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# Deciphering the Policy-Technology Nexus: Enabling Effective and Transparent Carbon Capture Utilization and Storage Supply Chains

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## ABSTRACT

In response to the global imperative to address climate change, this research focuses on enhancing the transparency and efficiency of the Carbon Capture Utilization and Storage (CCUS) supply chain under carbon tax. We propose a decision-making framework that integrates the CCUS supply chain's optimization model, emphasizing carbon tax policies, with a blockchain network. Smart contracts play a pivotal role in automating the exchange and utilization of carbon emissions, enhancing the digitalization of the CCUS supply chain from source to sink. This automation facilitates seamless matching of carbon sources with sinks, efficient transfer of emissions and funds besides record-keeping of transactions. Consequently, it improves the monitoring, reporting, and verification processes within the CCUS framework, thereby simplifying compliance with regulatory mandates for net emission reductions and carbon taxation policies. By eliminating reliance on third-party verifiers, our blockchain-based CCUS system reduces verification costs and ensures reliable tracking of emissions, mitigating the risk of carbon leakage. Policymakers and stakeholders gain valuable insights to optimize the CCUS network design, specifically considering the impact of carbon tax. This study represents an advancement in sustainable practices, providing a robust tool for decision-makers engaged in climate change mitigation efforts.

**Keywords**: Carbon Dioxide, Carbon Capture, Carbon Dioxide Sequestration, Carbon Capture Utilization and Storage (CCUS), Supply Chain, Optimization, Carbon Reduction Policies, Carbon Tax, Blockchain, digitalization

## INTRODUCTION

Climate change arises as an escalating global crisis, primarily fueled by soaring levels of greenhouse gas emissions, notably carbon dioxide. Alarming statistics from 2019 reveal a 54 % surge in net anthropogenic greenhouse gas emissions since 1990, underscoring the urgency of transformative solutions [1]. Carbon Capture Utilization and Storage (CCUS) emerges as a pivotal intervention. Projections from the International Energy Agency [2] highlight the growing significance of CCUS, foreseeing a 12 % cumulative reduction in emissions by 2050, particularly in sectors like cement, steel, and chemicals.

The intersection of CCUS with carbon tax policies introduces a nexus laden with challenges and promises. Precise measurement and verification of captured and stored carbon dioxide pose intricate hurdles in a carbon tax regime. Challenges like low capture efficiency, operational costs, and the lack of international cooperation inhibit the holistic development of CCUS [3,4]. Carbon taxes, wielding economic influence, are instrumental in steering industries toward sustainable practices. They not only curtail energy consumption but also propel advancements in emission reduction technologies [5].

However, the amalgamation of carbon taxes and CCUS confronts multifaceted obstacles encompassing cost implications, technology maturity, and governance complexities. The efficacy of carbon taxes hinges on meticulous governance mechanisms to ensure precision in measurement, verification, and transparency, necessitating innovative solutions. Blockchain technology emerges as a disruptive force, offering a decentralized, transparent, and tamper-proof solution to address these

