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CO_2-Echain: An Integrated Digital Framework for Carbon Removal Credits Management in Full-Scale Carbon Capture and Storage Projects

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ABSTRACT

In response to the Paris Agreement's 2050 target for net-zero Green House Gas (GHG) emissions, the European Commission forecasts a net-negative cap in the EU Emissions Trading System (EU ETS) by 2045, mostly through carbon removal. In 2022, the EU initiated a Carbon Removal Credits (CRCs) certification framework to advance this goal. However, the effective integration of CRCs into the EU ETS still presents a significant challenge.

This paper introduces CO_2-Echain, a comprehensive digital framework designed to manage CRCs across full-scale Carbon Capture and Storage (CCS) processes, and to enable third-party CRCs certification within the EU ETS.

To ensure effective CRCs integration, the framework focuses on vital criteria such as data integrity and security, transparency and auditability, compliance, alignment with existing infrastructure and workflow, flexibility and scalability, and operational efficiency.

CO_2-Echain employs an edge-to-cloud architecture, leveraging distributed edge nodes and Internet of Things (IoT) devices to supervise the entire CO_2 life cycle - from capture to transport and injection. It records standard CRCs certification methodologies (once established), procedures, and results into the InterPlanetary File System (IPFS). To maintain data integrity, a private blockchain deploys Smart Contracts to manage these files. A synchronized cloud platform allows authorized third-party access to IPFS files, thereby enhancing the integration of CRCs with the EU ETS. Ultimately, CO2-Echain aims to facilitate a more robust, efficient, and effective market mechanism for carbon emissions removal.

Keywords: Net Zero, Carbon Capture and Storage (CCS), European Union Emissions Trading System (EU ETS), Carbon Removal Credits (CRCs), Blockchain, Carbon Accounting

NONMENCLATURE

Abbreviations

CCS	Carbon Capture and Storage
CID	Content Identifier
CRC	Carbon Removal Credit
EU ETS	European Union Emissions Trading System
GHG	Green House Gas
IoT	Internet of Thing
IPFS	InterPlanetary File System

1. INTRODUCTION

According to the Intergovernmental Panel on Climate Change (IPCC) report 2022, the deployment of Carbon Removal to counterbalance hard-to-abate residual emissions is unavoidable if net zero CO_2 or GHG emissions are to be achieved [1]. The adoption of the EU Green Deal, Climate Law, and subsequent proposals to increase energy and climate targets for 2030 have made Carbon Capture and Storage (CCS) technologies an integral component of the EU's decarbonization efforts [2].

Large-scale CCS projects are currently planned and operational worldwide. As of December 2022, IOGP Europe reported 72 planned CCUS projects across Europe, aiming to store 80 $MtCO_2$/yr by 2030 [3]. The Longship CCS project in Norway developing a full-scale CCS value chain to be operational by 2024, demonstrating this decarbonization approach to Europe and the global community [4].

To effectively scale up carbon removal activities, it is vital to enhance the monitoring, reporting, and verification of carbon removals. In response, the Commission adopted a Proposal for a Regulation on an

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EU certification for carbon removals [5] in 2022. The proposal aims to facilitate the deployment of a voluntary Union certification framework to transparently identify carbon farming and industrial solutions that remove carbon from the atmosphere. Although the current Commission's proposal does not cover the capture of fossil carbon for Storage (CCS) or Utilisation (CCU), this still represents the first crucial step towards enabling robust markets and regulatory uses of carbon certificates.

The EU ETS operates as a market-based mechanism to regulate and reduce GHG emissions within the EU. However, the existing EU ETS framework does not support the use of Carbon Removal Credits (CRCs), restricting incentives for carbon removal activities like CCS.

This paper introduces CO_2-Echain, a comprehensive digital framework for the management of CRCs with the full-scale CCS chain. Tailored to different companies involved in all stages of the CCS chain, including capture, transport, and storage, CO_2-Echain operates as a decentralized platform. This system links nodes in different companies, fostering consensus on CO_2 transfer and CRCs computations.

CO_2-Echain further enhances collaboration by facilitating interaction with third parties, such as auditors and carbon market platforms. It functions as a reliable provider of crucial documents and data required for CRCs certification and trading, emphasizing trust, transparency, and reliability, which are core requirements in CRCs calculation and certification.

