European Journal of Sustainable Development (2025), **14**, 3, 330-344 ISSN: 2239-5938
Doi: 10.14207/ejsd.2025.v14n3p330

Blockchain-enabled Carbon Dioxide Removal: A Decentralized Framework for Transparent and Scalable Climate Mitigation

By Zihan CHEN[1], Jia LI[2]

ABSTRACT:
Carbon Dioxide Removal (CDR) technologies are pivotal for achieving global climate targets, yet their scalability and operational efficiency remain constrained by fragmented data management, energy-intensive processes, and insufficient transparency in carbon accounting. This study explores the integration of consortium blockchain technology into CDR systems to tackle the barriers, emphasizing its potential to enhance environmental sustainability. A hybrid blockchain framework is proposed, combining decentralized governance with IoT-enabled monitoring to improve data integrity, automate carbon footprint verification, and optimize energy consumption across CDR operations. Key innovations include a dynamic consensus mechanism for real-time stakeholder collaboration and cryptographic protocols for secure, auditable record-keeping. Initial simulations demonstrate a 22-30% reduction in administrative overheads and a 15% improvement in data accuracy compared to conventional systems, highlighting the model's capacity to strengthen accountability in emissions reporting. By enabling interoperable, tamper-proof data sharing, the system fosters trust among policymakers, investors, and technology providers—critical for accelerating NET deployment under the Paris Agreement. This work advances the discourse on digital solutions for climate action, offering a scalable architecture to align CDR implementation with sustainable development goals. Further validation through industrial pilots will refine its economic and technical feasibility.

Keywords: Carbon Dioxide Removal, Blockchain, Carbon Emissions Reduction, Sustainability, Consensus Mechanism

1. Introduction

The Intergovernmental Panel on Climate Change (IPCC) emphasizes that constraining global temperature rise to under 1.5° C is imperative to avert irreversible ecological degradation, threats to agricultural stability, and urban infrastructure vulnerabilities (Calvin et al., 2023). Meeting this threshold demands slashing annual CO_2 emissions to 25–30 Gt by 2030, alongside large-scale adoption of carbon removal strategies, as mandated by the Paris Agreement's climate action protocols (Bongaarts, 2019; Levin, 2018). Carbon Dioxide Removal (CDR), a subset of Negative Emission Technologies (NETs), has gained prominence for its capacity to extract atmospheric CO_2 at dilute concentrations (around 0.04%), offering scalability absent in conventional Carbon Capture and Storage (CCS) systems, which grapple with site dependency and elevated operational costs (Erans et al., 2022; Wang et al., 2024). Notably, the International Energy

[1]Zihan CHEN, Affiliation: Thrust of Carbon Neutrality and Climate Change, The Hong Kong University of Science and Technology (Guangzhou), China
[2]Jia LI, Affiliation: School of Interdisciplinary Studies, Lingnan University, Hong Kong SAR, China.

Agency (IEA) identifies CDR' s dual utility: enabling permanent carbon sequestration for decarbonization pathways and supplying sustainable feedstocks for sectors like aviation and chemical manufacturing. Emerging applications extend to transportation systems (He et al., 2022), industrial decarbonization, and specialized environments such as indoor air quality enhancement (Miao et al., 2022).

Growing recognition of CDR's potential has driven substantial investment momentum: Over $4 billion has been allocated globally since 2020 for research and deployment efforts alongside private-sector capital raising exceeding $125 million annually (International Energy Agency, 2022). However, scaling CDR requires overcoming technical barriers, including energy intensity, lifecycle management, transparency in carbon tracking, secure trading mechanisms, financial viability, and stakeholder coordination (Bisotti et al., 2024).. These multidimensional challenges extend beyond engineering into policy economic domains necessitating integrated solutions. This paper proposes blockchain technology integration framework address these gaps enhancing efficiency accuracy scalability operations Specifically consortium system improves identity verification data collection cross-stakeholder collaboration while ensuring immutable secure record-keeping advancing both environmental goals technological innovation nexus.

2. Barriers to Large-Scale Deployment of CDR Technology

The global adoption of Carbon Dioxide Removal (CDR) technology faces multifaceted challenges, despite its recognition as a critical climate solution (Qiu et al., 2022). These barriers span technical, environmental, economic, social, and political dimensions. Scaling CDR requires overcoming material limitations and system integration complexities. Structured adsorbents show improved capture efficiency (e.g., Wu et al., 2024), but real-world durability remains uncertain. Laboratory conditions often miss dynamic stressors like humidity, temperature extremes, and aerosol interference (Bui et al., 2018), requiring accelerated aging tests and field pilots to validate performance. Trace pollutants (e.g., VOCs, heavy metals) in air streams (Küng et al., 2023) can poison adsorbents, necessitating adaptive designs like modular filtration or self-regenerating surfaces. Future CDR deployments should prioritize site-specific risk assessments with IoT sensors to optimize resilience across environments. Energy demand dominates CDR's environmental footprint. Studies project that removing 288 Mt CO_2 annually in Europe could increase electricity consumption by 385–495 TWh_{el} by 2050, necessitating sustainable energy to avoid emissions displacement (Erans et al., 2022). Life cycle assessments reveal trade-offs between sequestration efficiency and secondary impacts like ecotoxicity or metal depletion across sorbent types (Leonzio et al., 2022; Deutz & Bardow, 2021). Spatial planning is also critical: regional climatic anomalies–such as tropopause cooling–highlight site-specific risks requiring mitigation strategies during deployment (Bodai et.al., 2018). Economic considerations are pivotal in the widespread implementation of CDR technologies. Producers of solvent-based and sorbent-based CDR solutions have estimated cost estimates for atmospheric CO2 removal, which vary between approximately $95 and $600 per ton. Current cost estimates for CO_2 removal range widely (\$95–600/tCO_2), reflecting divergent assumptions about energy prices and technological maturity (Valentine et al., 2022). Though optimistic projections suggest costs could fall below \$150/tCO_2 with scaling these forecasts hinge on sustained RD&D investment infrastructure standardization(Lux et al., (2023).