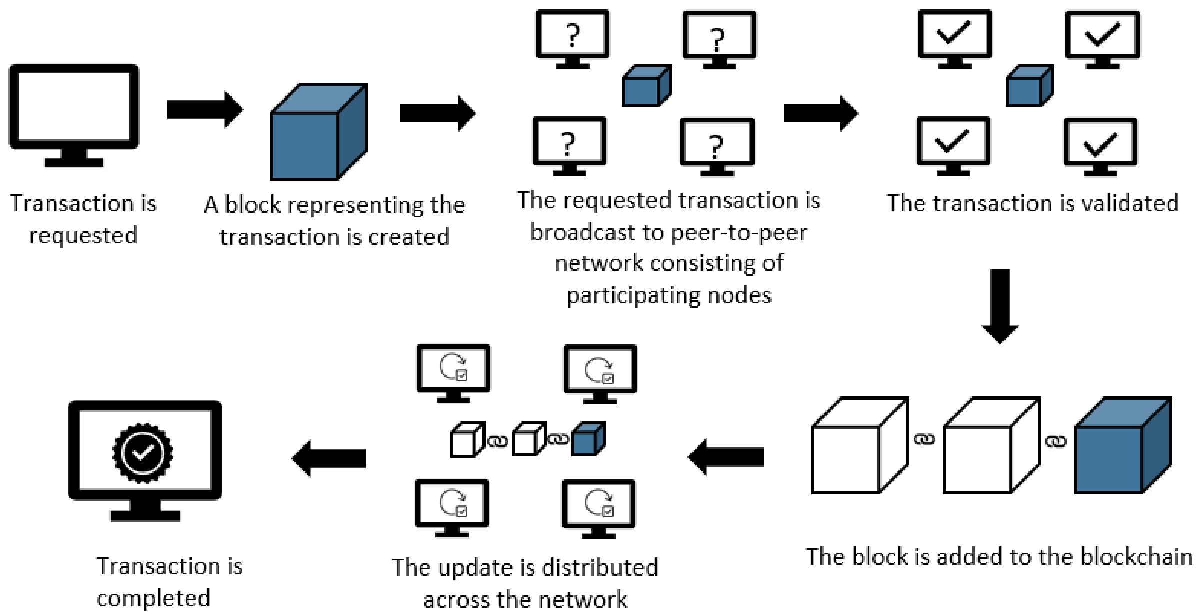


**Figure 1:** Schematic representation of the blockchain working mechanism.

challenges and fortify the CCUS-carbon tax framework.

Blockchain, with its immutable ledger system, stands poised to support the monitoring and verification of carbon emissions and cash flows. Its decentralized nature instills trust in reported data, mitigates fraud, and fosters international collaboration in the pursuit of climate change mitigation. This paper proposes a blockchain-based approach for CCUS-carbon tax nexus, propelling us toward a sustainable future. As we explore the challenging landscape of environmental responsibility and technological advancement, this study reveals a promising path where CCUS-carbon tax supply chains, and blockchain technology intersect. The subsequent sections delve into overview of blockchain technology, provide a summary of existing studies in the literature, elucidate the proposed framework, explore current challenges, and conclude with insights into future directions.

## BLOCKCHAIN TECHNOLOGY OVERVIEW

Blockchain is a decentralized technology for recording and managing data and transactions in a transparent, secure and tamper-proof manner [6]. The emerging technology is a distributed ledger that ensures integrity and immutability of data using cryptography and via the replication and allocation of transactions across a network of computers [7]. Blockchain technology has the potential to eliminate security vulnerabilities, eradicate fraudulent activities, and establish an unprecedented level of transparency obviating the necessity for a reliable third-party entity [8]. Blockchain technology is used to manage tangible and intangible assets using a chain of blocks each containing a set of digital transactions via a decentralized and peer-to-peer network [9].

The decentralization characteristic disperses authority among network nodes, eradicating the need for central oversight. Integral cryptographic techniques bolster data security and integrity [9]. The consensus mechanism arranges validation and transaction sequencing, often via Proof of Work (PoW) or Proof of Stake (PoS). This distributed ledger is bolstered by redundancy across network nodes, thwarting single points of failure. Smart contracts enable self-executing agreements. Blockchains can be public or private, and they imbue data with immutability, making alterations difficult. Furthermore, their permissioned or permissionless nature adds a layer of flexibility to their applications. These multifaceted features collectively empower blockchain's versatility in diverse domains, from cryptocurrencies to supply chain management and beyond [8]. Figure 1 represents blockchain working mechanism, showcasing decentralized, secure, and transparent data sharing among validating nodes, ensuring integrity and traceability in information recording and verification.

## LITERATURE REVIEW

CCUS plays a pivotal role in global climate change mitigation, particularly in challenging industries. Recent advancements emphasize trade-offs between economics and environmental impact, showcasing the benefits of CCUS in achieving net-zero energy systems [10].

