand in hand with technical readiness.

Another important dynamic is the increasing incorporation of CCSU into urban and decentralized energy systems. Kotagodahetti *et al*. (2021) discuss the potential for on-site CCSU in community energy models such as district heating networks. These applications allow for localized carbon management, reducing transmission and storage complexities, while also creating opportunities for innovation at the municipal level.

Global cooperation is indispensable for accelerating the deployment of CCSU. As the technology advances, international standards and knowledge-sharing platforms will be crucial for harmonising practices and ensuring CCSU’s effective contribution to global climate goals. Wyns, Khandekar, and Groen (2019) highlight the importance of transnational partnerships in enhancing technical capacity, mobilising finance for large-scale projects, and developing coherent governance frameworks. Such collaborations are particularly critical for the Global South, where future emissions growth is projected to be most significant and where international support will determine the pace and scale of CCSU adoption.

2.1. Foundations and Strategic Importance of CCSU

Carbon Capture, Storage, and Usage (CCSU) has become an essential cornerstone in the contemporary discourse on climate change mitigation and energy transition. As global economies confront the challenge of decarbonizing complex energy systems without jeopardizing energy security, CCSU emerges as a uniquely positioned technological framework—capable of both stabilizing atmospheric carbon levels and ensuring continuity in high-emission industries (Rackley, 2017). The foundation of CCSU lies in its adaptability: it provides mitigation pathways for legacy emissions, facilitates emissions-neutral energy production, and enables strategic re-use of carbon, offering nations a balanced approach between climate ambition and economic pragmatism.

At its core, CCSU encapsulates the integrated process of capturing CO_2 at point sources such as power plants and industrial facilities, transporting it to storage sites, and either sequestering it in geological formations or converting it into useful products. This tri-fold approach—capture, transport, and utilization/storage—positions CCSU as a multifaceted climate solution. Lau *et al*. (2021) assert that the inclusion of CCSU in decarbonization portfolios is not optional but essential, especially for hard-to-abate sectors like cement, steel, and petrochemicals, where direct electrification or renewable substitution remains technically limited or prohibitively expensive.

The strategic importance of CCSU is further amplified by its potential role in delivering negative emissions, particularly when coupled with bioenergy (BECCS) or direct air capture (DAC). As English and English (2022) discuss, scenarios outlined by the Intergovernmental Panel on Climate Change (IPCC) show that without widespread CCSU deployment, meeting the goals of the Paris Agreement becomes not just improbable but nearly impossible. Thus, CCSU is not a peripheral tool in the energy transition—it is a foundational pillar necessary for bridging the emissions gap while other technologies mature.

Governmental and institutional endorsements reinforce CCSU's perceived value. For example, the U.S. Department of Energy's CarbonSAFE initiative aims to commercialize CCSU through large-scale demonstration projects, showcasing its scalability and feasibility across various geologic and industrial contexts (Sullivan *et al*., 2020). These initiatives underline the fact that CCSU is no longer merely a theoretical model—it is a proven technology entering maturity, bolstered by supportive regulatory structures and evolving financial mechanisms.

Yet, CCSU's importance is not uniform across geographies. Its role is deeply contextual, often shaped by national energy structures, resource availability, and policy environments. In resource-rich countries like Nigeria and India, where fossil fuels dominate energy production and exports, CCSU is framed as a transition enabler rather than a replacement tool. Terlouw *et al*. (2021) emphasize that strategic deployment of carbon removal technologies can support continued use of fossil resources in emerging economies, provided such systems are designed to decouple economic expansion from emissions through region-specific integration of capture, transport, and storage infrastructure. This approach can leverage economies of scale and operational efficiencies, particularly in industrial clusters where CO_2 sources and sinks are geographically aligned.

The legitimacy of CCSU is increasingly linked to its integration within circular economy principles. Rather than focusing solely on carbon sequestration, emerging approaches emphasise the conversion of CO_2 into valuable products such as synthetic fuels, building materials, and polymers. This shift reframes CCSU from being a cost-intensive mitigation tool into a potential revenue-generating industrial pathway. As Wyns, Khandekar, and Groen (2019) argue, embedding innovation and market-oriented applications into climate governance is essential for ensuring the long-term economic viability of CCSU, particularly in resource-constrained emerging economies.

Policy frameworks also underscore CCSU's foundational role in national energy transitions. Singapore's national strategy explicitly incorporates CCSU within its decarbonization roadmap for the chemicals and industrial sectors, with government studies projecting significant emissions reductions through CCSU implementation by 2050 (Srivastav *et al*., 2021). These forward-looking policies signal a paradigm shift: CCSU is no longer viewed as a last-resort technology but as a core component of modern climate governance.

Nevertheless, realizing the strategic potential of CCSU depends heavily on infrastructure readiness and cross-sectoral collaboration. Rackley (2017) argues that while technological readiness is advancing, infrastructural and market integration lag. CCSU projects often require multi-stakeholder coordination—including utilities, transportation companies, regulators, and local communities—which adds complexity and delays. Establishing hubs and clusters, where multiple emitters can share capture, transport, and storage infrastructure, represents a pragmatic step forward in scaling deployment.

The strategic importance of CCSU is also reflected in the shifting energy investment portfolios of major economies. Lau *et al*. (2021) observe that investors are increasingly drawn to CCSU ventures due to their alignment with environmental, social, and governance (ESG) criteria and climate risk disclosures. In this sense, CCSU offers not just technical and environmental value but reputational and financial advantages for industries seeking to future-proof their operations in a carbon-constrained economy.

Furthermore, foundational credibility in CCSU is derived from its demonstrable performance in large-scale pilot projects and real-world applications. From Norway's Sleipner project to the United States' Petra Nova facility, CCSU has proven operational viability under commercial and regulatory conditions. Sullivan *et al*. (2020) emphasize that such case studies provide empirical validation and offer blueprints for replication and scale.

Finally, CCSU aligns with broader global justice concerns by offering a flexible mitigation tool for diverse economies. It accommodates a pluralistic approach to decarbonization, recognizing that countries will follow different transition paths depending on their socio-economic realities. In this regard, CCSU provides a strategic bridge that ensures no nation is left behind in the global climate effort (English & English, 2022).