To maximize its practicality and efficiency, the development of CO_2-Echain took into account the regulatory requirements set by the EU and the infrastructural and commercial agreements embedded in the Longship project. This project, chosen as a representative case study, guides the framework's adaptability and ensures its seamless implementation across a wide array of CCS chains.

This paper organized as follows. The background section introduces the design considerations for CO_2-Echain, with a focus on the technical requirements for integrating CRCs into the EU ETS, as well as the unique challenges posed by a full-scale CCS chain, such as those in the Longship project. Given the current underdevelopment of carbon market standards for certifying CRCs, particularly in relation to CCS, we outline the governing equation and the vital components of the certification methodologies that will be incorporated into the CO_2-Echain.

In the Technical Framework of CO_2-Echain section, we introduce the edge-to-cloud architecture of the CO_2-Echain. We explain how this integrated digital framework calculates CRCs in real-time throughout the full-scale CCS chain and facilitates third-party certification within the EU ETS. We also discuss the advantages and potential challenges of developing and adopting such a framework.

In the final section, we explore the ways in which the benefits of this approach outweigh the drawbacks and conclude with a summary of the contributions made by this paper.

2. BACKGROUND

2.1 Integrate Carbon Removal in EU ETS in CO_2-Echain

The EU ETS is a cap-and-trade system that operates as a key tool for EU to manage greenhouse gas emissions. The cap-and-trade system works by setting a cap on the total amount of certain GHG emissions that can be emitted by regulated entities within EU. This creates a market-based mechanism that incentivizes companies to reduce their emissions, either by improving efficiency or investing in low-carbon technologies, in order to avoid purchasing additional allowances. Conversely, companies with excess allowances can sell them to generate revenue, further encouraging the reduction of emissions. The EU ETS has played a crucial role in enabling the EU to reach its climate objectives, as it facilitates cost-effective emission reduction [6].

The EU ETS price has risen to 100 euros per tonne (February 2023) from 20 euros per tonne when the investment decisions for Longship were made in 2020. The primary catalyst for this long-term rise in EU ETS price has been the enforcement of more stringent climate policies across Europe [7].

Driving by the high carbon price, there is an increasing interest among EU ETS installers to integrate carbon removal technologies as a strategy to mitigate operational costs associated with these elevated carbon prices [8, 9]. However, the current EU ETS framework does not facilitate the certificating or trading of CRCs, which hampers incentives for carbon removal practices such as CCS.

One significant technical challenge to integrating carbon removal with EU ETS lies in the necessity for accountable and auditable certification of CRCs. Ensuring the high quality of carbon removals and establishing trustworthiness in the certification process to effectively combat greenwashing.

2.2 The Longship and Northern Lights CCS Projects

CCS refers specifically to the process of capturing carbon dioxide from large point sources such as power plants and industrial facilities, and then transporting and storing it permanently in geological formations deep underground.

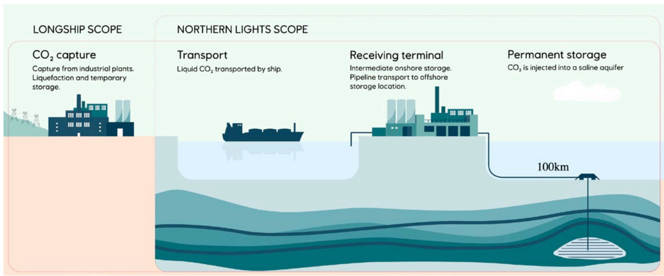

Figure 1. The Long-ship and the Northern Lights Carbon Capture and Storage project [11].

Full-scale CCS activities in Europe often involve cross-border collaborations. For instance, Longship, the first industrial CCS chain under construction within the current European legal framework, exemplifies such cooperation. Longship includes capturing CO_2 from industrial sources and shipping liquid CO_2 from capture sites to an onshore terminal. From there, the liquefied CO_2 will be transported by pipeline to an offshore storage location for permanent storage. As shown in Figure 1, the Northern Lights company is responsible for the transport and storage components of the project. The Northern Lights facility is designed to receive CO_2 captured from Norway in the initial phase, but is prepared for various industrial emitters across Europe, positioning it as the first-ever cross-border, open-source CO_2 transport and storage infrastructure network [11].

Cross-border CCS activities present specific requirements for carbon credits certification due to the involvement of multiple industry partners and countries. It is crucial to ensure trust from stakeholders and industry, prevent greenwashing, and practice the "responsibility for CO_2" (the responsibility for monitoring and reporting any leakage of CO_2 in the CCS chain and for submitting allowances under the EU ETS) for industry partners and countries according to regional regulations and commercial agreements.