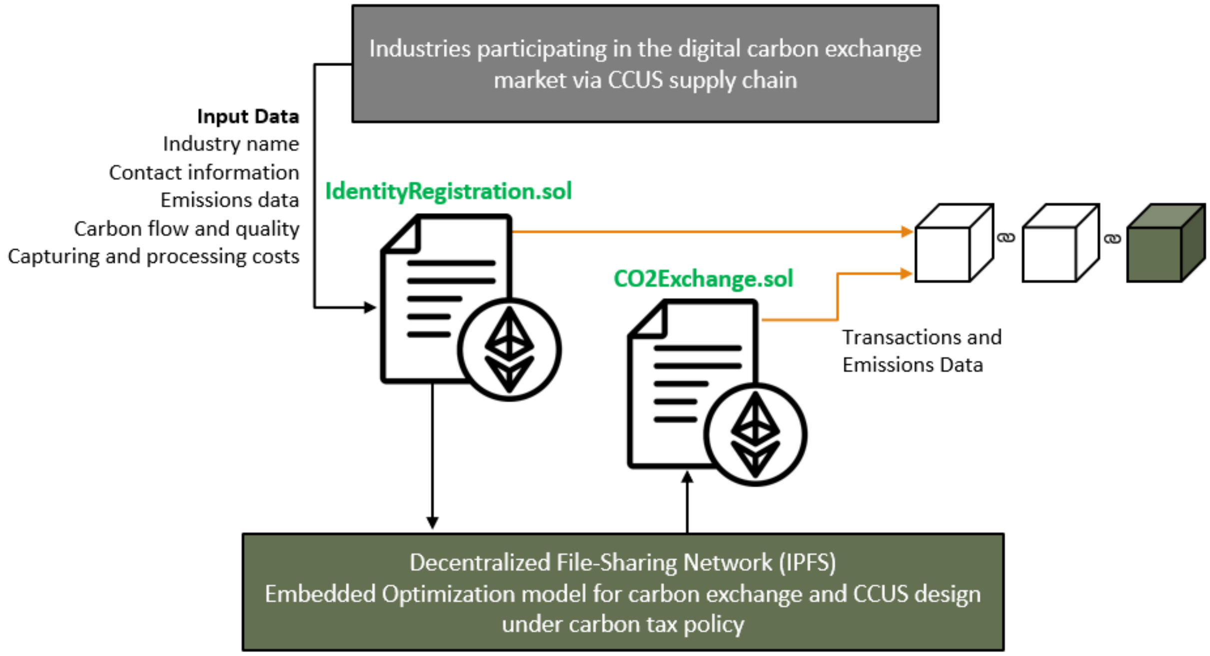


**Figure 2:** Depicting the interactions among developed smart contracts within the proposed framework.

Another study focused on optimal cost and environmental benefits of deploying CCUS supply chains at scale in Guangdong Province, China [11]. Some researchers evaluated comprehensive benefits of CCUS networks in coal-fired power plants [12], while others optimized CCUS deployment considering carbon neutrality, cost efficiency, and water stress [13]. These studies highlight evolving CCUS models, addressing economic viability, environmental impact, and sector-specific applications.

Carbon tax is pivotal in incentivizing CCUS adoption. The impact on CCUS source-sink matching in China was analyzed [14], and a stepwise deployment strategies was proposed in Canada based on varying carbon tax levels [15]. CCUS systems in Italy and Germany were explored considering carbon tax in their comprehensive objective function [16]. Other work delved into a risk management framework under carbon tax uncertainties [17], and $CO_2$ storage potential in shale reservoirs was assessed factoring in economic viability and carbon tax implications [18]. These studies emphasize the role of carbon taxes in shaping CCUS strategies.

Blockchain integration transforms CCUS governance. A blockchain-based carbon trading mechanism was proposed [19], and a permissioned blockchain for emissions trading was modeled [20]. A Sovereign blockchain for carbon trading was explored [21] and a token-based economy for carbon trading was suggested [22]. The intersection of blockchain, carbon trading, and CCUS governance offers a promising avenue for transparency and efficiency in climate change mitigation.

Existing literature focuses largely on CCUS modeling, optimization, and the impact of carbon taxes, leaving a research gap in exploring blockchain's potential beyond carbon trading in the CCUS landscape. This study addresses this gap by proposing an approach for integrating blockchain into CCUS supply chain optimization models under carbon tax influence. By harnessing blockchain's transparency and tamper-proof nature, we aim to enhance data accuracy, prevent fraud, and foster global collaboration for effective climate change mitigation. This integration offers a comprehensive solution to key challenges in CCUS governance, contributing to a sustainable future.

## PROPOSED APPROACH

Transparency of the CCUS supply chains necessitates the inclusion of emissions and cost data from various stages, encompassing $CO_2$ capture, compression, utilization, and geological storage. To enhance transparency in designing CCUS supply chains with consideration of carbon tax, this study provides a framework integrating blockchain technology. This integration involves embedding the CCUS-carbon tax optimization model with the blockchain network, aiming for an optimal CCUS network design that fosters improved transparency in emissions reduction, tracking, and cost management. The integration ensures the recording of emissions and cost data, facilitating transparent emission reduction verification and limiting carbon leakage. The proposed framework empowers CCUS network optimization under carbon tax, fostering a distributed ledger containing transparent CCUS emissions and cost data across various stages.

