Technological Convergence for CCS Optimization: Innovations and Challenges

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***Abstract*—Rising carbon emissions from energy, transportation, and industry demand innovative monitoring and mitigation strategies. This survey examines the convergence of Artificial Intelligence (AI), Blockchain Technology (BCT), and the Internet of Things (IoT) within an Internet of Blockchain (IoB) framework for predictive Carbon Capture and Storage (CCS) analytics. It reviews advancements, limitations, and optimization opportunities in scalability, data integrity, predictive analytics, and security. The study also identifies emerging research trends and challenges that must be addressed to enhance the efficiency, transparency, and reliability of CCS systems for sustainable carbon management.**

***Index Terms*—artificial intelligence, blockchain, carbon emission, convergence, capture and storage, monitoring.**

I. Introduction

Carbon Capture and Storage (CCS) is a cornerstone of global decarbonization strategies aimed at limiting atmospheric CO_2 concentrations [1]. The International Energy Agency (IEA) projects that approximately 6 gigatonnes of CO_2 must be captured and stored annually by 2050 to meet the Paris Agreement targets [2]. At present, the capture capacity stands at merely 25 megatonnes in the United States and Europe, illustrating the stark disparity between current performance and future requirements. To close this gap, incremental improvements will be insufficient; instead, convergence of advanced digital and engineering technologies is required. Fig. 1 shows the adoption levels (in percentage) of different carbon capture approaches around the world.

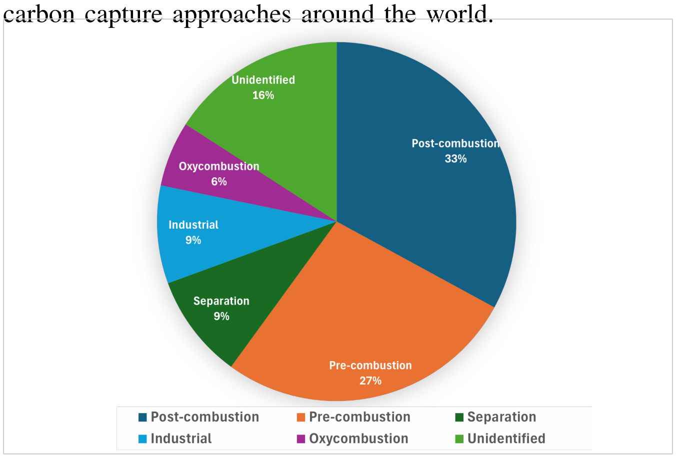

Fig. 1. The utilization rates of various carbon sequestration methods in different CCS plant projects across the globe.

II. CCS Fundamentals and Challenges

Carbon Capture and Storage (CCS) comprises three stages—CO_2 capture, transport, and secure geological storage—each facing technical, economic, and regulatory hurdles that limit large-scale adoption [3]. High capture costs of about $60 per ton, along with transport and storage risks like corrosion, hydrate formation, and leakage, make deployment financially and technically challenging. Regulatory uncertainty, public resistance, and scale-up risks further deter investment and delay implementation. To overcome these barriers, this survey investigates AI-enhanced Internet of Blockchain (IoB) systems as innovative solutions to improve scalability, predictive analytics, and carbon credit verification in CCS operations [4].

III. Technological Convergence for CCS Optimization

1) Internet of Things (IoT) for Real-Time CCS Monitoring: IoT-enabled CCS systems in industrial plants integrate sensors to facilitate real-time monitoring of production cycles, energy consumption, and storage conditions. IoT sensors deployed in energy plants, capture CO_2 concentrations and methane emissions, allowing data-driven decision-making. Also, transportation networks leverage IoT to track vehicle emissions, optimize routes, and improve fuel efficiency [5], [6]. However, scalability concerns and latency in IoT data transmission remain significant challenges.