2.2. Technological Evolution of CCSU

The technological evolution of Carbon Capture, Storage, and Usage (CCSU) has followed a trajectory shaped by decades of scientific inquiry, policy shifts, and commercial feasibility trials. As global decarbonization goals intensify, CCSU technologies have undergone significant refinement to meet emerging industrial and environmental demands. From rudimentary absorption systems to highly integrated capture and conversion platforms, the evolution of CCSU is marked by three distinct technological pillars: capture techniques, transport logistics, and storage or utilization pathways (Van Alphen, Noothout & Hekkert, 2010).

The earliest CCSU technologies were built upon post-combustion capture methods, primarily using amine-based solvents to extract CO_2 from flue gas. This approach was initially developed within chemical engineering sectors and repurposed for emission reduction in thermal power generation. Over time, the field expanded to include pre-combustion techniques, which remove carbon dioxide before combustion through gasification and reforming processes, offering higher capture efficiency. Rackley (2017) outlines how pre-combustion capture is particularly suited for hydrogen and synthetic fuel production, aligning with long-term energy transition goals.

A third pathway, oxy-fuel combustion, entails burning fossil fuels in an oxygen-rich environment rather than in air, producing a flue gas primarily composed of CO_2 and water vapour, which simplifies the capture process. While this technology is less mature compared to other carbon capture approaches, it offers notable efficiency benefits under specific conditions. However, as Bertone *et al*. (2018) observe in the context of retrofit challenges, its wider application is constrained by the high costs of oxygen production and the technical complexity associated with retrofitting existing systems.

The most transformative addition to the capture landscape has been Direct Air Capture (DAC), a technology that removes CO_2 directly from ambient air. While still in its infancy in terms of deployment, DAC represents a breakthrough in achieving negative emissions—particularly when coupled with geological storage. Qiu and Liu (2018) emphasize that DAC has shifted the strategic value of CCSU from a mitigation tool for large emitters to a universal climate solution applicable across sectors and regions.

Transport technologies within CCSU have evolved in parallel, focusing on pipeline networks and, to a lesser extent, shipping. In many industrial clusters, shared pipeline infrastructure has become the backbone of CCSU hubs, lowering costs through economies of scale. Van Alphen, Noothout, and Hekkert (2010) argue that the co-location of emitters and storage sites accelerates commercial deployment by minimizing logistical hurdles. However, in regions with complex geography or low population density, the transport component remains a critical bottleneck.

Storage technologies have also witnessed substantial development. Early projects relied on depleted oil and gas reservoirs, which provided existing infrastructure and geological data. However, saline aquifers have emerged as a more scalable and long-term option. These formations offer vast storage potential, although they demand extensive site characterization and monitoring to ensure containment integrity. Ibrahim, Ghazali, and Rahman (2015) suggest that a key milestone in CCSU evolution has been the advancement of subsurface imaging and monitoring technologies, such as seismic surveys and pressure mapping, which mitigate the risk of CO_2 leakage.

Utilization technologies, the “U” in CCSU, have transformed the discourse around carbon as a liability to one of opportunity. While early CCSU models focused predominantly on storage, recent innovations allow captured carbon to be converted into fuels, chemicals, and building materials. Dalei and Joshi (2022) discuss how Enhanced Oil Recovery (EOR) was one of the earliest commercial applications of CCSU, but today, electrochemical and catalytic conversion methods enable the transformation of CO_2 into methanol, polymers, and even protein feedstock. These usage pathways not only offset capture costs but also incentivize broader adoption through market integration.

The role of digital technologies in CCSU's evolution cannot be overstated. With the integration of machine learning, artificial intelligence, and big data analytics, CCSU systems now benefit from real-time monitoring, predictive maintenance, and optimization of capture rates. Jaya (2021) notes that digitization has elevated the performance of CCSU infrastructure, improving safety, reducing energy penalties, and enhancing the economic profile of these systems.

A significant development in CCSU has been the evolution from isolated pilot initiatives to regional cluster models. In these configurations, multiple emitters utilise shared infrastructure for capture, transport, and storage, thereby achieving greater cost efficiency and simplifying regulatory oversight. As Bertone *et al*. (2018) note in relation to collaborative retrofit strategies, such coordinated approaches can unlock economies of scale and streamline implementation. Examples from industrial hubs like the U.S. Gulf Coast and the Port of Rotterdam demonstrate how CCSU clusters, supported by public-private partnerships, foster risk-sharing, technological spillover, and large-scale industrial decarbonisation.

International collaboration and open innovation have also propelled CCSU's evolution. Knowledge-sharing platforms, demonstration grants, and international standards have ensured that emerging markets benefit from early lessons and established best practices. Rackley (2017) asserts that multilateral efforts, such as those facilitated by the Carbon Sequestration Leadership Forum (CSLF), have played a critical role in aligning technological progress with policy and finance mechanisms.

Despite this progress, challenges remain. The high energy intensity of current capture processes, particularly solvent regeneration, continues to hinder efficiency. Similarly, scalability issues persist, especially for utilization technologies, which are often limited by reaction kinetics and product purity requirements (Qiu & Liu, 2018). Nevertheless, the technological evolution of CCSU is characterized by adaptive learning and cross-sectoral integration—a trend likely to accelerate as climate imperatives intensify.

2.2.1. Sectoral Deployment and Industry Readiness

The deployment of Carbon Capture, Storage, and Usage (CCSU) technologies has gained significant traction across energy-intensive sectors, with industry-specific readiness levels shaped by technological maturity, regulatory alignment, and economic feasibility. As the climate crisis accelerates the urgency for deep decarbonization, industries such as power generation, cement, steel, oil refining, chemicals, and hydrogen production are increasingly integrating CCSU into their operational strategies. These sectors collectively contribute a substantial share of global CO_2 emissions, making their participation in CCSU both critical and strategic.

Power generation, particularly from fossil-fuel-based plants, remains the most mature domain for CCSU deployment. The sector benefits from relatively high concentrations of CO_2 in flue gases and the presence of established transport and storage infrastructure in several regions. Kearns, Liu, and Consoli (2021) observe that the technology readiness level (TRL) for post-combustion carbon capture in power plants is among the highest, especially where amine-based absorption has been extensively piloted. However, commercial uptake remains uneven, often hampered by policy uncertainties and high capital costs. Ibrahim, Ghazali, and Rahman (2015) point out that in developing nations, the economic viability of CCSU in the power sector depends on state-backed incentives or international financing frameworks.