In this study, we developed two smart contracts utilizing Solidity, the primary programming language for crafting smart contracts on the Ethereum blockchain platform. These contracts, named IdentityRegistration.sol and CO2Exchange.sol, were meticulously designed to support our research framework. To verify their integrity and operational effectiveness, both smart contracts underwent a comprehensive process of compilation, testing, and deployment. This rigorous validation process ensured that they met our stringent requirements for security, efficiency, and reliability, making them integral components of our blockchain-based CCUS system.

The IdentityRegistration.sol smart contract constitutes the foundational layer of our blockchain-based system. This pivotal contract is designed to facilitate a range of critical activities, including the registration of new industries and verification entities. It enables the enrollment of carbon sources, sinks, and verifiers by capturing essential details such as name, industry, address, contact information, email address, industry identification number (ID), verifier ID, carbon flow characteristics, quality parameters, physical properties, and associated costs, including treatment expenses for sources and processing charges for sinks, alongside data on secondary emissions. This smart contract incorporates functions that allow for the retrieval of information about registered entities, enhancing transparency and accessibility within the system. A significant feature of this contract is its built-in mechanism to prevent duplicate registrations, thereby ensuring the integrity of the registration process. It achieves this by conducting preliminary checks against existing records before finalizing any new registrations, thus maintaining an accurate and reliable database of participants in the CCUS ecosystem.

The CO2Exchange.sol smart contract is a critical component of our blockchain-based framework for managing the CCUS supply chain under carbon tax, facilitating the effective exchange and utilization of captured carbon dioxide. This contract is designed to execute several key functions crucial for the transparency and efficiency of the CCUS process. It is responsible for accurately documenting carbon emissions at each stage of the CCUS supply chain, including emission sources, treatment units, transportation mechanisms, and storage or utilization sinks. Additionally, it enables the seamless transfer of funds among carbon sources, sinks, and the government, thereby ensuring compliance with carbon tax regulations and supporting the economic aspects of carbon trading by managing the flow of funds within the system. This includes the recording of all related transactions, providing a transparent and immutable ledger of carbon emissions and financial exchanges.

**Table 1:** Algorithms of Smart Contracts.

**IdentityRegistration.sol: Initializing $CO_2$ utilization and exchange**

1. Declare a contract called IdentityRegistration.
2. Define structs for Sources, and Sinks considering relevant information such as industry name, type, address, contact information, email, industry ID, carbon flow, and quality.
3. Define struct for Verifiers including relevant information such as verifier name, industry, contact information, email, and verifier ID.
4. Define mapping variables to map industry ID to Source/Sink structs.
5. Define mapping variables to map verifier ID to verifier struct.
6. Define events for NewSource, NewSink, and NewVerifier.
7. Define functions to register new industries and verifiers and retrieve their information.

**CO2Exchange.sol: Transaction and tokenization process**

1. Declare a contract called CO2Exchange.
2. Define struct for $CO_2$ transaction.
3. Define mapping variables to map transaction ID to the transaction struct.
4. Define function to record emissions from each stage including sources, capturing units, transportation, and sinks.
5. Define function to transfer funds from sinks to sources and from sources to government.
6. Define function to record transactions.

The operational logic and step-by-step functionality of these smart contracts are detailed in Table 1, providing a clear schematic of their roles within the CCUS system. Figure 2 visually depicts the dynamic interactions facilitated by the developed smart contracts, illustrating how they interconnect within the blockchain-enabled CCUS supply chain under carbon taxation. This representation underscores the smart contracts' pivotal role in streamlining the CCUS process to form a cohesive system that not only tracks carbon emissions and transactions but also facilitates the regulatory and economic mechanisms essential for effective carbon management and mitigation efforts.

The commencement of the CCUS-blockchain system takes place upon the availability of emissions and cost data, resulting in the creation of a new block. This block then undergoes a secure and decentralized distribution process among validating and authorizing nodes, with the assumption that both government entities and