Despite expert consensus advocating policy incentives governments lag allocating resources integrate into national strategies. Through a survey, Kerner (2023) found strong support for BECCS and CDR among climate experts, emphasizing that policy support and market incentives are essential for advancing CDR technologies. Bisotti et al. (2023) examine how national-level context and dynamics influence CDR deployment within specific countries. For instance, Norway case underscores importance tailoring deployments local energy contexts natural resource availability rather than one size fits all approaches. Moreover, persistent fossil fuel subsidies with regulatory inertia hinders transition carbon negative economies. Public acceptance of CDR is essential for successful implementation. Support for CDR often depends on perceived fairness and alignment with broader climate objectives. Cox et al. (2020) highlight skepticism about whether technological fixes address the root causes of the climate crisis. Motlaghzadeh et al. (2023), after analyzing Direct Air Capture (DAC) deployment in the AR6 database, examined 54 CDR scenarios and identified key factors influencing model projections. Their research team suggests that the utilized carbon reduction models in the future should incorporate diverse CDR technologies and pathways for carbon utilization and storage.

The global deployment of CDR technologies remains nascent, requiring coordinated strategies to address scalability challenges in both industrial-scale plants and modular urban applications (Meckling and Biber, 2021). To navigate these complexities blockchain technology emerges as a transformative tool enabling transparent traceable management frameworks critical for CDRs multifaceted demands For instance Regional CDR Hubs could leverage decentralized systems streamline data sharing verification processes The subsequent sections detail this integration proposing structured blockchain framework optimize deployment accountability.

3. Advancing CDR Deployment via Utilizing a Blockchain-enabled Strategy

For large-scale deployment of Carbon Dioxide Removal (CDR), it is crucial to enhance efficiency, reduce costs, and increase societal acceptance. Studies show that CDR impacts multiple dimensions and synergizes with other Negative Emission Technologies (NETs) to meet global climate mitigation and carbon neutrality goals. Scott-Buechler et al. (2024) emphasize incorporating environmental justice in CDR projects to ensure community benefits, such as infrastructure improvements and job creation, which are vital for public support. Wang et al. (2020) suggest that improving efficiency and reducing CO_2 capture costs through innovation is essential. Innovations include optimizing integrated systems, monitoring energy use and carbon footprints, and improving adsorbent performance. While blockchain's immutability and transparency address CDR's data integrity needs (Drescher, 2017; Vigna and Casey, 2016), competing technologies like machine learning (ML)-based platforms offer energy-efficient analytics, and cloud systems provide scalable storage. However, blockchain's decentralized consensus and tamper-proof ledger uniquely solve cross-stakeholder trust and auditability challenges critical for CDR accountability. The paper focuses on standalone blockchain framework. Notably, hybrid models integrating AI-driven insights or cloud infrastructure could enhance performance, and future research will explore these synergies to further improve CDR data transparency and operational efficiency.

3.1 Blockchain Fundamentals and Cross-Sector Applications

Blockchain technology operates as a decentralized, tamper-evident digital ledger that enables secure and transparent data sharing across distributed networks (Nakamoto, 2008; Wood, 2014). Its core characteristics—decentralization, immutability, security, and transparency (Table 1)—underpin its transformative potential.

Table 1: Core Characteristics of Blockchain

Characteristic	Description
Decentralization	Data storage and processing are distributed across nodes, eliminating reliance on centralized authorities.
Immutability	Blocks' cryptographic chain ensures data cannot be retroactively altered.
Security	Cryptographic hashing and consensus mechanisms protect data integrity.
Transparency	Participants can audit transaction records while preserving pseudonymity.

Blockchain relies on cryptographic hash functions to ensure data integrity (Hua et al., 2020). These functions convert variable-length inputs into fixed-length outputs (e.g., SHA-256 generates 256-bit digests). Key properties include: 1. Determinism: Identical inputs always produce the same hash. 2. Randomness: Minor input changes yield entirely distinct hashes. 3. Collision resistance: The probability of two inputs generating the same hash is negligible (Cachin, 2016; Nakamoto, 2008). For instance, altering a single character in the input string resulted in entirely unrelated hash values, demonstrating sensitivity to data modifications (Chen et al., 2024). Blockchain has been applied in diverse sectors, promoting industry integration and advancement (Zhai et al., 2019). Blockchain's applications span diverse sectors, particularly in enhancing sustainability through integration with Negative Emissions Technologies (NETs). Xu et al. developed a carbon management platform on Ethereum, leveraging public blockchain's transparency to securely disclose carbon data while enabling access to green finance markets (Xu et al., 2024). Similarly, Climeworks and CrabFix pioneered a permanent direct air capture and storage system using geothermal energy, though prior studies lacked blockchain integration in CDR systems. Cross-domain applications highlight blockchain's versatility: In supply chains, it ensures traceability and reduces fraud (He et al., 2023). The integration of IoT and AI ensures secure communication between devices and enhances data-driven decision-making (Sadawi et al., 2021, Pan et al., 2019, Hua et al., 2020). According to Upadhyay et al. (2021), blockchain contributes to sustainability and carbon reduction by reducing costs, enhancing supply and demand chain efficiency, and improving information and data sharing. Additionally, it supports green bonds and other green financial instruments, to make sure that funds are allocated to sustainable projects (Kim and Huh, 2020). Energy systems utilize blockchain for smart grid management and renewable energy distribution (Van Cutsem et al., 2020). In engineering management, via utilizing blockchain, efficiency and transparency are improved and the technology reduces resource waste, mitigates CO_2 emissions, then minimizes environmental damage and carbon dioxide increase (Chen, 2023; Mahmudnia et al., 2022; Yang et al., 2020). By combining decentralized trust with cryptographic security, blockchain enhances accountability in carbon tracking, supply chains, and environmental governance, positioning it as a cornerstone for sustainable digital infrastructure (Parmentola et al., 2022; Saari et al., 2022; Tönnissen and Teuteberg, 2020; Yeung, 2021).

3.2 Consortium Blockchain Architecture for CDR Deployment

Blockchain technology offers diverse frameworks for managing CDR projects, with consortium blockchain emerging as the optimal choice for multi-stakeholder collaboration. This section evaluates blockchain types and presents a tailored architecture for CDR deployment.