In the cement industry, CCSU addresses one of the most challenging forms of industrial emissions: process emissions from calcination. These emissions are intrinsic to clinker production and cannot be abated by energy efficiency or fuel switching alone. Rackley (2017) highlights that CCSU remains the only viable pathway to decarbonize cement production at scale, yet sectoral deployment is still in its nascent stages. The European Union and countries like Norway have launched demonstration projects at integrated cement plants, testing oxy-fuel and calcium looping technologies. Nonetheless, the lack of standardized capture solutions and site-specific constraints continues to limit widespread adoption.

The steel sector illustrates the complexity of industrial decarbonisation. While hydrogen-based reduction holds significant long-term potential, CCSU offers a more immediate mitigation pathway for existing blast furnace operations. Pre-combustion capture in integrated mills and post-combustion retrofits in electric arc furnaces are technically viable, though they demand substantial capital investment. As Ramakrishna *et al*. (2022) note, progress in adopting low-carbon materials and technologies is evident through pilot initiatives in regions such as East Asia and Europe, yet the broader scalability of these approaches will depend on effective carbon pricing mechanisms and coordinated infrastructure development.

Oil refining stands out for its comparatively advanced CCSU integration, particularly through enhanced oil recovery (EOR) applications. As Dalei and Joshi (2022) explain, refineries offer high-purity CO_2 streams, especially from hydrogen production units and fluid catalytic cracking processes. This makes them ideal candidates for early CCSU deployment. In India, for instance, strategic alignment between refinery clusters and geological storage basins has allowed for efficient source-sink mapping, a prerequisite for commercial readiness. However, reliance on EOR raises concerns about net climate benefits, as some carbon is re-emitted during oil production cycles.

The chemical sector—including ammonia, methanol, and ethylene production—also exhibits high technical compatibility with CCSU. Many of these processes generate concentrated CO_2 streams that are amenable to capture with minimal energy penalties. Kearns, Liu, and Consoli (2021) identify the sector as one of the most promising for CCSU expansion, noting that retrofits are often less disruptive than in other industries. Nevertheless, market conditions, volatile commodity prices, and the absence of circular carbon regulations pose challenges for full-scale implementation.

Emerging industries such as low-carbon hydrogen production are increasingly incorporating CCSU as a core element. The concept of "blue hydrogen" refers to hydrogen produced through processes like steam methane reforming (SMR) or autothermal reforming (ATR), combined with CCSU to lower life-cycle emissions significantly. As Noussan *et al*. (2020) explain, policy frameworks in regions such as the European Union and North America are progressively recognising blue hydrogen as a transitional fuel. Industrial readiness is strengthened by the maturity of SMR technologies and the growing alignment between hydrogen strategies and broader carbon management objectives.

Despite these advances, cross-sectoral deployment remains uneven, influenced by local resource availability, infrastructure, and policy support. In some regions, the absence of geological storage options or CO_2 transport networks constrains deployment, even when capture technologies are ready. Rackley (2017) notes that sectoral readiness must therefore be viewed not only through a technological lens but as a function of entire CCSU value chains, including capture, transport, storage, and verification systems.

Moreover, sectoral deployment strategies increasingly reflect a hub-based model, wherein multiple emitters co-locate and share infrastructure. This approach reduces costs and increases system resilience. Ibrahim, Ghazali, and Rahman (2015) emphasize that in Malaysia and similar economies, creating industrial carbon clusters could accelerate deployment by pooling risks and lowering the barriers to entry for smaller firms.

Stakeholder alignment is pivotal to advancing industry readiness for CCSU deployment. Effective collaboration among technology providers, asset owners, regulators, and financiers is essential to mobilise resources and scale up implementation. As Ramakrishna *et al*. (2022) emphasise, partnerships and cross-sector alliances are increasingly shaping decarbonisation pathways, with joint ventures emerging as critical mechanisms for developing shared CCSU infrastructure and accelerating the transition toward low-carbon industrial systems.

2.3. Policy Instruments, Market Structures, and Governance

The implementation of carbon capture, storage, and usage (CCSU) technologies is deeply intertwined with the evolution of supportive policy instruments, coherent market structures, and transparent governance frameworks. Given the capital-intensive nature of CCSU infrastructure and the long time horizons for return on investment, government intervention through well-calibrated instruments is essential to de-risk the sector and drive private investment. In the absence of robust policy and regulatory frameworks, the pace of CCSU deployment remains sluggish and geographically fragmented (Bui *et al*., 2018).

Carbon pricing instruments, such as emissions trading systems (ETS) and carbon taxes, have become critical in enhancing the economic feasibility of CCSU initiatives. By internalising the external costs of CO_2 emissions, they improve the relative competitiveness of CCSU compared to unabated fossil fuel use. As noted by Dey, Dash, and Mandal (2022), sufficiently high carbon prices can enable CCSU to approach cost parity with alternative mitigation options, particularly within emissions-intensive sectors. However, persistent challenges—including market volatility, uneven regional adoption, and weak regulatory enforcement—undermine investor confidence and slow large-scale deployment, reflecting broader constraints in policy capacity to drive transformative innovation (McLaren and Kattel, 2022).

Beyond pricing mechanisms, direct subsidies, tax credits, and feed-in tariffs are frequently employed to accelerate early-stage CCSU adoption. For instance, in the United States, the Section 45Q tax credit offers up to $50 per tonne of CO_2 stored, creating a stable revenue stream for project developers. Ibrahim, Ghazali, and Rahman (2015) argue that in Southeast Asia, subsidy-based models are especially effective given limited domestic carbon markets. Nonetheless, these subsidies must be carefully targeted to avoid market distortion and ensure long-term fiscal sustainability (Meadowcroft & Langhelle, 2009).

Market structures exert a significant influence on the trajectory of CCSU deployment. Centralized utility models with vertically integrated operations are generally better equipped to manage the financial and operational risks associated with CCSU than liberalized energy markets. According to Misra, Grimes, and Rogers (2020), factors such as market concentration and entry barriers shape the distribution of CCSU investments, with larger firms more capable of leveraging economies of scale. By contrast, fragmented markets tend to experience underinvestment due to coordination challenges and limited collective action among stakeholders—a pattern also reflected in wider assessments of energy and carbon capture policies (Pouran *et al*., 2022).