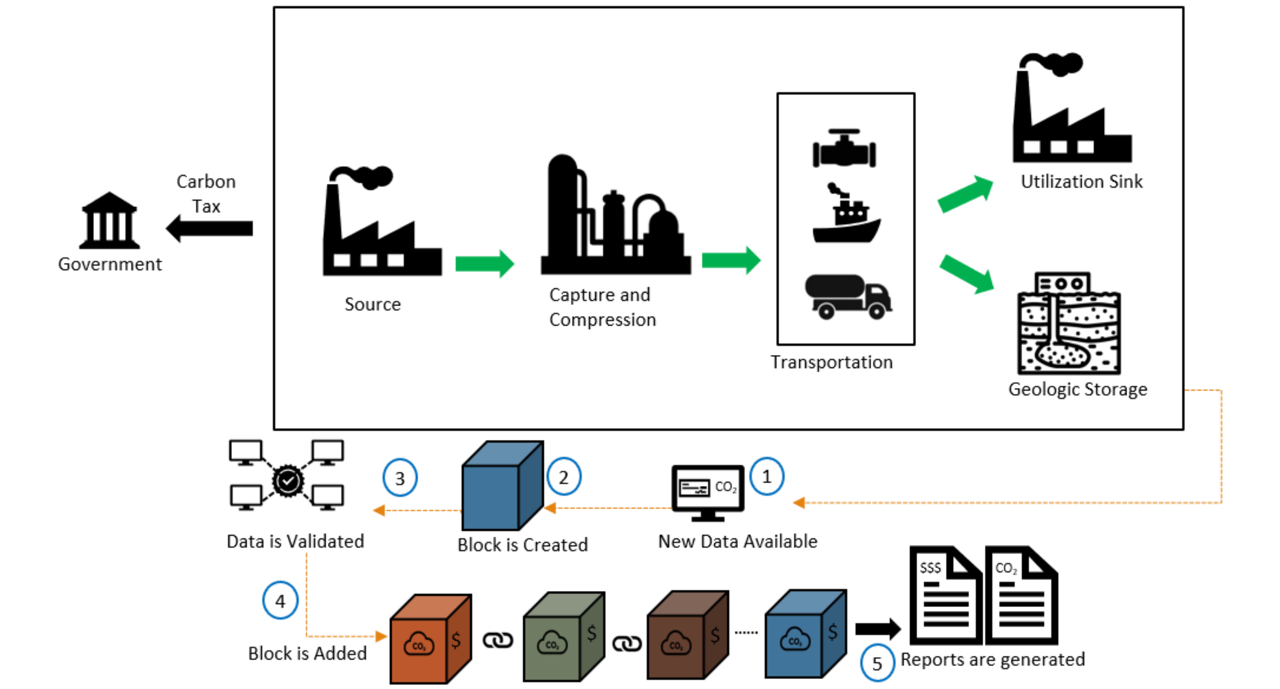


**Figure 3:** Illustrating the synergy: blockchain, CCUS optimization, and carbon tax compliance for sustainable

participating industries hold authorized access. The confirmed data blocks are smoothly added to the ongoing sequence by network nodes, safeguarded by distinctive hashes and the hash of the preceding block. Emissions and cost data from each stage are documented within authenticated and encrypted blocks, assuring the preservation of data integrity across the entire blockchain network. Figure 3 demonstrates the proposed approach, integrating CCUS-carbon tax optimization models with a blockchain network for enhanced transparency in emission and cash flow tracking.

Incorporating blockchain technology within the CCUS carbon tax nexus presents a promising avenue for enhancing data integrity, transparency, and stakeholder trust. However, it introduces certain risks and drawbacks that necessitate careful consideration for successful implementation. The adoption of blockchain technology significantly increases the operational complexity of the CCUS supply chain. Establishing a blockchain infrastructure requires substantial initial investments not only in technology but also in training personnel and developing new operational protocols. This upfront cost and the effort needed for integration can deter stakeholders, particularly in regions where CCUS technologies are still in nascent stages. The complexity associated with blockchain can also slow down the decision-making processes, potentially delaying critical CCUS deployments needed to meet urgent carbon reduction targets.

While blockchain enhances data sharing and transparency, it raises significant data privacy concerns. The immutable nature of blockchain means that once data is entered, it cannot be altered or removed, posing potential risks in handling sensitive or proprietary information. Ensuring that the blockchain architecture complies with global data protection regulations requires sophisticated solutions that can segregate and protect sensitive data without undermining the benefits of transparency and traceability that blockchain offers. A notable paradox in utilizing blockchain for environmental initiatives like CCUS is the technology's own environmental footprint, particularly for systems that rely on energy-intensive consensus mechanisms like Proof of Work (PoW). The additional energy consumption required for blockchain operations could contribute to the greenhouse gas emissions that CCUS seeks to
mitigate. This aspect is critically important when considering the
overall sustainability and environmental impact of integrating blockchain into CCUS frameworks.

