**Supporting Carbon Capture, Utilization, and Storage Supply Chains (CCUS) with Blockchain Technology: A Sustainable Solution for Climate Change Mitigation**

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Abstract

The urgency for adopting emission reduction mitigation strategies is growing as the consequences of climate change become more threatening. Carbon Capture, Utilization, and Storage (CCUS) emerges as a pivotal solution, facilitating substantial carbon dioxide abatement in high-emission industries. However, CCUS encounters challenges related to supply chain transparency, as well as emission accounting and reduction verification. This study introduces a framework, proposing the integration of blockchain technology into the optimization models of CCUS supply chains. Emissions data from various elements of the optimal CCUS supply chain are securely stored in blocks within the proposed blockchain system, ensuring the integrity and tamper-proof nature of the recorded data. This innovative approach empowers decision-makers to optimize the design of CCUS supply chains, improve computational efficiency, transparently trace emissions from CCUS elements, and verify emission reductions. Anticipated to play a pivotal role in climate change mitigation and sustainable practices, the developed blockchain-based approach is poised to contribute significantly to ongoing efforts in designing and enhancing the effectiveness of the optimal CCUS supply chains.

**Keywords**: Carbon Capture Utilization and Storage (CCUS), Optimization, Emissions Reduction Verification, Blockchain technology.

* 1. Introduction

Climate change is one of the most significant challenges nowadays, necessitating innovative approaches to mitigate the impact of greenhouse gases (GHG) and facilitate the transition towards a net zero economy. The global surface temperature has increased by 1.1 °C in the last decade compared to 1850 - 1900 temperatures. In 2019, the global net anthropogenic GHG emissions were about 54 % higher than 1990 levels (IPCC, 2023). Carbon capture, utilization, and storage (CCUS) is a promising decarbonization technology, especially for hard-to-abate industries including iron, steel, refineries, and chemical production plants (Azadnia et al., 2023). Approximately 40 operational commercial capture facilities globally currently have an annual capture capacity exceeding 45 million tons (Mt) of CO2. However, this falls significantly short, constituting roughly a third of the 1.2 Gt CO2 per year needed to align with the Net Zero Emissions by 2050 (NZE) Scenario (IEA, 2023).

The effectiveness of CCUS is influenced by various factors, including technological maturity, policy and regulatory frameworks, stakeholders' acceptance, economic viability, and robust emission reduction verification (Luo et al., 2023). Ensuring emission reduction reliability is crucial for the transparency and effectiveness of CCUS systems, fostering stakeholder trust and contributing significantly to climate change mitigation. However, the intricate nature of CCUS networks, combined with challenges in data accuracy, poses transparency obstacles. Reliable emission reduction verification is essential for policymakers to comprehend the true potential of CCUS networks, gain stakeholder approval, and ensure project success (GAO, 2022). The verification process typically involves monitoring through emission factors or sensors, self-reporting, and third-party verification, which can be time-consuming, resource-intensive, and costly.

A promising avenue for achieving optimal and transparent design of CCUS supply chains is through the integration of blockchain technology. Blockchain technology, initially conceived as the underlying framework for Bitcoin proposed by Satoshi Nakamoto (Nakamoto, 2008). Blockchain serves as a decentralized, distributed ledger that records transactions across a network of computers in a tamper-proof manner. Blockchain comprises a sequential linkage of data blocks, fostering an indelible ledger. Integral cryptographic techniques bolster data security and integrity (Thakur et al., 2023). This work introduces a novel method for integrating blockchain technology into CCUS supply chains optimization models. The next sections review relevant literature, detail the proposed approach and current challenges followed by conclusions.

* 1. Literature Review

Research in the modeling and optimization of carbon capture, utilization, and storage (CCUS) has garnered significant attention, particularly in the pursuit of improving cost-effectiveness and environmental performance. Zhang et al. (2020) contributed to this field by developing an optimization-based framework that integrates CO2 storage and utilization, exploring various paths within the CCUS supply chain, with a primary focus on economic performance. Rakhiemah and Xu (2022) conducted an in-depth analysis of the economic viability of CCUS with Enhanced Oil Recovery (EOR) in Indonesia, placing emphasis on cost-benefit considerations and the potential for additional oil recovery. Simultaneously, environmental aspects have been scrutinized by various researchers, including Leonzio et al. (2023) and Facchino et al. (2022), who utilized life cycle assessments to systematically evaluate the impact of large-scale CCUS supply chains on carbon emissions reduction in Germany, Italy, and Poland.