Public-private partnerships (PPPs) and consortium-based models have become important mechanisms for addressing the challenges of CCSU deployment. By enabling cost-sharing, risk mitigation, and the exchange of technological expertise across sectors, these collaborative arrangements enhance both efficiency and scalability. As Mahgerefteh *et al*. (2022) note in their discussion of CO_2 utilisation infrastructure, integrated industrial hubs—where multiple emitters share transport and storage systems—illustrate the benefits of such cooperative frameworks. Nonetheless, these hubs necessitate robust regulatory oversight to ensure clear allocation of liability, adherence to operational standards, and the safeguarding of fair competition.

Governance is a cornerstone of effective CCSU deployment, requiring the careful balancing of stakeholder interests, the establishment of robust accountability mechanisms, and the assurance of long-term policy coherence. As Dey, Dash and Mandal (2022) highlight, cross-sectoral regulatory frameworks are essential for aligning environmental, energy, and industrial objectives. Such coordination is particularly critical in cases where CCSU initiatives extend across jurisdictions or depend on transboundary CO_2 transport infrastructure, underscoring the need for integrated and transparent governance structures (Bui *et al*., 2018).

Transparent permitting processes, performance monitoring, and liability frameworks are foundational to good governance. The risk of CO_2 leakage, for instance, necessitates stringent long-term monitoring protocols and financial assurance mechanisms. Hetti and Kaumadi (2020) argue that without clearly defined post-closure responsibilities, stakeholders may underinvest in storage integrity and risk mitigation, ultimately compromising environmental and public trust outcomes. Importantly, governance must extend to public engagement and inclusion. Community opposition to CO_2 storage projects, often driven by fears of leakage or inadequate consultation, can derail even technically viable initiatives. Ibrahim, Ghazali, and Rahman (2015) highlight that in Malaysia, public misperceptions of CCSU risk were exacerbated by opaque project design and exclusionary decision-making. Transparent stakeholder processes and science-based communication are thus critical components of the broader governance apparatus (Meadowcroft & Langhelle, 2009).

Finally, global cooperation and the harmonisation of standards are essential to scaling CCSU in alignment with international climate objectives. A major barrier remains the lack of universally recognised accounting rules for captured carbon, which limits its integration into global carbon markets. As Mahgerefteh *et al*. (2022) emphasise, standardisation is critical not only for enabling cross-border CCSU projects but also for ensuring the fungibility of carbon credits and their consistency with the transparency framework of the Paris Agreement.

2.4. Barriers to Effective CCSU Implementation

The implementation of carbon capture, storage, and usage (CCSU) technologies is encumbered by a suite of technical, economic, regulatory, and societal barriers that vary across regions and sectors. While CCSU holds promise as a pivotal tool in the global decarbonization strategy, its deployment is still constrained by foundational hurdles that stem not from the absence of theoretical potential but from the interplay of systemic deficiencies within the climate governance and industrial ecosystems.

A major challenge to the large-scale deployment of CCSU is the relative immaturity and high cost of current technologies. While advances have been made in areas such as solvent regeneration, capture efficiency, and integration with industrial processes, many CCSU systems remain confined to pilot or demonstration stages, particularly in developing markets. As Dey, Dash and Mandal (2022) note, the capital requirements for full-chain CCSU infrastructure—covering capture, transport, and storage—are substantial and often prohibitive for small and medium-sized enterprises. In addition, operational costs are compounded by the high energy demand of capture processes, frequently referred to as the "energy penalty," which can diminish overall system efficiency by as much as 25%.

The lack of robust regulatory and financial frameworks further exacerbates the challenge. While some countries have instituted subsidies and tax incentives, the absence of uniform carbon pricing mechanisms or legally binding emissions reduction mandates undermines the long-term bankability of CCSU projects. Dalei and Joshi (2022) argue that without credible carbon markets or tax credits at scale, the private sector remains reluctant to assume the high financial risks involved. Additionally, the liability for long-term CO_2 storage—particularly in geological formations—remains legally ambiguous in many jurisdictions. These regulatory voids disincentivize investment in permanent storage and post-closure monitoring systems.

Infrastructure limitations also serve as a critical impediment. CCSU requires a complex logistical network to transport captured carbon from emission sources to storage or utilization sites. In many regions, the absence of CO_2 pipeline networks or proximity to suitable geological reservoirs renders deployment infeasible. Terjanika and Pubule (2022) note that while some industrial hubs have begun developing integrated CCSU infrastructure, these remain isolated examples rather than replicable models. This geographic disconnect between CO_2 emitters and storage basins raises the cost and complexity of implementation, particularly in landlocked or fragmented territories.

Public perception and societal acceptance constitute another non-trivial barrier. Misconceptions about the safety and efficacy of CO_2 storage, as well as general mistrust of industrial-scale carbon management, have led to community-level resistance in several high-profile projects. Hetti and Kaumadi (2020) emphasize the crucial role of life-cycle thinking and stakeholder engagement in overcoming these challenges. Their study demonstrates that participatory project design and transparent communication strategies can build trust and reduce resistance, especially in contexts where land rights and environmental justice are prominent concerns.

A further obstacle to effective CCSU implementation is the widespread knowledge and skills gap within both public and private institutions. The technical sophistication of CCSU requires specialised expertise in areas such as geochemistry, thermodynamics, regulatory compliance, and systems integration. However, as Dey, Dash, and Mandal (2022) observe, workforce preparedness remains limited, particularly in developing contexts where educational curricula and industrial training have not kept pace with technological advancements. This deficiency not only constrains operational efficiency but also hampers the development of coherent policies and the advancement of cross-sector collaboration.

2.4.1. Risk, Safety, and Public Perception Management

The success of carbon capture, storage, and usage (CCSU) technologies hinges not only on technical performance and economic feasibility but also on robust strategies for managing risk, ensuring safety, and fostering public trust. Risk perception—often grounded more in social interpretation than scientific assessment—can significantly affect the deployment of CCSU initiatives, particularly in regions where community engagement is insufficient or perceived transparency is lacking.

Safety concerns dominate public discourse surrounding CCSU, despite a robust scientific foundation for the secure containment of CO_2 in deep geological formations. These concerns often stem from a lack of familiarity with the technology, combined with historical distrust of large-scale industrial projects (Leiss & Larkin, 2019). While industry experts stress that the likelihood of CO_2 leakage is minimal, particularly under monitored and regulated conditions, public fears remain potent, especially when communities are not adequately engaged in decision-making. Mistrust can be further compounded by miscommunication or overly technical presentations that fail to address core emotional and social concerns.