3.2.1 Blockchain Type Selection for CDR Deployment

Blockchain architectures are systematically classified into four primary categories according to three operational dimensions: data transmission protocols, network accessibility parameters, and authorization frameworks. These classifications comprise public chains (Nakamoto, 2008; Pilkington, 2016), private chains (restricted-permissioned)(Helliar et al., 2020), hybrid configurations combining both paradigms(Helliar et al., 2020; Zhu et al., 2020), and consortium networks governed by multi-institutional consensus(Dib et al., 2018; Li et al., 2017). Specifically, 1. Public Blockchain: Fully decentralized with open participation but limited scalability and energy-intensive consensus mechanisms (e.g., PoW). 2. Private Blockchain: Centralized control by a single entity, prioritizing speed and privacy but lacking transparency. 3. Hybrid Blockchain: Combines public and private features, enabling selective data transparency. 4. Consortium Blockchain: Governed by pre-authorized stakeholders, balancing decentralization with controlled access. CDR infrastructure demands rigorous data management across its lifecycle—from planning to decommissioning—encompassing energy consumption, carbon footprints, and stakeholder coordination (International Energy Agency, 2022). A consortium blockchain architecture is optimal for CDR deployment, addressing multi-stakeholder collaboration and tiered data access (Dib et al., 2018; Du et al., 2021; Meng et al., 2021; Zhu et al., 2020). Key considerations for blockchain selection includes 1. Database requirements: track energy use and carbon metrics, 2. Shared editorial access: assign role-based permissions (e.g., operators, suppliers). 3. Trust and consensus: validate data authenticity across organizations. 4. Decentralized maintenance: ensure collective accountability. Consortium blockchains excel in scenarios demanding controlled decentralization, such as CDR projects with predefined stakeholders (e.g., regulators, investors, and operators). Their role-based permissioning ensures sensitive data (e.g., proprietary sorbent formulations or financial transactions) remains restricted, while shared editorial access enables collaborative auditing without compromising privacy. This aligns with ISO 14064 standards for verifiable carbon credits, where immutability and stakeholder consensus are non-negotiable. As shown in Figure 1, by applying the blockchain type selection framework proposed by Turk and Klinc (2017), a consortium blockchain is selected as the most suitable approach to manage CDR project data deployment (Database and shared editorial access are needed, shareholders are trusted but their interests are not consistent, a trusted 3rd party is no need, functionality needs to be controlled, and the consensus is reached among different organizations). CDR projects benefit from consortium blockchain, which provides a transparent and tamper-proof system for monitoring CDR data, ensuring reliable traceability and alignment with climate goals.

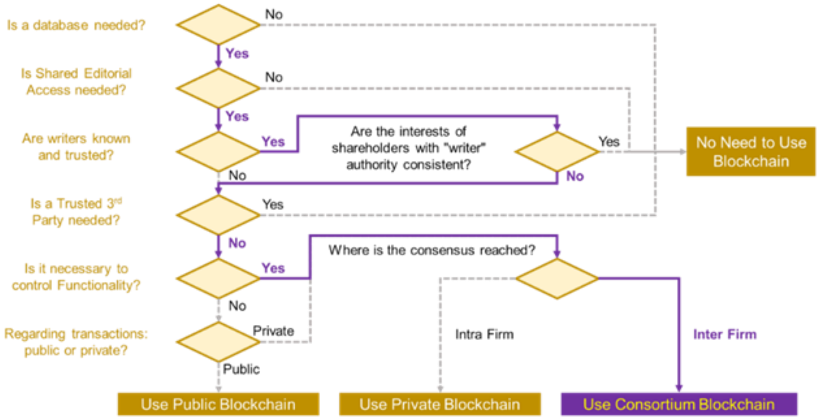

***Figure 1**: The Blockchain Type Selection Strategy for DAC Deployment.*

3.2.2 Decentralized CDR Management Framework

Currently, Carbon Dioxide Removal (CDR) projects are predominantly implemented in affluent regions such as the U.S., EU, Switzerland, and Canada. While these initiatives represent significant efforts to mitigate climate change, the total volume of CO_2 captured remains insufficient to address the greenhouse effect and global warming (Calvin et al., 2023; International Energy Agency, 2022). A critical challenge lies in the absence of blockchain encryption technology and decentralized storage solutions in global CDR projects, which undermines data authenticity and compromises traceability – particularly for cumulative emissions tracking over time. Integration hurdles with legacy infrastructure and limited blockchain literacy among CDR operators further exacerbate these gaps. Addressing this requires targeted capacity-building initiatives and modular system design to facilitate phased transitions from traditional to blockchain-based frameworks, ensuring scalable adoption without operational disruptions.

Blockchain technology, as a distributed ledger system, consists of interconnected blocks that record transactions over a defined period (Nakamoto, 2008; Wood, 2014). Each block is structured into two primary components: "Header" and "Body," as illustrated in Figure 2. The Header, essential for block identity and integrity, contains six key elements: version number, hash of the previous block header, Merkle Root, timestamp, current difficulty, and Nonce. These elements undergo cryptographic hashing to generate a unique hash value, which links successive blocks and ensures data immutability (Cachin, 2016). The Body stores transaction data, which is encapsulated in the Merkle Root, contributing to the overall hash of the block. The timestamp embedded in each block header enables chronological series g, allowing blockchain nodes to trace data back to its origin and verify its authenticity, thereby enhancing transparency and security across the blockchain network (Cachin, 2016). The block body's data is organized within a Merkle tree structure, which leverages hash functions to create a binary tree where each leaf node represents individual data blocks or transactions (Alzubi, 2021; Cachin, 2016). Each leaf node contains the hash of specific data, while higher-level nodes aggregate these hashes, culminating in the Merkle Root. This structure relies on collision-resistant properties of Hash functions, making it computationally infeasible to alter data without any detection (Alzubi, 2021; Cachin, 2016). Each data file within the block body is hashed using the SHA-256 algorithm, with the resulting hashes forming the lowest level of the tree. These hashes are then paired and rehashed iteratively to produce the Merkle Root. Any modification to the data within the body of the block will alter the value of Merkle Root due to pointer linkage. The cryptographic hash function's collision-resistant and one-way properties ensure that data tampering results in detectable changes to hash values, underpinning the blockchain's tamper-proof nature. Consequently, the Merkle Root serves as a critical mechanism for securing the integrity of both the header and body.

