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*Editorial*

# Carbon Capture, Utilization, and Storage (CCUS) for Clean Energy

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## 1. Introduction

The accelerating pace of climate change continues to challenge global energy systems, industrial sectors, and natural environments. Despite decades of scientific warnings, international agreements, and rapid growth in renewable energy, global anthropogenic carbon dioxide ($CO_2$) emissions remain at historically high levels. Recent assessments indicate that fossil fuel and industrial emissions reached new peaks in 2022 and 2023, driven by persistent dependence on coal, oil, and natural gas across power generation, transportation, and heavy industry [1–3]. The Intergovernmental Panel on Climate Change (IPCC) has repeatedly emphasized that limiting warming to 1.5 °C or even 2 °C requires rapid, deep, and sustained reductions in greenhouse gas emissions, alongside large-scale deployment of carbon dioxide removal (CDR) technologies [4].

Within this context, Carbon Capture, Utilization, and Storage (CCUS) has emerged as a critical component of global decarbonization strategies. CCUS encompasses a suite of technologies capable of capturing $CO_2$ from point sources or directly from the air, upgrading it into valuable products, or storing it securely in geological formations for centuries or longer [5–7]. Its versatility allows it to address emissions from sectors where alternatives remain technologically immature or economically prohibitive, such as cement, steel, chemicals, and dispatchable power generation [8–10]. Moreover, CCUS enables low-carbon hydrogen production via reforming with capture, supports negative-emission pathways such as bioenergy with CCS (BECCS), and contributes to industrial symbiosis through $CO_2$ utilization in fuels, materials, and biological systems [11–13].

Despite its promise, CCUS deployment faces significant challenges. Capture technologies must become more energy-efficient and cost-effective; solvent and sorbent stability must be improved; geological storage must be monitored with high precision; and $CO_2$ utilization pathways must demonstrate environmental integrity and economic viability [14–16]. Equally important are enabling conditions such as regulatory frameworks, public acceptance, infrastructure planning, and cross-sectoral coordination [17–19]. Addressing these challenges requires coordinated advances in engineering, geoscience, biotechnology, data science, and policy analysis.

This Special Issue, "Carbon Capture, Utilization, and Storage (CCUS) for Clean Energy," was established to bring together high-quality research that reflects the breadth and depth of contemporary CCUS innovation. The contributions span the entire CCUS value chain: from molecular-scale solvent degradation mechanisms to national-scale supply chain optimization; from biological $CO_2$ valorization to advanced seismic monitoring of subsurface storage; and from AI-enhanced predictive modeling to integrated assessments of policy-driven decarbonization pathways. Collectively, these works illustrate the rapid

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evolution of CCUS as a multidisciplinary field and highlight the synergies emerging at the intersection of engineering, geoscience, biotechnology, and sustainability policy.

The papers published in this Special Issue provide a timely and comprehensive snapshot of the state of CCUS research. They offer new insights into technological performance, system integration, environmental impacts, and strategic planning, contributing to a more coherent and actionable understanding of how CCUS can support global clean-energy transitions. By synthesizing these contributions, this editorial aims to contextualize their significance, identify cross-cutting themes, and outline future directions for research and deployment.

## 2. An Overview of Published Articles

The Special Issue opens with a contribution by Borhani and Short (Contribution 1), who investigate one of the most persistent challenges in post-combustion $CO_2$ capture: the degradation of amine solvents. Their study develops predictive models for both thermal and oxidative degradation pathways, offering new insights into solvent stability under realistic operating conditions. By quantifying degradation kinetics and identifying key operational sensitivities, the authors provide a foundation for improving solvent management and enhancing the long-term sustainability of amine-based capture systems.

A complementary perspective on capture technologies is provided by Szczęśniak et al. (Contribution 2), who examine the performance of molten carbonate fuel cells (MCFCs) when exposed to industrial flue-gas compositions. Their review synthesizes experimental and modeling evidence to evaluate how impurities, temperature variations, and gas-stream characteristics influence MCFC operation when used as $CO_2$ separation devices. The authors highlight both the promise and the operational constraints of MCFC-based capture, offering guidance for future integration into industrial decarbonization strategies.

Moving toward $CO_2$ utilization, Dębowski et al. (Contribution 3) explore the potential of using exhaust-gas $CO_2$ to cultivate Tetraselmis subcordiformis, a microalgal species capable of producing both biomass and biohydrogen. Their experimental results demonstrate that flue-gas $CO_2$ can enhance algal growth and hydrogen productivity, suggesting a viable biological pathway for $CO_2$ valorization. This work contributes to the growing interest in microalgal systems as multifunctional platforms for carbon mitigation, renewable fuels, and high-value bioproducts.