A key component of mitigating such perceptions lies in preemptive and inclusive public engagement. As Riesch *et al*. (2013) emphasize, two-way communication frameworks—especially those employing digital and localized channels—offer valuable platforms for sharing information and collecting feedback. Their work on online focus groups in Poland and Spain revealed that where communities were engaged early and sincerely, acceptance of CCS projects increased, even in initially skeptical regions. Conversely, late-stage consultation or tokenistic outreach often intensified opposition, reinforcing notions of imposed risk.

Building public confidence also requires demonstrating a credible commitment to long-term safety. Hetti and Kaumadi (2020) argue that community-level approaches to lifecycle risk management can play a pivotal role in normalizing CCSU technologies. Their study suggests that when communities are involved in lifecycle assessments and monitoring processes, they are more likely to internalize a shared responsibility for climate mitigation and infrastructure safety. This shift from a passive to an active role in governance fundamentally reconfigures public trust dynamics and legitimizes CCSU as a public good rather than a corporate imposition.

In this context, risk communication must go beyond technical risk probabilities to address values, emotions, and historical grievances. Leiss and Larkin (2019) stress that effective communication is grounded in empathy and relevance, tailored to specific community contexts, and delivered through trusted messengers. It is not sufficient to cite containment statistics or regulatory safeguards; communities must see evidence of responsiveness, accountability, and continuous engagement. In regions with histories of environmental degradation or disenfranchisement, this relational aspect becomes even more critical.

Public perception is also influenced by the tangible benefits that CCSU projects bring to host communities. Mulyasari *et al*. (2021), in their case study of the Gundih Pilot Project in Indonesia, illustrate that perceptions of CCSU risk are moderated when local populations are included in employment, training, and infrastructure planning. Social license to operate (SLO), as the authors demonstrate, is not merely a communication outcome but a product of visible socio-economic reciprocity. When CCSU projects are positioned as contributors to local development rather than extractive enterprises, acceptance tends to rise.

A recurring barrier to these ideal conditions is the absence of standardized public engagement protocols across jurisdictions. Parmiter and Bell (2020) identify wide variability in how CCSU projects incorporate stakeholder perspectives, ranging from intensive co-design models in Scandinavia to more technocratic approaches in parts of Asia and Eastern Europe. This inconsistency undermines the sector's credibility and hinders the development of a universally accepted best-practice model for engagement. The authors advocate for internationally endorsed guidance that treats risk, safety, and public perception not as afterthoughts, but as core design criteria.

Finally, transparency in incident reporting and ongoing risk assessments is crucial for maintaining legitimacy over the long term. Communities are more likely to support CCSU deployment when they have access to real-time data, independent monitoring results, and clear channels for redress. This transparency should extend beyond the project's operational lifespan and include decommissioning and post-closure safety plans.

2.5. CCSU in Nationally Determined Contributions and Net-Zero Strategies

The global effort to achieve net-zero greenhouse gas emissions under the Paris Agreement has placed increasing emphasis on the deployment of carbon capture, storage, and usage (CCSU) technologies. As signatories to the agreement develop and update their Nationally Determined Contributions (NDCs), the integration of CCSU has emerged as both a strategic necessity and a political challenge. Although CCSU technologies do not feature uniformly across all NDCs, their potential to decarbonize hard-to-abate sectors has become more pronounced in global climate discourse.

Central to the inclusion of CCSU in climate strategies is the recognition that certain industrial emissions—such as those from cement, steel, and chemical production—are difficult to abate through renewable energy or efficiency measures alone. Akimoto *et al*. (2021) argue that CCSU can play a vital role in offsetting residual emissions from these sectors, acting as a technological bridge toward deep decarbonization. Their modeling shows that CCSU and Direct Air Capture (DAC) become indispensable when net-zero scenarios are pursued at a global scale.

Despite this potential, the actual integration of CCSU into NDCs has been inconsistent. Martin-Roberts *et al*. (2021) highlight that only a small subset of countries explicitly include CCSU in their submitted NDCs, and those that do often lack detailed implementation pathways. This underrepresentation is not due to a lack of technical feasibility but rather the high costs, governance complexities, and infrastructure dependencies that characterize CCSU systems. These challenges make it difficult for many countries, particularly in the Global South, to commit to CCSU without international financial and technological support.

The Global CCS Institute's 2020 status report identifies this gap between policy ambition and technological deployment. According to Page *et al*. (2020), while over 65 large-scale CCS projects exist globally, their cumulative impact falls well short of the levels required to meet mid-century net-zero targets. They emphasize that for CCSU to make a meaningful contribution, national strategies must align policy incentives with long-term emissions goals and integrate CCSU into a broader green industrial policy. Without such alignment, CCSU risks being marginalized as an "optional" mitigation measure rather than a core component of climate action.

In terms of policy coherence, the emergence of net-zero frameworks has accelerated momentum behind CCSU, particularly in advanced economies. Regufe *et al*. (2021) observe that many countries with net-zero targets for 2050 have begun to recognize the necessity of CCSU, not only for industrial decarbonization but also for producing low-carbon hydrogen and facilitating negative emissions. The authors argue that countries like the UK and Norway are leading examples, embedding CCSU into national climate strategies through supportive legislation and public investment.

However, the same cannot be said for emerging and developing economies. Shen *et al*. (2022) caution that CCSU uptake in Asia, Africa, and Latin America is limited by economic feasibility and lack of infrastructure. Their study on China's carbon neutrality pathway indicates that while CCSU is critical for long-term targets, the current policy landscape lacks strong incentives for deployment. Moreover, the uncertainties surrounding long-term storage liability, monitoring, and governance mechanisms contribute to risk aversion among both public and private stakeholders.

A significant enabler of CCSU inclusion in NDCs and net-zero strategies is the Article 6 mechanism under the Paris Agreement, which allows for international cooperation through carbon markets. Although not yet fully operationalized in many countries, this mechanism offers a platform for financing transboundary CCSU projects and generating certified carbon credits. Arlota and de Medeiros Costa (2021) discuss how Article 6 can be leveraged to incentivize investment in CCSU by enabling high-emitting nations to offset emissions through overseas CCSU initiatives. However, they also warn of potential equity concerns if such projects fail to deliver co-benefits to host communities.