As CCUS initiatives expand, the blockchain system must be able to scale accordingly without compromising performance or security. Achieving scalability while maintaining the decentralized nature of blockchain poses technical challenges. Furthermore, the decentralized decision-making process inherent in blockchain networks requires consensus among all participants, which can be difficult to achieve across a diverse stakeholder group with varying interests, technological readiness, and priorities. To overcome these challenges, collective efforts from stakeholders, government bodies, and technological experts are imperative to ensure the smooth integration of CCUS supply chains with blockchain technology, facilitating transparent and effective strategies for emission reduction and cost management.

Considering these complexities, our research emphasizes the need for a balanced approach that leverages blockchain's strengths while addressing its inherent drawbacks. We propose a blockchain architecture that combines the transparency and immutability of public and private blockchain features through smart contracts. This approach, coupled with the development of smart contracts tailored to automate and streamline CCUS-specific operations, aims to minimize the operational and environmental drawbacks of blockchain, ensuring that its integration into the CCUS carbon tax nexus contributes positively to the global effort against climate change.

The consensus mechanism adopted in this study is the Delegated Proof of Stake (DPoS), which is strategically chosen for its efficiency in reducing the computational power required for transaction validation and consensus achievement. Unlike the conventional Proof of Work (PoW) mechanism, which is known for its high energy consumption and consequent environmental emissions, DPoS significantly minimizes these impacts. This approach not only aligns with our environmental sustainability goals but also enhances the overall efficiency and scalability of the blockchain network by delegating the responsibility of transaction validation and block creation to a select group of trusted elected representatives. This mechanism ensures a more environmentally friendly and cost-effective solution for the blockchain framework employed in our CCUS system under carbon tax policy.

Our approach introduces a blockchain architecture within the CCUS carbon tax nexus, significantly advancing current methodologies by balancing the need for transparency, data integrity, and stakeholder privacy. The proposed approach utilizes public and private features of smart contracts. It ensures the immutability and transparency critical for public trust and regulatory compliance while also providing the privacy and scalability necessary for industrial adoption and efficient operation. This innovative framework addresses key concerns around data privacy, scalability, and operational complexity that have hampered broader blockchain application in environmental and carbon management systems.

A cornerstone of our approach is the strategic use of smart contracts to automate critical processes within the CCUS supply chain, from carbon emission verification to carbon tax computation and compliance reporting. This automation significantly reduces administrative overhead, minimizes human error, and speeds up the decision-making process, allowing for more dynamic and responsive CCUS operations. Moreover, by eliminating the need for third-party verification, we expect to see a reduction in operational costs, further incentivizing the adoption of CCUS technologies by industries.

The expected benefits of our approach are profound. By enhancing the transparency and integrity of carbon and tax data, we aim to foster greater trust among stakeholders, including regulatory bodies, industries, and the public, thereby facilitating a more collaborative and efficient approach to carbon management. The reduction in operational costs and the improved efficiency of regulatory compliance processes are anticipated to accelerate the deployment of CCUS technologies, contributing significantly to global efforts to mitigate climate change. Furthermore, the environmental impact of blockchain operations is minimized through our energy-efficient blockchain design, aligning the technology's application with the overarching goal of reducing greenhouse gas emissions.

In essence, our approach not only addresses the immediate challenges faced by the CCUS carbon tax nexus but also sets a new standard for the integration of blockchain technology in environmental governance, promising a more sustainable, transparent, and efficient framework for global climate change mitigation efforts.

## ILLUSTRATIVE EXAMPLE

This section presents an illustrative case study for the proposed approach of integrating CCUS optimization models with consideration for carbon tax implications through blockchain technology. The methodology builds upon a previously developed Mixed Integer Non-Linear Optimization Model (MINLP) [23]. The objective function, as expressed in Equation (1), seeks to minimize the Total Annual Cost (TAC), encompassing tax cost $C_s^{Tax}$, treatment $C_{s,k}^{Treat}$, compression $C_{s,k}^{Comp}$, transportation $C_{s,k}^{Trans}$, and utilization $C_{s,k}^{Sinks}$ costs.