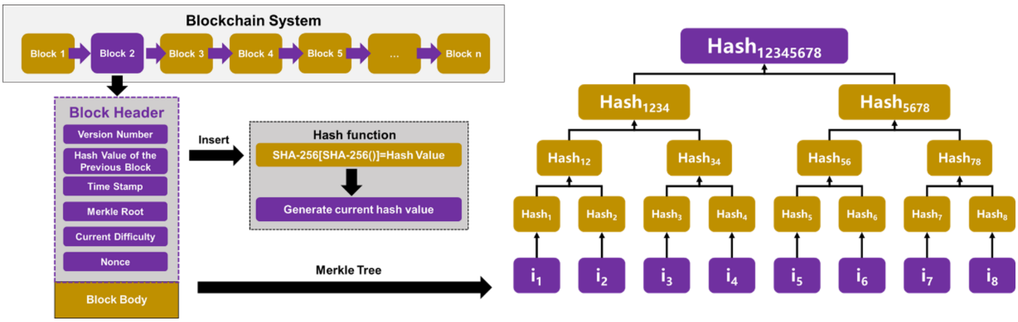

***Figure 2**: Components of the "header" and "Body" with structure of "Merkle Tree".*

This consortium blockchain architecture (as shown in Figure 3) establishes a permissioned network that integrates diverse stakeholders in CDR projects. Within this framework, premium nodes–such as CDR operators and technology providers–are granted full editorial rights to manage core functionalities, while standard nodes–including suppliers, investors, and regulators–operate under restricted access protocols. Automated governance, enforced through smart contracts, ensures role-based permissions and generates immutable audit trails. To safeguard data integrity, the system employs consensus protocols like Proof of Stake or Delegated PoS[1], where validators stake tokens to authenticate transactions. Cryptographic hashing and timestamped block chaining create tamper-evident records, while hierarchical aggregation of transactional data via Merkle trees embeds a root hash into the block header. Any unauthorized alteration disrupts this root hash, enabling rapid tamper detection. Secure data sharing is achieved

[1] Delegated Proof-of-Stake (DPoS) is an enhanced variant of the Proof-of-Stake consensus mechanism. In this framework, stakeholders elect designated delegates to validate transactions and maintain network security. DPoS introduces a scalable and democratic approach to blockchain transaction validation, enabling efficient consensus through decentralized delegation while balancing performance and governance. (Source: Wikipedia)

through digital signatures for identity authentication and dual-key encryption for confidential peer-to-peer communication, eliminating reliance on third-party intermediaries.

This architecture enhances transparency by enabling real-time auditing of critical metrics (e.g., CO_2 capture volumes, energy consumption) across stakeholders. Interoperability is achieved by integrating IoT[2] sensors that feed operational data directly into the blockchain, automating compliance reporting. Immutable records align with carbon credit verification standards (e.g., ISO 14064), fostering regulatory trust. However, implementation challenges include technical integration with legacy systems via API-driven middleware, prioritizing energy-efficient consensus mechanisms to align with CDR sustainability goals, and adopting scalable solutions like sharding or sidechains to manage expanding datasets. A phased pilot approach, beginning with regional CDR initiatives, is recommended to validate the framework's efficacy before global scaling, ensuring robustness and adaptability to evolving regulatory and operational demands.

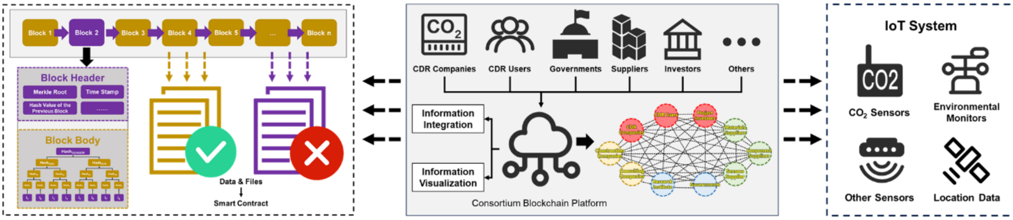

***Figure 3**: Decentralized CDR Deployment Consortium Blockchain System.*

In the designed blockchain system, access privileges and roles for CDR project stakeholders are clearly defined, allowing data to be securely shared according to permissions. The decentralized nature enhances data security, as tampering would require altering the entire network. The consensus mechanism ensures proper enforcement of differentiated access rights, validating data and permissions. However, due to the distributed nature of CDR project data and contractual constraints, disparities in data access and trust issues may arise. Themechanism of consensus tackles it by fostering a trustless situation, where the validation of data relies on network consensus rather than individual trust. Sensitive information is managed through a "double authentication" strategy, using digital signatures for confidential sharing without third-party verification, thus reducing energy consumption and communication costs. The proposed system could significantly advance carbon neutrality efforts by ensuring data immutability and security, reducing fraud risks, and allowing transparent tracking of carbon capture data. By utilizing smart contracts, it streamlines operations, enhances efficiency, and supports regulatory compliance, potentially attracting investment. Digital signature technology further secures identity verification.

Challenges include integrating existing CDR infrastructure with blockchain, which may require significant investment and technical adjustments. Scalability issues and

[2] The Internet of Things refers to a network of interconnected devices equipped with sensors, processing capabilities, and other technologies, enabling seamless communication and data exchange with other devices and systems over the Internet or other networks. These devices are characterized by their ability to collect, process, and transmit data autonomously, thereby facilitating intelligent interactions within distributed environments. (Atzori et al., 2010; Gazis, 2017; Gillis, 2021).

evolving regulatory landscapes could also hinder adoption, while efficiency in blockchain operations must be prioritized to avoid increasing footprints. Interoperability with other systems and cybersecurity must also be addressed. To overcome these challenges, a phased implementation approach is recommended, beginning with pilot projects. Developing integration frameworks, exploring funding, and using scalable architectures are essential. Energy efficiency can be improved by selecting platforms with energy-efficient consensus mechanisms and considering renewable energy sources. Interoperability should be achieved through open standards and cross-chain technologies, while robust cybersecurity measures and stakeholder education are crucial for successful adoption.