Public perception and justice considerations further complicate the policy landscape. Martin-Roberts *et al*. (2021) note that despite growing political support, CCSU often lacks public legitimacy due to concerns over safety, environmental justice, and the perceived prolongation of fossil fuel use. These socio-political factors must be addressed if CCSU is to be scaled under the social license required by net-zero mandates.

Moreover, the role of CCSU is being reevaluated in light of climate equity and differentiated responsibilities. While high-income nations possess the technical capacity to integrate CCSU at scale, lower-income nations risk being left behind. Akimoto *et al*. (2021) emphasize that equitable financing frameworks and North–South technology transfer will be crucial for enabling wider CCSU adoption in national climate strategies. This perspective underscores the importance of CCSU not just as a technological intervention, but as a politically and ethically sensitive component of global climate governance.

2.5.1. Life Cycle and Long-Term Sustainability Assessments

The evaluation of carbon capture, storage, and usage (CCSU) technologies through the lens of life cycle and long-term sustainability assessments has emerged as an essential component of climate mitigation discourse. As the world transitions toward net-zero emissions, comprehensive assessments of the full environmental, economic, and operational impacts of CCSU technologies are required to inform policy, guide investment, and ensure responsible deployment.

Life cycle assessment (LCA) is a widely adopted methodological tool that enables a holistic evaluation of environmental impacts across all stages of a technology's lifecycle—from material extraction to end-of-life. When applied to CCSU systems, LCA reveals not only the potential benefits in terms of emissions reductions but also the embedded emissions, resource consumption, and trade-offs associated with infrastructure development, capture processes, transportation, and storage phases. Hetti and Kaumadi (2020) argue that CCSU, although promising as a mitigation tool, must be scrutinized for its entire environmental footprint. Their analysis, rooted in community-level applications, shows that upstream and downstream emissions can substantially affect the net climate benefit of CCSU if not properly accounted for.

Liyanage (2020) advances this perspective by examining CCSU at the building level, highlighting the scalability and variability of CCSU's effectiveness across contexts. His feasibility study based on life cycle thinking found that carbon reduction outcomes varied significantly depending on regional energy mixes, materials used, and operational efficiencies. This reinforces the need to localize sustainability assessments rather than rely solely on generalized models. Such context-specific analysis supports more targeted policy and investment decisions and avoids overgeneralizing CCSU's benefits or limitations.

Sustainability assessments of CCSU must also take into account temporal dimensions. While short-term evaluations may suggest strong performance through significant CO_2 capture volumes, longer-term analyses often expose vulnerabilities such as potential leakage risks, intensive maintenance requirements, or carbon debt linked to emissions embedded in construction processes. As van der Gun *et al*. (2016) argue in relation to subsurface governance, the feasibility of ensuring effective monitoring and regulatory oversight over extended timescales is critical for maintaining environmental integrity. This underscores that the permanence of storage, rather than the volume alone, must be central to sustainability frameworks.

Another key aspect of long-term assessments is economic sustainability. Dalei and Joshi (2022) discuss how enhanced oil recovery (EOR)-linked CCSU applications in Indian oil refineries offer a dual revenue stream by coupling emissions reductions with fossil fuel extraction. However, they caution that such models may undermine the overall sustainability narrative if they extend fossil fuel lifecycles or create lock-in effects. Life cycle and sustainability frameworks must therefore assess not only direct emissions reductions but also indirect behavioral and market consequences of CCSU deployment pathways.

A crucial advancement in this space is the integration of greenhouse gas (GHG) emissions modeling with LCA metrics to evaluate net climate impact more accurately. Liyanage, Hewage, and Karunathilake (2021) used the TRACI 2.0 method to evaluate GHG emissions from building-level CCSU systems. Their results indicated that while carbon capture devices at the source reduce atmospheric emissions, the electricity required to power such systems—if drawn from fossil sources—can offset these gains. Their findings emphasize the importance of coupling CCSU systems with renewable energy sources to ensure that sustainability gains are real and sustained.

From a systems perspective, long-term assessments also need to account for social sustainability indicators. While often overlooked, community acceptance, employment potential, land use impacts, and resource conflicts all play a role in determining the long-term viability of CCSU projects. Hetti and Kaumadi (2020) explore this dimension through their life cycle thinking approach, noting that CCSU systems that fail to deliver local co-benefits tend to face greater public resistance. This social dimension is not merely ancillary—it is intrinsic to sustainability.

Policy and regulatory frameworks must adapt to fully integrate life-cycle principles into CCSU project evaluation and approval. At present, most policies place disproportionate emphasis on capture capacity and storage volume, often neglecting broader sustainability considerations. As van der Gun *et al*. (2016) highlight in their discussion of subsurface governance, robust frameworks should embed environmental, economic, and social dimensions into long-term planning. Moving towards integrated assessment models is therefore essential to ensure that CCSU contributes not only to emissions reduction but also to holistic sustainability objectives.2.6 Innovation Frontiers and Digital Transformation

As the urgency of climate action intensifies, innovation in carbon capture, storage, and usage (CCSU) technologies has become an essential pillar in global decarbonization strategies. The intersection of digital transformation and CCSU represents a crucial frontier, enabling increased efficiency, cost reduction, operational safety, and long-term scalability. Through advanced digital tools such as machine learning, digital twins, and AI-driven predictive analytics, the CCSU sector is undergoing a transformation that mirrors broader trends across clean energy systems.

Historically, CCSU has been challenged by high capital and operational costs, infrastructure complexity, and limited deployment outside of pilot or demonstration-scale projects. These barriers have spurred a wave of innovation designed to optimize performance across the CCSU lifecycle—from CO_2 capture at point sources to transportation, storage, and utilization. Beck (2020) asserts that the commercialization of climate technologies in the United States, particularly CCSU, has been strongly driven by policy-induced innovation ecosystems. She highlights that a convergence of venture capital, public R&D, and regulatory frameworks has created a fertile ground for advanced capture technologies and automated monitoring systems to evolve.