For example, the measurements and inventories of CO_2 transportation must adhere to both commercial and regulatory standards. These include guidelines in the Monitoring and Reporting Regulation (an EU Commission implementing regulation), which defines the maximum permissible uncertainty for CO_2 measurement systems during transfers. Additionally, according to EU Commission regulations, a CO_2 capturing installation can only deduct CO_2 from its EU ETS allowances after the CO_2 has been transported from the shipping or trucking point to the storage site. In order to mitigate the risk of leakage during the transportation phase for the CO_2 capturing

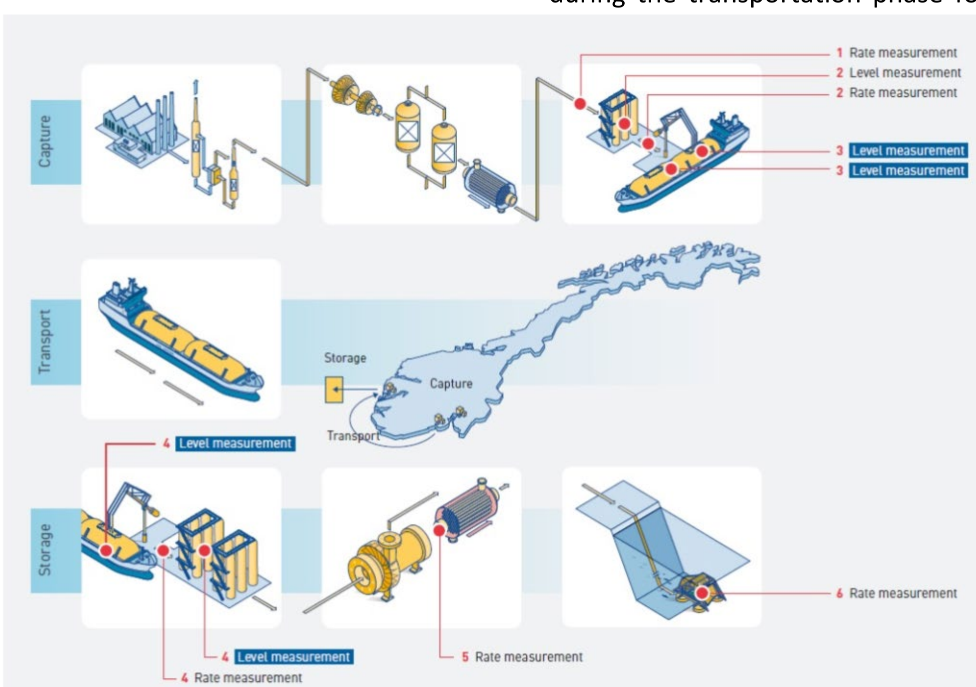

Figure 2: Outline diagram of the main process steps and CO_2 measurements points in the Longship Carbon Capture and Storage project [12].

installation, Northern Lights and the Norwegian State have agreed to bear the costs associated with any CO_2 leakage during transportation.

It is therefore crucial to monitor and report the total amount of CO_2 transferred between parties. As illustrated in Figure 2, the CO_2 is measured at several key stages of the process within the Longship Project, including capture, transportation, and storage. The carbon removed at capture sites equates to the mass of CO_2 received by the ship, which is then adjusted to a reference temperature of -26°C (point 3 in Figure 2). This is accomplished using the ship's Custody Transfer Measurement System, which gauges changes in the liquid CO_2 level within the ship's tanks, factoring in aspects like CO_2 composition, pressure, temperature, trim, and list [12]. This procedure is replicated to ascertain the amount of carbon removed across the entire CCS value chain when the CO_2 is transported from the ship to the storage receiving terminal (point 4 in Figure 2).

Given the context, we can define the essential criteria for the effective implementation of CO_2-Echain in a CCS project. The CO_2-Echain should align with the current infrastructure and procedures for CO_2 measurement. It ought to augment operational efficacy while guaranteeing data integrity and security. Furthermore, it must ensure compliance with national regulatory authorities and commercial contracts, while fostering transparency and mutual trust among all stakeholders.