Blockchain technology is increasingly recognized as a solution to enhance transparency in emissions reduction, although its application has primarily been in carbon trading markets. Shu et al. (2022) proposed a blockchain-enhanced trading system for the construction industry, incorporating smart contracts to improve efficiency and reliability. Sadawi et al. (2021) presented a hierarchical blockchain framework for carbon emission trading, leveraging Blockchain of Things (BoT) and smart contracts. Muzumdar et al. (2022) focused on a permissioned blockchain system for emission trading, addressing issues like scams and poor monitoring. A comprehensive blockchain-based platform for carbon accounting and trading in the UK construction industry for increased transparency was introduced by Blumberg and Sibilla (2023). In parallel, Lu et al. (2022) proposed STRICTs, a blockchain-enabled system for curbing carbon emissions in road transport, showcasing practical performance through a Hyperledger Fabric-based prototype.

Commercial initiatives by Mitsubishi Heavy Industries and IBM Japan, such as "CO2NNEX," demonstrate the integration of blockchain and IoT devices in CCS infrastructures to streamline the CO2 supply chain (MHI, 2021). CarbonKerma, in 2023, introduced a blockchain-based marketplace for carbon credits from CCUS, symbolized as digital tokens, ensuring traceability and legitimacy in a transparent distributed ledger system (CarbonKerma, 2023). These initiatives highlight the practical applications of blockchain technology in enhancing transparency and reliability in the CCUS sector.

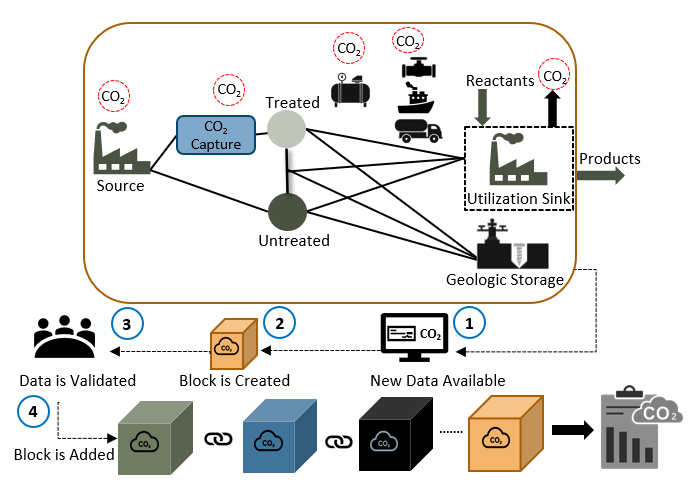
The literature review highlights a notable research gap in emission reduction verification within the framework of Carbon Capture, Utilization, and Storage (CCUS). Previous studies have explored the intricacies of modeling and optimizing the CCUS supply chain infrastructure. The emergence of blockchain technology presents a promising avenue to address the need for transparency in emission tracing within CCUS supply chains. Although prior applications of blockchain in emission reduction have predominantly focused on creating transparent markets for carbon trading, this study introduces an innovative approach. It proposes an integrated decision-making framework that combines blockchain technology with an optimization-based model, offering a strategic and transparent approach to carbon planning within the CCUS context.

* 1. Proposed Approach

CCUS supply chains include emissions reduction data from source-sink matching besides emissions data from different elements such as capturing units, compression, transportation, utilization, and geological storage. The proposed approach advocates the enhancement of transparency in designing CCUS supply chains through the integration of blockchain technology. This integration involves incorporating the blockchain network into the CCUS optimization model, aiming to achieve an optimal design for the CCUS network that facilitates improved transparency in emissions tracking and reduction. Emissions from sources, and different stages of the CCUS supply chains are considered during the optimization. By integrating the blockchain network into the optimization model, the recording of emissions data and emission reduction verification becomes transparent. The developed framework advocates the optimization of the CCUS network and the establishment of a distributed ledger encompassing CCUS emissions data related to various source-sink matches and elements using the blockchain network.

The CCUS-blockchain system is initiated as follows: when new emissions data is available from the CCUS supply chain, a new block is generated. This block undergoes a secure and decentralized sharing process with authorizing and validating nodes, in accordance with the chosen consensus mechanism. This approach assumes that only participating plants have authorized access as validating nodes to maintain the data privacy of the CCUS sources and sinks. Once validated, the new emissions data block is seamlessly appended to the existing sequence of blocks by the nodes within the network. The block is safeguarded by its unique hash and the hash of the preceding block. Emissions data originating from each stage is recorded in a block that is validated, encrypted, and added to the sequence of preceding blocks.

Emissions data are recorded in blocks in an order that is equivalent to the elements sequence in the CCUS supply chain. The recorded data undergoes meticulous processing through smart contracts, culminating in the creation of comprehensive CCUS performance reports and emissions profiles. These reports function as invaluable tools for stakeholders, providing a systematic evaluation of CCUS performance and identifying specific areas for potential improvement. The generated reports serve as a transparent monitoring, reporting and verification mechanism for ensuring regulatory compliance, thereby obviating the necessity for third-party verification. Figure 1 illustrates the developed framework for integrating blockchain technology to design optimal CCUS supply chains with enhanced transparency of emissions tracking and verification.