TABLE I
KEY AI APPLICATIONS IN CCS

Ref.	CCS Stage	AI Application	Impact
[7], [8]	Capture	Genetic Algorithms-Generative Adversarial (GA-GAN mix) network; GNNs-based solvent models	Improved CO_2 adsorption capacity
[9]	Transport	Digital twin, Random Forest flow models	15% high reliability, availability and maintainability at lower transportation cost, and pipeline integrity
[10]	Storage	SVMs, CNN + LSTM anomaly detection	95% accuracy in leakage detection
[11]	Operations	ANFIS model	30% increase in CO2 capture adsorption from 4.27 (mmol/g) to 5.25 (mmol/g)

2) Artificial Intelligence in CCS: Artificial Intelligence has demonstrated measurable improvements across multiple CCS stages as captured in Table I. In capture processes, convolutional neural networks (CNNs), GA-GAN, GNNs have been used to model solvent behavior in amine-based systems, leading to a reduced energy consumption and improved CO_2 adsorption capacity in projects such as Petra Nova [7], [8].

This addresses directly one of the most energy-intensive bottlenecks in post-combustion capture. In materials research, machine learning accelerates the discovery of novel sorbents and membranes such as Metal-Organic Frameworks (MOFs), drastically reducing the time needed for R&D cycles. In the transport domain, ensemble learning methods and digital twin [9] optimize flow dynamics in pipelines, reducing pressure losses and improving throughput. The Gorgon project in Australia reported cost savings of up to 15% due to such optimizations. Geological storage also benefits from AI, as support vector machines (SVMs), CNN + LSTM achieve 95% accuracy in detecting anomalies that may indicate CO_2 leakage, as demonstrated by [10].

3) Blockchain for Secure and Transparent Carbon Accounting: Blockchain technology mitigates key structural challenges in Carbon Capture and Storage (CCS) by enhancing data integrity, transparency, and trust [12]. Its decentralized and immutable ledger ensures tamper-proof CO_2 capture and storage records, supporting auditable and verifiable MRV systems essential for regulatory compliance and public confidence. Smart contracts automate reporting and accountability, while blockchain's secure linkage of carbon credits to verified emission reductions boosts credibility and market liquidity, encouraging private investment. Moreover, blockchain extends accountability through supply chain traceability, strengthening corporate sustainability reporting [13]. However, high energy demands from consensus mechanisms like Proof-of-Work challenge sustainability, prompting the adoption of greener alternatives such as Proof-of-Stake (PoS), Proof-of-Authority (PoA), and PoA2 to align blockchain with CCS sustainability goals as seen in Table II.

TABLE II
SUMMARY OF RELATED WORKS ON BCTC

Ref.	Blockchain Network	Concensus Protocol	Scope
[12]	Purechain	Proof-of-Authority and Association(PoA^2)	Carbon Emission Trading Scheme
[13]	Ethereum	Proof-of-Stake (PoS)	Sustainable CCUS supply chain management
[14]	Peer-to-Peer blockchain enabled network	Proof-of-Work (PoW)	Carbon and energy trading integration involving prosumers

IV. FUTURE RESEARCH DIRECTION

The integration of AI and blockchain into Carbon Capture and Storage (CCS) systems presents major research challenges, particularly in scalability for handling large real-time data. Interoperability standards and regulatory frameworks are required to ensure seamless data exchange, clear governance, and ethical boundaries for autonomous AI systems. Future research should focus on economic modeling to attract investment and on public trust mechanisms, such as transparent data-sharing platforms, to boost acceptance. Moreover, combining agentic AI with blockchain-based audit trails and developing quantum-resistant cryptography will be vital for secure, autonomous, and future-proof CCS operations

V. CONCLUSION

Integrating AI, IoT, and blockchain into IoB systems enables predictive, secure, and transparent carbon capture and storage analytics through real-time monitoring and intelligent data management. However, overcoming challenges in scalability, efficiency, and authentication is vital, with future research focusing on energy-efficient blockchain, AI-driven emission forecasting, and real-time carbon credit verification to achieve global carbon neutrality by 2050.

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