The objective function subject to constraints ensuring that the carbon flow from each source equals the treated flowrate $T_{s,k,t}$ ,untreated flowrate $U_{s,k}$, and $CO_2$ emissions to the atmosphere $R_{s,emit}$ as indicated via Equation (2). The $CO_2$ utilized in each sink $F_k$ defined as the sum of treated $T_{s,k,t}$ and untreated $U_{s,k}$ $CO_2$ transported from different sources as shown in Equation (3). Chemical absorption amine units were employed for $CO_2$ treatment due to its maturity. The costs associated with capturing, compression, transportation, and utilization were computed following the methodology outlined in [23].

$$TAC = C_s^{Tax} + C_{s,k}^{Treat} + C_{s,k}^{Comp} + C_{s,k}^{Trans} + C_k^{Sinks} \quad (1)$$

$$R_s = \sum_{k\in K}\sum_{t\in T} T_{s,k,t} + \sum_{k\in K} U_{s,k} + R_{s,emit} \; ; \; \forall \; s \mathcal{E} S \quad (2)$$

$$F_k = \sum_{s\in S}\sum_{t\in T} T_{s,k,t} + \sum_{s\in S} U_{s,k} \; ; \; \forall \; k \mathcal{E} K \quad (3)$$

Data detailing $CO_2$ composition ($X_{CO2}$), flow rate, treatment cost parameter ($C_t$), sink processing cost parameter ($C_s$), and emission factors ($C_e$) which are expressed in tons of $CO_2$ emitted per tons of $CO_2$ processed, for $CO_2$ sources and sinks were acquired following the registration of emission sources and sinks through the IdentityRegistration.sol smart contract. The data are presented in Tables 2 and 3, respectively. $CO_2$ compositions and flow rates exhibit variations across industries. This study examined four carbon emission sources: ammonia production facility, steel-iron mill, power generation plant, and refinery. Furthermore, it included five carbon dioxide sinks, specifically: algae-based carbon utilization system, saline aquifer storage, and the production processes for methanol, urea, and acetic acid. The study sets a target net emission reduction limit of 2.48 MM t $CO_2$/yr and a tax rate of 50 $/t $CO_2$. Industrial facilities face a decision to either adopt CCUS technologies or remit a carbon tax to meet the government-mandated net emissions reduction target. The choice is based on minimizing the total annual cost. All plants are assumed to operate 8000 h per year. The blockchain-based CCUS-carbon tax optimization model was implemented, and the results are discussed below.

**Table 2:** Carbon dioxide source data.

| **Source** | **$X_{CO2}$ (wt%)** | **$CO_2$ Flow (t/d)** | **$C_t$ ($/t $CO_2$)** |
|---|---|---|---|
| Ammonia | 100 | 977 | 0 |
| Steel-iron | 44 | 3451 | 29 |
| Power plant | 7 | 9385 | 43 |
| Refinery | 27 | 1092 | 35 |

**Table 3:** Carbon dioxide sink data.

| **Sink** | **$X_{CO2}$ (wt%)** | **Flow (t/d)** | **$C_s$ ($/t $CO_2$)** | **$C_e$ (t/t $CO_2$)** |
|---|---|---|---|---|
| Algae | 6 | 344 | -7 | 0.28 |
| Storage | 94 | 7500 | 9 | 0 |
| Methanol | 99 | 2072 | -20 | 0.17 |
| Urea | 99 | 1488 | -17 | 0.11 |
| Acetic Acid | 99 | 2500 | -26 | 0.34 |

The optimal design achieved, through the implementation of CCUS, a carbon reduction of 1.5 million tons of $CO_2$ per year, while the remainder of the net reduction goal was released into the atmosphere and subsequently subjected to taxation. The total annual cost of the optimal design is 19 MM $/yr, with a carbon tax cost amounting to 49 MM $/yr. Table 4 delineates the composition of the net carbon dioxide reduction target, illustrating that a significant portion was achieved through the implementation of CCUS technology, while the remainder, not captured, was emitted, and subsequently subjected to taxation. This underscores the efficacy of carbon taxation as a driving force behind the adoption of CCUS technologies.

**Table 4:** Analysis of carbon dioxide emission reduction target.

| **Element** | **Flow (MM t $CO_2$/yr)** |
|---|---|
| Net reduction target | 2.48 |
| Carbon captured | 1.5 |
| Carbon emitted | 0.98 |

Optimal source to sink carbon allocations were identified and presented in Figure 4. The percentages on the left side of Figure 4 depict the $CO_2$ usage across different sources, whereas the percentages on the right show how well the $CO_2$ demands of each sink were satisfied. $CO_2$ from all sources was fully captured, utilized, or stored, except from the power plant as the low carbon quality limited utilization. To meet the government's targeted net reduction, $CO_2$ was directed towards economically profitable sinks such as algae, methanol, urea, and acetic acid, where the demand for carbon was completely satisfied, leveraging the economic benefits derived from these $CO_2$ utilization pathways. Conversely, the use of saline storage as a sink was not maximized due to its associated higher costs, including those for treatment, transport, and processing. Consequently, the $CO_2$ that was not sequestered or utilized was released into the atmosphere, resulting in it being subject to carbon taxation.