**Figure 1:** Integration of blockchain technology for designing CCUS supply chains with enhanced emissions tracking.

The proposed methodology presents opportunities to significantly enhance computational efficiency by leveraging decentralization and distributed computing, enabling parallel processing across a network of nodes. The approach enables streamlining verification processes and reduces the need for redundant computations. Overall, these advancements contribute to a more streamlined and efficient CCUS optimization framework. However, integrating blockchain technology into the CCUS framework presents several challenges that merit careful consideration such as regulatory compliance, stakeholder acceptance, and scalability (Uddin et al., 2023). Gaining approval and active participation from all stakeholders in the CCUS network is a key success element of the proposed framework. Resistance or hesitancy from stakeholders may impede the successful implementation.

The limited scalability of blockchain technology may be a concern as CCUS projects expand and involve an increasing number of participants. Finally, non-compliance with regulatory frameworks may lead to legal issues and undermine the credibility of the proposed system. Addressing these challenges requires a concerted effort from stakeholders, technology developers, and policymakers to ensure the seamless integration of blockchain technology into CCUS supply chains, maximizing its potential benefits for transparent and effective emission reduction strategies.

* 1. Case Study

This example illustrates the proposed approach that integrates blockchain network into CCUS optimization models. Blockchain technology was integrated into a previously developed mixed-integer nonlinear optimization model (MINLP) by Al-mohannadi and Linke (2016) aiming to minimize the total cost considering capturing, transportation, sink utilization and storage as expressed in Eq. (1). The model incorporates constraints to ensure carbon balance around carbon sources and sinks, as indicated by Eq. (2) and Eq. (3), respectively. Detailed data, including carbon compositions and flows from sources, as well as required carbon quality and flows for sinks, are presented in Table 1.

|  |  |
| --- | --- |
|  | (1) |
|  | (2) |
|  | (3) |

Cost elements were considered as illustrated by Al-mohannadi and Linke (2016). The net capture emission was constrained to 80% of total emissions. Employing a Python implementation on a desktop with an Intel® CoreTM i7-10700 CPU @ 2.90GHz, 2904 Mhz, 32 GB memory and 64-bit operating system, the optimal design was identified. The total cost was 142 MM $/yr, and the source to sink carbon connections are determined. The emissions data within the blockchain-based network are visualized by Figure 2. Each block provides specific information, enhancing transparency in the CCUS process. The initial block sets the baseline emissions from carbon sources. The second block focuses on capturing unit emissions, while the third block represents emissions due to transportation. Block 4 showcases carbon flows from sources to sinks, emphasizing matching emissions with sinks and the last block outlines sink emissions. The proposed blockchain-based optimization model enables a transparent tracking and verification of each stage's emissions and environmental impact for the optimal CCUS design.

**Table 1:** Data of carbon dioxide sources and sinks.

|  |  |  |
| --- | --- | --- |
| **industry** | **YCO2 (wt%)** | **CO2 Flow (t/d)** |
| Power plant 1 (S1) | 6 | 3843 |
| Power plant 2 (S2) | 5.6 | 4654 |
| Urea (J1) | 99 | 1488 |
| Saline storage (J2) | 94 | 7500 |

**Source-sink matchings (t/d)**

S1 to J1 = 1488

S1 to J2 = 1976

S2 to J1 = 0

S2 to J2 = 4083

**Transportation Emissions (t/d)**

S1 Units = 138

S2 Units = 164

**Capturing unit Emissions (t/d)**

S1 Unit = 130

S2 Unit = 153

**Sources Emissions (t/d)**

S1 = 3843

S2 = 4654

**Sinks Emissions (t/d)**

J1 = 163

J2 = 0

**Figure 2:** Blockchain visualization of emissions data in the optimal blockchain-based CCUS network.

* 1. Conclusions

The devised approach harnesses the capabilities of blockchain technology in conjunction with CCUS supply chains optimization models, elevating the transparency of emission reductions and improving computational efficiency. Comprehensive emissions data, encompassing CO2 utilization, storage, and various CCUS processes, is systematically recorded in discrete blocks which undergo a rigorous validation process and are seamlessly integrated into the blocks sequence. This blockchain-integrated CCUS framework restricts data validation exclusively to authorized nodes, safeguarding data privacy and security. The cryptographic foundation of the blockchain ensures the utmost reliability and immutability of the recorded data. Despite the potency of the proposed system, potential obstacles such as scalability, stakeholder acceptance, and regulatory compliance need to be addressed to fully unlock its capabilities.

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