The role of digital infrastructure in this innovation wave cannot be overstated. Modern CCSU facilities are increasingly integrating sensor networks and real-time data platforms to enhance monitoring and verification. Stephens and Jiusto (2010) provide a socio-technical analysis of innovation in CCS and enhanced geothermal systems (EGS), emphasizing that the maturation of CCSU requires alignment between technological systems and social institutions. Their study underscores that digital transformation is not simply a matter of software upgrades; it involves the reconfiguration of organizational workflows, risk assessment protocols, and public engagement strategies.

In the industrial sector, digital transformation is revolutionizing the deployment and operation of CCSU systems through process automation and predictive diagnostics. For instance, Dalei and Joshi (2022) note that in Indian oil refineries, the integration of CCSU with digital mapping and reservoir modeling tools enables more precise matching of emission sources with geological sinks. This reduces both costs and uncertainties associated with enhanced oil recovery (EOR)-linked CCSU projects. Their findings demonstrate that the coupling of data science with CCSU engineering significantly improves the feasibility of such projects in emerging economies.

Cross-sectoral innovation is another defining feature of digital transformation in CCSU. As Naims and Eppinger (2022) explain, carbon capture is increasingly being linked with other technological domains—such as green hydrogen, synthetic fuels, and biomass gasification—through digitally orchestrated systems. Their configurational study shows that digital integration allows for dynamic management of input-output streams, facilitating multi-purpose carbon valorization pathways. This flexible approach to system design improves economic resilience and sustainability, positioning CCSU as part of a larger decarbonization toolkit.

However, the innovation landscape is uneven. Van Alphen, Noothout, and Hekkert (2010) identify that while the U.S. and some European countries lead in CCSU innovation system development, many nations still face structural bottlenecks. These include fragmented research efforts, limited cross-industry coordination, and inadequate intellectual property regimes. Digital transformation can help mitigate some of these challenges by fostering data-sharing platforms, collaborative design tools, and virtual prototyping environments. Nonetheless, institutional support remains crucial for scaling these innovations globally.

Artificial intelligence (AI) and machine learning (ML) are also redefining the way CCSU projects are planned and executed. Through AI-powered simulations, developers can model CO_2 behavior in subsurface storage formations, anticipate leakage risks, and optimize well placements. This reduces the reliance on costly field trials and accelerates the timeline from feasibility to full-scale implementation. Beck (2020) highlights that in the United States, national laboratories and private firms are investing heavily in these digital capabilities to de-risk CCSU projects and enhance investor confidence.

Digital twins—virtual replicas of physical systems—are further enhancing operational resilience. They allow real-time synchronization of physical infrastructure with digital models, enabling operators to test scenarios, diagnose anomalies, and manage contingencies without physical intervention. Stephens and Jiusto (2010) note that such technologies not only improve system performance but also address social acceptance challenges by providing transparent and traceable data streams that can be shared with regulators and communities.

2.6. Future Perspectives and Multidisciplinary Research Directions

The advancement of Carbon Capture, Storage, and Usage (CCSU) technologies is closely linked to the establishment of interdisciplinary research frameworks and long-term innovation pathways. As global climate targets tighten and decarbonisation pressures intensify, the capacity of CCSU to transcend current technological limitations will hinge on integrating engineering solutions with environmental science, social systems thinking, and coherent policy design (Olfe-Kräutlein, 2020).

The future of CCSU depends less on incremental gains in capture efficiency or reductions in energy penalties and more on its integration within a wider decarbonisation framework. As Angélil *et al*. (2019) suggest in the context of science–technology–policy linkages, forward-looking CCSU strategies must connect with hydrogen production, renewable energy systems, and circular economy principles. Achieving this integration will require innovation across multiple domains, from material science for advanced sorbents to systems engineering for scalable carbon transport and storage infrastructure. In this way, CCSU is positioned not as a standalone technology but as a vital component within a broader, multi-actor and multi-technology landscape of climate solutions.

Interdisciplinary research is particularly vital in addressing the socio-technical complexities of CCSU adoption. Stephens and Jiusto (2010) emphasize that technological maturity alone does not guarantee success; public perception, institutional inertia, and stakeholder governance must be managed simultaneously. The authors call for systemic research approaches that merge technical analysis with political economy, communication studies, and behavioural sciences to unlock more effective deployment models. For example, public resistance to subsurface CO_2 storage in some regions has been linked not to the technology's risks but to trust deficits in operators and institutions. Thus, interdisciplinary research must also focus on frameworks for transparency, community engagement, and equitable risk distribution.

A forward-looking research agenda for CCSU must also address regional and economic disparities in implementation capacity. Goel and Johri (2019) examine CCSU potential in coal-dependent economies, highlighting the need for tailored research that reflects local infrastructure, industrial structure, and energy demand patterns. Their study reveals that the successful deployment of CCSU in India, for example, requires coupling capture units with existing coal-fired plants while simultaneously reforming national energy governance structures. This reinforces the value of site-specific multidisciplinary strategies that go beyond generic global models.

Moreover, future research directions must consider the economics of CCSU not merely in terms of cost reductions, but as part of dynamic market and policy ecosystems. Goel *et al*. (2019) argue that CCSU investments will be influenced by carbon pricing mechanisms, tax incentives, international climate finance, and technology transfer pathways. This view expands the research horizon from isolated cost-benefit studies to macroeconomic and regulatory analyses that incorporate global trade, emissions accounting, and industrial decarbonisation pathways. The need to integrate legal, financial, and economic research with technical innovation underscores CCSU's complexity as a policy-embedded technology.

Emerging research also points to the importance of education and capacity building as critical enablers of future CCSU development. Goel (2017) advocates for the creation of specialized academic programs and research institutes that focus not only on CCSU engineering but on multi-disciplinary curricula incorporating climate law, environmental ethics, and sustainable business practices. This approach ensures that future CCSU professionals are equipped to navigate both the technical and societal challenges inherent in deploying such infrastructure at scale.

Furthermore, as digital transformation accelerates, multidisciplinary CCSU research must begin to incorporate data science, artificial intelligence, and predictive modeling. These tools can enable real-time optimization of capture processes, improve leakage risk assessment in geological formations, and guide policy simulations under various climate scenarios. However, this requires collaboration between climate modelers, computer scientists, and engineers—teams that have historically worked in parallel rather than in synergy.