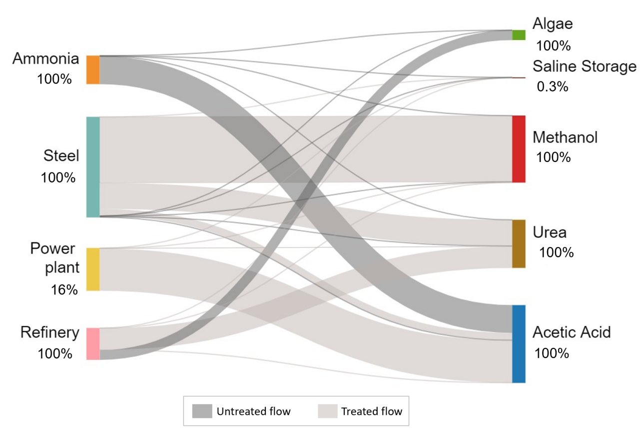


**Figure 4:** $CO_2$ source to sink allocation for the proposed system.

Most of the carbon demands for the algae sink are satisfied by the refinery's emissions, which do not require further treatment to align with the algae's carbon flow and quality specifications. Carbon from the steel-iron sector is predominantly processed and then used to supply the necessary carbon flow for both methanol and urea production. The carbon requirements for the methanol sink are primarily fulfilled using processed carbon emitted by the steel-iron facility, whereas urea benefits from treated carbon emissions from both steel and refinery operations. Additionally, the carbon demands for acetic acid production are mainly met by emissions from ammonia and power generation plants. Notably, most of the carbon utilized in these processes is treated, except for the direct use of pure $CO_2$ from ammonia sources and emissions from refineries to algae sinks. This exception is due to the refinery's emissions directly meeting the algae's relatively low-quality carbon requirements.

Table 5 illustrates carbon emissions at various stages of the CCUS process, encompassing emissions from sources, capture units, transportation, and sinks. The emissions detailed on the source side reflect those discharged post-CCUS implementation. The predominant sources of emissions are identified as the main source of emissions, succeeded by carbon sinks, transportation, and capture facilities in terms of contribution. All emissions data are logged as transactions in the blockchain, facilitating the monitoring of $CO_2$ emissions throughout the CCUS supply chain.

**Table 5:** Carbon dioxide emissions from CCUS subsystems.

| CCUS module | Flow (t $CO_2$/d) |
|---|---|
| Sources | 7883 |
| Capturing unit | 190 |
| Transportation | 245 |
| Sinks | 1462 |

Each transaction plays a crucial role in ensuring accountability, traceability, and reliability throughout the optimal CCUS network. The first transaction provides carbon dioxide generation data from sources, providing a foundation for mitigation strategies. The second transaction records emissions data from treatment units and the third transaction details emissions during compression and pumping, crucial for evaluating the environmental impact of transportation. The fourth transaction monitors sinks emissions, offering insights into sink's effectiveness. The final transaction summarizes financial aspects, including carbon tax payments, and total annual cost essential for assessing the project's economic viability and ensuring sustainable carbon management.

The blockchain-based optimal CCUS supply chain ensures transparency, accountability, and trust throughout the CCUS process, supporting environmental and economic goals. The study successfully meets the net emission capture target, and comprehensive results, encompassing both carbon dioxide flow rates and financial implications, are securely recorded in the blockchain, ensuring tamper-proof integrity.

## CONCLUSIONS

This study highlights the significant potential of blockchain technology to enhance transparency, efficiency, and regulatory compliance in CCUS supply chains under carbon tax regimes. By developing and implementing the IdentityRegistration.sol and CO2Exchange.sol smart contracts, we established a framework for automating carbon emissions tracking and regulatory reporting, addressing key challenges such as emission verification and carbon leakage. The adoption of the Delegated Proof of Stake (DPoS) consensus mechanism further aligns our approach with environmental sustainability by minimizing the energy consumption of blockchain operations. Our case study demonstrates that a substantial portion of carbon reduction targets can be met through CCUS, with carbon taxation serving as a compelling incentive for technology adoption. This research contributes to the optimization of CCUS networks, offering a scalable and sustainable solution to climate change mitigation and highlighting the critical role of innovative technologies in achieving global sustainability goals.

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