4. CDR Deployment Consortium Blockchain System

The consortium blockchain system for CDR deployment integrates functional modules and stakeholder interactions (Fig. 4) to streamline project lifecycle management. Figure outlines core modules – Creation, Contract Management, Document Review, Upload, and Modification, and employs a UML use case diagram to map interactions among key stakeholders: CDR companies, investors, construction firms, and regulators.

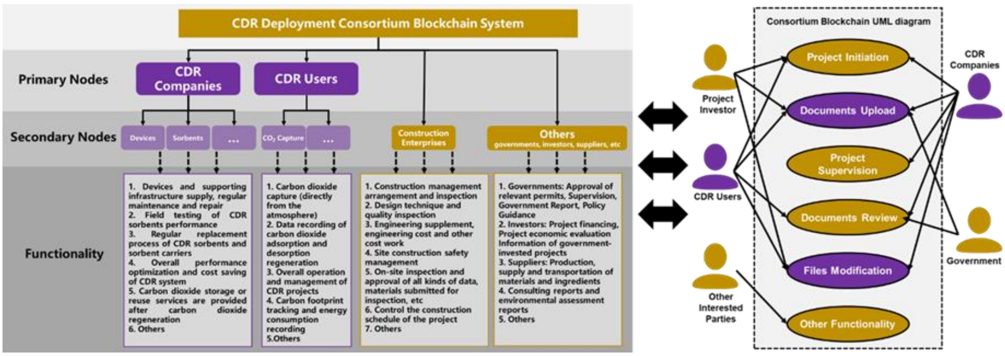

***Figure 4**: Functional Diagram of Consortium Blockchain System and UML Use Case Diagram.*

The system categorizes nodes into primary nodes (e.g., operators with transaction validation rights) and secondary nodes (e.g., suppliers with restricted access). Primary nodes manage critical functions such as ledger maintenance and carbon footprint tracking, aligning with the conceptual model in Section 3.3 Secondary nodes support auxiliary tasks like material supply. This hierarchical structure ensures accountability while enabling multi-stakeholder collaboration. Smart contracts[3] define tabular data structures (Tables 2-4) to enforce traceability and access control:

[3] Smart contracts are digitally encoded agreements residing on a blockchain, designed to automatically execute predefined terms and conditions upon fulfillment of specified criteria. By automating agreement execution, smart contracts ensure immediate certainty of outcomes for all parties involved, eliminating the need for intermediaries and reducing delays. Additionally, they streamline workflows by automatically initiating subsequent actions once predetermined conditions are satisfied, thereby enhancing efficiency and reducing reliance on manual intervention. (Source: Wikipedia)

Table 2: User Information Structure

Attribute	Type	Purpose	Constraints
Address	String	Unique blockchain node identifier	Valid blockchain address format.
Identity	String	Predefined user role (e.g., operator)	One of the predefined roles.

Table 3: Project Participant Structure

Attribute	Type	Purpose	Constraints
Project	String	CDR project name where participants are involved in.	Less than 100 characters, and unique in the organization.
Stakeholder	String	Key participants (e.g., investors, CDR providers, CDR Users, Suppliers)	Less than to 100 characters.

Table 4: The Document Structure of CDR Project

Attribute of the Structure	Type	Purposes of the Structure	Constraints of the Structure
Hash of the Hash	String	IPFS hash for integrity verification	IPFS hash (Valid)
ID of the Project	Integer	Links documents to projects	project Id (Valid)
The Validity of Hash	Boolean	Verification status (“approved” or “not”).	Approved→“True”, Not→ “False”

Table 2 outlines the user information structure for storing user details in the blockchain system. Each user is uniquely identified by an "Address," which indicates their node location in the blockchain. The structure includes fields such as "Address" (the blockchain address in a valid format), "Name" (the user's name with character and length restrictions), and "Identity" (the user's role within the system, predefined for consistency). Table 3 details the project participant structure, capturing information about individuals involved in CDR projects. Key fields include "Id" (each participant’s unique identifier), "Project" (the associated name of CDR project with character limits), "Investor" (the entity funding the project), "CDR Users" (the entity utilizing CDR services), , "Suppliers" (information on material suppliers), "Others" (other stakeholders), and "Time" (the date of registration). Additionally, Table 4 manages various file types related to CDR projects, linking each project file to its "project_id." It includes fields such as "The Hash of the File" (the IPFS hash used for file integrity and file retrieval), "Project Id" (the corresponding project identifier), and "Validity" (the file's verification status). The blockchain system utilizes smart contracts to securely manage CDR project data, ensuring accessibility, traceability, and security essential for project success. The consortium blockchain system uses smart contracts for secure and efficient management of CDR project data. Its structured tables organize user information and file management to ensure data accessibility, traceability, and security essential for project success.

The consortium blockchain system implements six core functional modules to automate and secure CDR management. The login and registration module ensures unique node authentication through blockchain address validation, while the project initiation module prioritizes creation requests using timestamps and authorization to prevent conflicts. File management integrates IPFS for cryptographic hashing and storage, coupled with control mechanisms that employ timestamped locks to prevent concurrent edits and maintain an immutable audit trail. The audit module enforces compliance with regulatory standards by validating document integrity against predefined criteria, triggering corrective actions for discrepancies. Contract management facilitates role-based document classification and soft deletion. Key innovations include IPFS-driven file integrity, conflict resolution via prioritized edits, and smart contract-enforced access control, collectively ensuring transparent, tamper-proof governance across multi-stakeholder CDR operations.

5. Conclusion

The study demonstrates that consortium blockchain technology can provide a robust framework to enhance the transparency, accountability, and scalability of Carbon Dioxide Removal (CDR) deployment. By integrating decentralized governance, cryptographic security, and IoT-enabled monitoring, the proposed system reduces administrative costs and improves data accuracy, addressing critical challenges such as fragmented data management and stakeholder mistrust. The architecture's role-based access control, Merkle tree-driven data integrity, and energy-efficient consensus mechanisms (e.g., PoS/DPoS) ensure tamper-proof carbon tracking while aligning with sustainability goals. Innovations like dual-key encryption and smart contract automation streamline compliance reporting and foster trust among policymakers, investors, and operators, essential for accelerating CDR under the Paris Agreement.