The long-term success of CCSU will hinge on aligning innovation trajectories with core sustainability principles. Future research must extend beyond measuring capture volumes to interrogating the ecological costs and socio-economic consequences of deployment. As Angélil *et al*. (2019) emphasise in their discussion of science–technology–policy integration, life cycle assessments, water consumption metrics, and biodiversity impacts should be embedded in CCSU system design and evaluation from the outset. Addressing these dimensions requires cross-disciplinary collaboration, bringing together environmental science, industrial ecology, and policy expertise to ensure that CCSU contributes meaningfully to sustainable decarbonisation.

2.7. Integration of CCSU in Circular Economy and Sustainable Industrial Ecosystems

The incorporation of carbon capture, storage, and usage (CCSU) into circular economy frameworks represents a significant step toward redefining sustainability within industrial systems. As global emphasis intensifies on reducing carbon footprints while sustaining economic development, CCSU technologies are increasingly being explored as both a mitigation tool and a value-creation mechanism. The shift from linear models of carbon disposal to regenerative approaches that reintegrate CO_2 into industrial cycles aligns directly with the core tenets of the circular economy.

The circular economy promotes the continuous reuse of materials and energy, minimizing waste and maximizing resource efficiency. Within this context, CCSU facilitates the transformation of carbon dioxide from an undesirable emission to a reusable asset. Budzianowski (2017) articulates how CCSU can be employed not only to mitigate emissions but also to create carbon-based inputs for synthetic fuels, building materials, and other value-added products. Such integration allows industrial systems to close the loop on carbon, transforming CO_2 into a resource instead of relegating it as waste.

Industrial ecosystems, particularly in high-emission sectors like cement, steel, and petrochemicals, stand to benefit considerably from CCSU within circular economy strategies. Wang *et al*. (2022) demonstrate how integrating carbon capture with sustainable industrial process optimization enhances both environmental performance and operational efficiency. By leveraging real-time data and energy integration strategies, industrial facilities can significantly reduce carbon intensity while maintaining production goals. The researchers emphasize that such integration requires holistic systems design, which includes CCSU as a fundamental node in a network of interdependent technologies.

The potential of CCSU to support circular models is also reinforced by the evolution of carbon reuse applications. Tcvetkov *et al*. (2019) note that CO_2 is no longer seen merely as a waste stream but as a feedstock for a wide range of products, including carbonates, fuels, and polymers. This revaluation supports the transition from a linear carbon model to a circular carbon economy. In this framework, the sequestration of carbon is not limited to geological formations but extended into material flows that prolong its industrial utility. The implication is that carbon becomes embedded within products that either delay or negate its return to the atmosphere.

A compelling example of this approach is evident in the plastics sector. Pires da Mata Costa and Vaz de Miranda (2021) explore how captured CO_2 is increasingly being used as a raw material in the synthesis of polymers, contributing to a more circular plastics economy. Their findings suggest that when CCSU is integrated into product manufacturing, it not only reduces upstream emissions but also supports downstream sustainability through recyclable and carbon-embedded goods. The long-term environmental benefits are twofold: emissions reduction and the creation of carbon reservoirs in durable products.

However, for CCSU to be effectively embedded into circular and sustainable industrial ecosystems, systemic policy support and infrastructure development are necessary. Lau *et al*. (2017) examine the Norwegian waste-to-energy sector, highlighting how policy incentives, carbon pricing, and waste management strategies converge to create an enabling environment for CCSU deployment. They argue that aligning waste-to-energy operations with carbon capture technologies ensures that residual emissions from otherwise necessary waste incineration are mitigated, closing the loop on both carbon and material cycles.

Despite the promising potential, challenges remain. Integrating CCSU into existing industrial and economic systems requires significant capital investments, regulatory alignment, and technological adaptation. Moreover, market demand for CO_2-derived products must be scaled to absorb captured volumes meaningfully. Budzianowski (2017) emphasizes the importance of cross-sector collaboration and innovation ecosystems to facilitate this transition. Only through coordinated efforts involving industry, academia, and policy institutions can the barriers to circular CCSU adoption be systematically addressed.

The future of CCSU lies in its dual role—as an environmental safeguard and a circular value generator. Its integration into sustainable industrial ecosystems is not merely about emissions reduction but about rethinking carbon as a strategic material. Wang *et al*. (2022) highlight the transformative potential of digital technologies and life cycle assessment tools to optimize CCSU configurations within complex industrial networks. When guided by circular economy principles, these innovations enable the decoupling of economic growth from carbon emissions, a central goal of sustainable development.

3. Conclusion

This study has delivered an in-depth exploration of the mechanisms, enablers, and barriers associated with large-scale carbon management technologies within the context of global decarbonization efforts. Through a structured and multidisciplinary approach, it successfully fulfilled its primary aim: to critically evaluate how carbon mitigation systems can be strategically deployed to accelerate energy transition, industrial sustainability, and environmental resilience. Each objective—ranging from evaluating technological evolution, sectoral deployment, policy frameworks, long-term assessments, to integration within circular systems—has been addressed with clarity and scholarly rigour.

The findings reveal that while technical feasibility and environmental value are well-established, widespread implementation remains challenged by fragmented governance, capital-intensive infrastructure, and limited cross-sectoral coordination. Notably, significant progress has been observed in digital innovations that enhance operational transparency, reduce costs, and improve safety through data-driven modeling and automation. These advancements, combined with the development of market mechanisms and value-creation through reuse applications, are positioning carbon mitigation systems as more than just interim solutions. They are emerging as strategic assets capable of supporting sustainable industry transformation.

This work also underscores the importance of life cycle thinking, socio-political legitimacy, and interdisciplinary collaboration in driving acceptance and effectiveness. When embedded in national and international policy instruments, these technologies have demonstrated potential to complement net-zero ambitions and to enhance the credibility of mitigation commitments. Furthermore, sector-specific analyses confirm that integration into heavy-emitting industries—when paired with policy incentives and innovative financing models—can yield considerable emissions reductions without sacrificing competitiveness.

In light of these insights, the study recommends targeted investment in research and development, harmonization of global regulatory standards, enhanced public communication strategies, and strategic alignment with broader sustainability agendas. These actions will not only improve deployment outcomes but will also solidify the role of carbon management systems in shaping future industrial ecosystems. Ultimately, the study confirms that with the right institutional support and multidisciplinary engagement, these systems can be pivotal to achieving climate resilience and sustainable growth in a carbon-constrained world.

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