In another utilization-focused study, Bahmani et al. (Contribution 4) investigate the incorporation of waste marble sludge into self-compacting concrete as a partial replacement for cement and fine aggregates. Although not a direct $CO_2$ conversion pathway, this approach reduces the carbon footprint of concrete production by lowering cement demand and promoting circularity in construction materials. The authors evaluate mechanical performance, durability, and workability, demonstrating that marble sludge can be effectively valorized without compromising structural integrity.

Biological mitigation strategies are further explored by Gambelli et al. (Contribution 5), who assess the anaerobic co-digestion of brewery spent grain with Lemna minor. Their study shows that co-digestion improves biogas yields and enhances process stability, offering a route to reduce $CO_2$ emissions associated with organic waste management. By integrating waste valorization with renewable energy production, the work highlights the role of optimized bioprocesses in broader carbon-mitigation frameworks.

Subsurface storage emerges as a central theme in the contribution by Vulin et al. (Contribution 6), who analyze $CO_2$ injection strategies in Croatian gas-condensate reservoirs with high native $CO_2$ content. Using reservoir simulations, the authors evaluate how injection timing, well placement, and reservoir characteristics influence storage efficiency and operational performance. Their findings provide actionable insights for designing storage projects in complex geological settings, particularly in regions with legacy hydrocarbon infrastructure.

The integration of geothermal energy and $CO_2$ storage is examined by Meneghini et al. (Contribution 7), who conduct a feasibility study of multi-tool active seismic monitoring at the Hellisheiði geothermal field. Their work demonstrates how advanced geophysical techniques can support safe and effective monitoring of $CO_2$ reinjection in geothermal systems. The study underscores the potential of hybrid geothermal-CCUS configurations as innovative pathways for low-carbon energy production.

Advances in predictive modeling are showcased in the paper by Shokrollahi et al. (Contribution 8), who apply explainable artificial intelligence (XAI) to estimate $CO_2$ solubility in brine solutions. Accurate solubility predictions are essential for assessing storage capacity, plume behavior, and long-term reservoir performance. By integrating machine learning with interpretability tools, the authors improve both predictive accuracy and transparency, contributing to more reliable subsurface modeling.

At the systems level, Nguyen and Leonzio (Contribution 9) present a techno-economic and environmental assessment of national-scale CCUS supply chains. Their study compares different optimization criteria, such as cost minimization, emission reduction, and multi-objective trade-offs, and evaluates how these choices influence infrastructure deployment and system performance. The results provide strategic insights for policymakers and planners designing large-scale CCUS networks.

A policy-oriented perspective is offered by Thepsaskul et al. (Contribution 10), who analyze pathways for Thailand to achieve carbon neutrality in its public power utilities by 2050. Their assessment evaluates the technical feasibility, economic implications, and policy requirements for deploying CCS in the national power sector. The study highlights the importance of coordinated planning, supportive regulation, and targeted investment to enable large-scale decarbonization in emerging economies.

The Special Issue concludes with a comprehensive review by Bui et al. (Contribution 11), who examine the opportunities and challenges associated with offshore CCUS. Their analysis covers capture technologies, transport logistics, storage potential in offshore reservoirs, and emerging utilization options in marine environments. The authors emphasize the vast storage capacity available offshore and discuss the regulatory, environmental, and technological considerations that will shape future deployment. This review serves as a roadmap for advancing offshore CCUS as a major component of global climate-mitigation strategies.

## 3. Conclusions

The contributions to this Special Issue collectively underscore the central role of CCUS in the global clean-energy transition. They demonstrate that CCUS is not a single technology but a diverse ecosystem of solutions spanning chemical engineering, geoscience, biotechnology, materials science, artificial intelligence, and systems analysis. Several cross-cutting themes emerge from the collected works. First, integration is essential: CCUS must be embedded within broader energy, industrial, and circular-economy systems to maximize impact. Second, modeling and AI are transforming CCUS design, enabling more accurate predictions of solvent behavior, subsurface dynamics, and system-level performance. Third, monitoring and verification remain critical for ensuring the safety and reliability of long-term storage. Fourth, utilization pathways are diversifying, with biological, mineral, and material-based approaches expanding the CCUS portfolio. Finally, national-scale planning and offshore deployment are gaining momentum as countries and regions evaluate CCUS as part of their net-zero strategies.

Together, the papers in this Special Issue provide a rich and forward-looking perspective on how CCUS can support climate mitigation while enabling sustainable energy systems. They highlight both the progress achieved and the challenges that remain: technical, economic, regulatory, and societal.

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