Future research should prioritize industrial pilots to validate scalability and cost-effectiveness in diverse geographic and regulatory contexts, including blockchain's performance under varying regulatory frameworks and power grid dependencies. Compared to emerging alternatives like decentralized identity systems– which primarily focus on individual identity verification but lack cross-organizational consensus mechanisms – this study's blockchain-centric approach uniquely enables multi-stakeholder collaboration and immutable audit trails critical for CDR accountability. While prior proposals (Xu e t al., 2024) explore standalone identity solutions, this work advances their concepts by integrating decentralized identity features within a blockchain framework to enforce role-based permissions across heterogeneous stakeholders (e.g., regulators, investors). This hybrid model diverges from siloed identity systems by embedding trustless authentication directly into CDR data workflows, reducing reliance on centralized authorities while enhancing traceability.

Optimizing blockchain energy footprint through renewable-powered consensus mechanisms and advancing AI-driven predictive analytics for anomaly detection could further refine CDR operations. Cross-sector collaboration involving policymakers, engineers, and financiers is essential to develop standardized frameworks for blockchain-CDR integration, ensuring interoperability with carbon credit markets and compliance with evolving environmental regulations. Additionally, exploring quantum-resistant cryptography and decentralized identity systems will strengthen resilience against emerging cybersecurity threats. Innovations in energy-efficient consensus protocols and interoperability standards represent critical frontiers for enhancing CDR monitoring and compliance systems, aligning technical innovation with societal and regulatory demands.

Acknowledgment: The authors are deeply grateful to funding received from Theme-based Research Scheme (TRS) funded via Research Grants Council (University Grants Committee, HK SAR), and the grant agreement number is T32-615_24/R. The author guarantees the originality and exclusivity of the article

References

Alzubi, J.A., 2021. Blockchain-based Lamport Merkle Digital Signature: Authentication tool in IoT healthcare. Comput. Commun. 170, 200–208. https://doi.org/10.1016/j.comcom.2021.02.002

Atzori, L., Iera, A., Morabito, G., 2010. The Internet of Things: A survey. Comput. Netw. 54, 2787–2805. https://doi.org/10.1016/j.comnet.2010.05.010

Bisotti, F., Hoff, K.A., Mathisen, A., Hovland, J., 2024. Direct Air capture (DAC) deployment: A review of the industrial deployment. Chem. Eng. Sci. 283, 119416. https://doi.org/10.1016/j.ces.2023.119416

Bisotti, F., Hoff, K.A., Mathisen, A., Hovland, J., 2023. Direct air capture (DAC) deployment: National context cannot be neglected. A case study applied to Norway. Chem. Eng. Sci. 282, 119313. https://doi.org/10.1016/j.ces.2023.119313

Bongaarts, J., 2019. Intergovernmental Panel on Climate ChangeSpecial Report on Global Warming of 1.5° CSwitzerland: IPCC, 2018. Popul. Dev. Rev. 45.

Bui, M., Adjiman, C.S., Bardow, A., Anthony, E.J., Boston, A., Brown, S., Fennell, P.S., Fuss, S., Galindo, A., Hackett, L.A., Hallett, J.P., Herzog, H.J., Jackson, G., Kemper, J., Krevor, S., Maitland, G.C., Matuszewski, M., Metcalfe, I.S., Petit, C., Puxty, G., Reimer, J., Reiner, D.M., Rubin, E.S., Scott, S.A., Shah, N., Smit, B., Trusler, J.P.M., Webley, P., Wilcox, J., Mac Dowell, N., 2018. Carbon capture and storage (CCS): the way forward. Energy Environ. Sci. 11, 1062–1176. https://doi.org/10.1039/C7EE02342A

Cachin, C., 2016. Architecture of the hyperledger blockchain fabric. Presented at the Workshop on distributed cryptocurrencies and consensus ledgers, Chicago, IL, pp. 1–4.

Calvin, K., Dasgupta, D., Krinner, G., Mukherji, A., Thorne, P.W., Trisos, C., Romero, J., Aldunce, P., Barrett, K., Blanco, G., Cheung, W.W.L., Connors, S., Denton, F., Diongue-Niang, A., Dodman, D., Garschagen, M., Geden, O., Hayward, B., Jones, C., Jotzo, F., Krug, T., Lasco, R., Lee, Y.-Y., Masson-Delmotte, V., Meinshausen, M., Mintenbeck, K., Mokssit, A., Otto, F.E.L., Pathak, M., Pirani, A., Poloczanska, E., Pörtner, H.-O., Revi, A., Roberts, D.C., Roy, J., Ruane, A.C., Skea, J., Shukla, P.R., Slade, R., Slangen, A., Sokona, Y., Sörensson, A.A., Tignor, M., Van Vuuren, D., Wei, Y.-M., Winkler, H., Zhai, P., Zommers, Z., Hourcade, J.-C., Johnson, F.X., Pachauri, S., Simpson, N.P., Singh, C., Thomas, A., Totin, E., Arias, P., Bustamante, M., Elgizouli, I., Flato, G., Howden, M., Méndez-Vallejo, C., Pereira, J.J., Pichs-Madruga, R., Rose, S.K., Saheb, Y., Sánchez Rodríguez, R., Ürge-Vorsatz, D., Xiao, C., Yassaa, N., Alegría, A., Armour, K., Bednar-Friedl, B., Blok, K., Cissé, G., Dentener, F., Eriksen, S., Fischer, E., Garner, G., Guivarch, C., Haasnoot, M., Hansen, G., Hauser, M., Hawkins, E., Hermans, T., Kopp, R., Leprince-Ringuet, N., Lewis, J., Ley, D., Ludden, C., Niamir, L., Nicholls, Z., Some, S., Szopa, S., Trewin, B., Van Der Wijst, K.-I., Winter, G., Witting, M., Birt, A., Ha, M., Romero, J., Kim, J., Haites, E.F., Jung, Y., Stavins, R., Birt, A., Ha, M., Orendain, D.J.A., Ignon, L., Park, S., Park, Y., Reisinger, A., Cammaramo, D., Fischlin, A., Fuglestvedt, J.S., Hansen, G., Ludden, C., Masson-Delmotte, V., Matthews, J.B.R., Mintenbeck, K., Pirani, A., Poloczanska, E., Leprince-Ringuet, N., Péan, C., 2023. IPCC, 2023: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)].

IPCC, Geneva, Switzerland. Intergovernmental Panel on Climate Change (IPCC). https://doi.org/10.59327/IPCC/AR6-9789291691647

Chen, Z., 2023. Enhancing the engineering supervision process in China: A solution enabled by integrating hybrid blockchain system. Innov. Green Dev. 2, 100091. https://doi.org/10.1016/j.igd.2023.100091

Chen, Z., Liu, Y., Wang, E., You, H., Gao, Q., Yeung, F.D., Li, J., 2024. Advancing the deployment and information management of direct air capture: A solution enabled by integrating consortium blockchain system. Carbon Capture Sci. Technol. 13, 100300. https://doi.org/10.1016/j.ccst.2024.100300

Coron, J.-S., Dodis, Y., Malinaud, C., Puniya, P., 2005. Merkle-Damgård Revisited: How to Construct a Hash Function, in: Shoup, V. (Ed.), Advances in Cryptology – CRYPTO 2005, Lecture Notes in Computer Science. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 430–448. https://doi.org/10.1007/11535218_26

Cox, E., Spence, E., Pidgeon, N., 2020. Public perceptions of carbon dioxide removal in the United States and the United Kingdom. Nat. Clim. Change 10, 744–749. https://doi.org/10.1038/s41558-020-0823-z

Dib, O., Brousmiche, K.-L., Durand, A., Thea, E., Hamida, E.B., 2018. Consortium blockchains: Overview, applications and challenges. Int J Adv Telecommun 11, 51–64.

Drescher, D., 2017. Blockchain basics: a non-technical introduction in 25 steps. Apress, Berkeley, California?

Du, M., Chen, Q., Chen, J., Ma, X., 2021. An Optimized Consortium Blockchain for Medical Information Sharing. IEEE Trans. Eng. Manag. 68, 1677–1689. https://doi.org/10.1109/TEM.2020.2966832

Erans, M., S. Sanz-Pérez, E., P. Hanak, D., Clulow, Z., M. Reiner, D., A. Mutch, G., 2022. Direct air capture: process technology, techno-economic and socio-political challenges. Energy Environ. Sci. 15, 1360–1405. https://doi.org/10.1039/D1EE03523A

Gazis, V., 2017. A Survey of Standards for Machine-to-Machine and the Internet of Things. IEEE Commun. Surv. Tutor. 19, 482–511. https://doi.org/10.1109/COMST.2016.2592948

Gillis, A.S., 2021. What is internet of things (IoT). IoT Agenda 17, 2024.

He, B., Yuan, X., Qian, S., Li, B., 2023. Carbon Neutrality: A Review. J. Comput. Inf. Sci. Eng. 23. https://doi.org/10.1115/1.4062545

He, Z., Wang, Y., Miao, Y., Wang, H., Zhu, X., Li, J., 2022. Mixed polyamines promotes CO2 adsorption from air. J. Environ. Chem. Eng. 10, 107239. https://doi.org/10.1016/j.jece.2022.107239

Helliar, C.V., Crawford, L., Rocca, L., Teodori, C., Veneziani, M., 2020. Permissionless and permissioned blockchain diffusion. Int. J. Inf. Manag. 54, 102136. https://doi.org/10.1016/j.ijinfomgt.2020.102136

Hua, W., Jiang, J., Sun, H., Wu, J., 2020. A blockchain based peer-to-peer trading framework integrating energy and carbon markets. Appl. Energy 279, 115539. https://doi.org/10.1016/j.apenergy.2020.115539

International Energy Agency, 2022. Direct Air Capture: A Key Technology for Net Zero. OECD Publishing.

Kerner, C., Thaller, A., Brudermann, T., 2023. Carbon dioxide removal to combat climate change? An expert survey on perception and support. Environ. Res. Commun. 5, 041003. https://doi.org/10.1088/2515-7620/accc72

Kim, S.-K., Huh, J.-H., 2020. Blockchain of Carbon Trading for UN Sustainable Development Goals. Sustainability 12, 4021. https://doi.org/10.3390/su12104021

Küng, L., Aeschlimann, S., Charalambous, C., McIlwaine, F., Young, J., Shannon, N., Strassel, K., Maesano, C.N., Kahsar, R., Pike, D., Van Der Spek, M., Garcia, S., 2023. A roadmap for achieving scalable, safe, and low-cost direct air carbon capture and storage. Energy Environ. Sci. 16, 4280–4304. https://doi.org/10.1039/D3EE01008B

Levin, K., 2018. 8 Things You Need to Know About the IPCC 1.5˚C Report | World Resources Institute [WWW Document]. WORLD Resour. Inst. URL https://web.archive.org/web/20231106134736/https://www.wri.org/insights/8-things-you-need-know-about-ipcc-15c-report (accessed 6.30.24).

Li, Z., Kang, J., Yu, R., Ye, D., Deng, Q., Zhang, Y., 2017. Consortium Blockchain for Secure Energy Trading in Industrial Internet of Things. IEEE Trans. Ind. Inform. 1–1. https://doi.org/10.1109/TII.2017.2786307

Lux, B., Schneck, N., Pfluger, B., Männer, W., Sensfuß, F., 2023. Potentials of direct air capture and storage in a greenhouse gas-neutral European energy system. Energy Strategy Rev. 45, 101012. https://doi.org/10.1016/j.esr.2022.101012

Mahmudnia, D., Arashpour, M., Yang, R., 2022. Blockchain in construction management: Applications, advantages and limitations. Autom. Constr. 140, 104379. https://doi.org/10.1016/j.autcon.2022.104379

Meckling, J., Biber, E., 2021. A policy roadmap for negative emissions using direct air capture. Nat. Commun. 12, 2051. https://doi.org/10.1038/s41467-021-22347-1

Meng, T., Zhao, Y., Wolter, K., Xu, C.-Z., 2021. On Consortium Blockchain Consistency: A Queueing Network Model Approach. IEEE Trans. Parallel Distrib. Syst. 32, 1369–1382. https://doi.org/10.1109/TPDS.2021.3049915

Miao, Y., Wang, Y., Zhu, X., Chen, W., He, Z., Yu, L., Li, J., 2022. Minimizing the effect of oxygen on supported polyamine for direct air capture. Sep. Purif. Technol. 298, 121583. https://doi.org/10.1016/j.seppur.2022.121583

Motlaghzadeh, K., Schweizer, V., Craik, N., Moreno-Cruz, J., 2023. Key uncertainties behind global projections of direct air capture deployment. Appl. Energy 348, 121485. https://doi.org/10.1016/j.apenergy.2023.121485

Nakamoto, S., 2008. Bitcoin: A peer-to-peer electronic cash system.

Parmentola, A., Petrillo, A., Tutore, I., De Felice, F., 2022. Is blockchain able to enhance environmental sustainability? A systematic review and research agenda from the perspective of Sustainable Development Goals (SDGs). Bus. Strategy Environ. 31, 194–217. https://doi.org/10.1002/bse.2882

Pilkington, M., 2016. Chapter 11: Blockchain technology: principles and applications.

Qiu, Y., Lamers, P., Daioglou, V., McQueen, N., de Boer, H.-S., Harmsen, M., Wilcox, J., Bardow, A., Suh, S., 2022. Environmental trade-offs of direct air capture technologies in climate change mitigation toward 2100. Nat. Commun. 13, 3635. https://doi.org/10.1038/s41467-022-31146-1

Saari, A., Vimpari, J., Junnila, S., 2022. Blockchain in real estate: Recent developments and empirical applications. Land Use Policy 121, 106334. https://doi.org/10.1016/j.landusepol.2022.106334

Sadawi, A.A., Madani, B., Saboor, S., Ndiaye, M., Abu-Lebdeh, G., 2021. A comprehensive hierarchical blockchain system for carbon emission trading utilizing blockchain of things and smart contract. Technol. Forecast. Soc. Change 173, 121124. https://doi.org/10.1016/j.techfore.2021.121124

Scott-Buechler, C., Cain, B., Osman, K., Ardoin, N.M., Fraser, C., Adcox, G., Polk, E., Jackson, R.B., 2024. Communities conditionally support deployment of direct air capture for carbon dioxide removal in the United States. Commun. Earth Environ. 5, 1–13. https://doi.org/10.1038/s43247-024-01334-6

Tönnissen, S., Teuteberg, F., 2020. Analysing the impact of blockchain-technology for operations and supply chain management: An explanatory model drawn from multiple case studies. Int. J. Inf. Manag. 52, 101953. https://doi.org/10.1016/j.ijinfomgt.2019.05.009

Turk, Ž., Klinc, R., 2017. Potentials of Blockchain Technology for Construction Management. Procedia Eng., Creative Construction Conference 2017, CCC 2017, 19-22 June 2017, Primosten, Croatia 196, 638–645. https://doi.org/10.1016/j.proeng.2017.08.052

Upadhyay, A., Mukhuty, S., Kumar, V., Kazancoglu, Y., 2021. Blockchain technology and the circular economy: Implications for sustainability and social responsibility. J. Clean. Prod. 293, 126130. https://doi.org/10.1016/j.jclepro.2021.126130

Valentine, J., Zoelle, A., Homsy, S., Mantripragada, H., Kilstofte, A., Sturdivan, M., Steutermann, M., Fout, T., 2022. Direct Air Capture Case Studies: Solvent System (No. DOE/NETL-2021/2864, 1893369). https://doi.org/10.2172/1893369

Van Cutsem, O., Ho Dac, D., Boudou, P., Kayal, M., 2020. Cooperative energy management of a community of smart-buildings: A Blockchain approach. Int. J. Electr. Power Energy Syst. 117, 105643. https://doi.org/10.1016/j.ijepes.2019.105643

Vigna, P., Casey, M.J., 2016. The age of cryptocurrency: how bitcoin and the blockchain are challenging the global economic order. Macmillan.

Wang, E., Navik, R., Miao, Y., Gao, Q., Izikowitz, D., Chen, L., Li, J., 2024. Reviewing direct air capture startups and emerging technologies. Cell Rep. Phys. Sci. 5, 101791. https://doi.org/10.1016/j.xcrp.2024.101791

Wang, T., Wang, X., Hou, C., Liu, J., 2020. Quaternary functionalized mesoporous adsorbents for ultra-high kinetics of CO2 capture from air. Sci. Rep. 10, 21429. https://doi.org/10.1038/s41598-020-77477-1

Wood, G., 2014. Ethereum: A secure decentralised generalised transaction ledger. Ethereum Proj. Yellow Pap. 151, 1–32.

Wu, J., Chen, Y., Xu, Y., Chen, S., Lv, H., Gan, Z., Zhu, X., Wang, R., Wang, C.-H., Ge, T., 2024. Facile synthesis of structured adsorbent with enhanced hydrophobicity and low energy consumption for CO2 capture from the air. Matter 7, 123–139. https://doi.org/10.1016/j.matt.2023.10.019

Xu, Y., Tao, X., Das, M., Kwok, H.H.L., Liu, H., Kuan, K.K.L., Lau, A.K.H., Cheng, J.C.P., 2024. A blockchain-based framework for carbon management towards construction material and product certification. Adv. Eng. Inform. 61, 102242. https://doi.org/10.1016/j.aei.2023.102242

Yang, R., Wakefield, R., Lyu, S., Jayasuriya, S., Han, F., Yi, X., Yang, X., Amarasinghe, G., Chen, S., 2020. Public and private blockchain in construction business process and information integration. Autom. Constr. 118, 103276. https://doi.org/10.1016/j.autcon.2020.103276

Yeung, K., 2021. The Health Care Sector's Experience of Blockchain: A Cross-disciplinary Investigation of Its Real Transformative Potential. J. Med. Internet Res. 23, e24109. https://doi.org/10.2196/24109

Zhai, S., Yang, Y., Li, J., Qiu, C., Zhao, J., 2019. Research on the Application of Cryptography on the Blockchain. J. Phys. Conf. Ser. 1168, 032077. https://doi.org/10.1088/1742-6596/1168/3/032077

Zhu, S., Cai, Z., Hu, H., Li, Y., Li, W., 2020. zkCrowd: A Hybrid Blockchain-Based Crowdsourcing Platform. IEEE Trans. Ind. Inform. 16, 4196–4205. https://doi.org/10.1109/TII.2019.2941735