2.3 Carbon Removal Certification Methodologies for Carbon Capture and Storage

A carbon removal activity such as CCS aims to provide a Carbon Removal Credit, which is defined as [5]:

$$\text{Carbon Removal Credit} = CR_{baseline} - CR_{total} - GHG_{increase}$$

where: $CR_{baseline}$ is the carbon removals under the baseline; CR_{total} is the total carbon removals of the CCS activity; $GHG_{increase}$ is the increase in direct and indirect greenhouse gas emissions which are due to the implementation of the CCS activity. These parameters shall be designated with a negative sign (-) if they are net greenhouse gas removals and with a positive sign (+) if they are net greenhouse gas emissions; they are expressed in tonnes of carbon dioxide equivalent. The quantification of the CRC shall account for uncertainties in accordance with recognised statistical approaches.

Several initiatives and organizations, such as the CCS+ initiative (https://www.ccsplus.org/), are presently developing methodologies to quantify and monetize the complete array of carbon capture, utilization, removal, and storage activities. These methodologies are designed to operate through both voluntary carbon markets and mandatory compliance regimes.

Certification methodologies for CRCs, while still in development, are built on a foundation of key elements: measurable data sources, standard calculation methods, and a set workflow. Figure 3 illustrates how this data is integrated into the calculation methodologies following the workflows. For consistency, a comprehensive certification method should define these elements, ensuring the quantification process for CRCs remains consistent across similar projects.

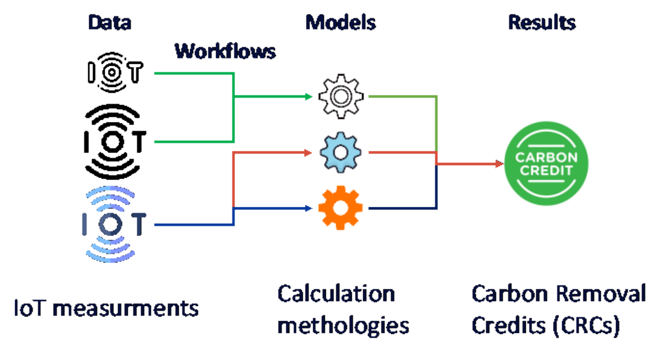

Figure 3. Input data, calculation algorithms and workflows are the three foundational elements to define the detailed procedures for quantifying Carbon Removal Credits

Given that CRCs certification methodologies are currently under development, it is crucial for the CO_2-Echain framework to be adaptable and scalable, facilitating future updates and integrations. Once a standard CRCs certification methodology for CCS is established, it is imperative that the digital framework incorporates it for accountable and auditable CRCs calculations. This incorporation should encompass the ability to record and retrieve the calculation processes and results to facilitate third-party verification and auditing.

2.4 The Design Criteria for CO_2-Echain

Based on the above discussions, we can conclude the following six design criteria for the CO_2-Echain digital framework:

1) **Data Integrity and Security**: Ensuring the accuracy, consistency, reliability, and security of data along the full-scale CCS chain is the fundamental objective for CO_2-Echain. It is important to ensure the high quality of carbon removals, establish strong security measures, including access controls and utilize secure communication channels.

2) **Transparency and Auditability**: The CO_2-Echain should provide a transparent record of CRCs calculations, as transparency plays a critical role in combating greenwashing and promoting trust among various partners. The recorded data should be easily retrievable to facilitate third-party verification and auditing, ensuring that the calculated CRCs are both accountable and auditable.

3) **Compliance**: The CO_2-Echain should comply with related EU Commission Regulations and any commercial agreements.

4) **Alignment with Existing Infrastructure and Workflow**: The CO_2-Echain needs to conform to the existing infrastructure and workflow for CO_2 measurement. It should be designed in a way that it integrates seamlessly with the current processes, minimizing disruptions and ensuring smooth operations.

5) **Flexibility and Scalability**: Given that the standard CRCs certification methodologies and schemes are under development, the CO_2-Echain must be adaptable to accommodate future updates and integrations. It should be scalable to handle potential growth in data volume and complexity of CRCs calculations.

6) **Operational Efficiency**: CO_2-Echain should also help to optimize the use of resources, reduce errors, and accelerate the entire CCS process. Ultimately, enhances the overall effectiveness and success of carbon capture and storage initiatives.

By adhering to these design principles, CO_2-Echain can provide an accountable and efficient framework for managing CRCs in CCS projects. This will, in turn, contribute to the successful implementation of CCS projects and ultimately facilitate the integration of CRCs into carbon markets like the EU ETS.

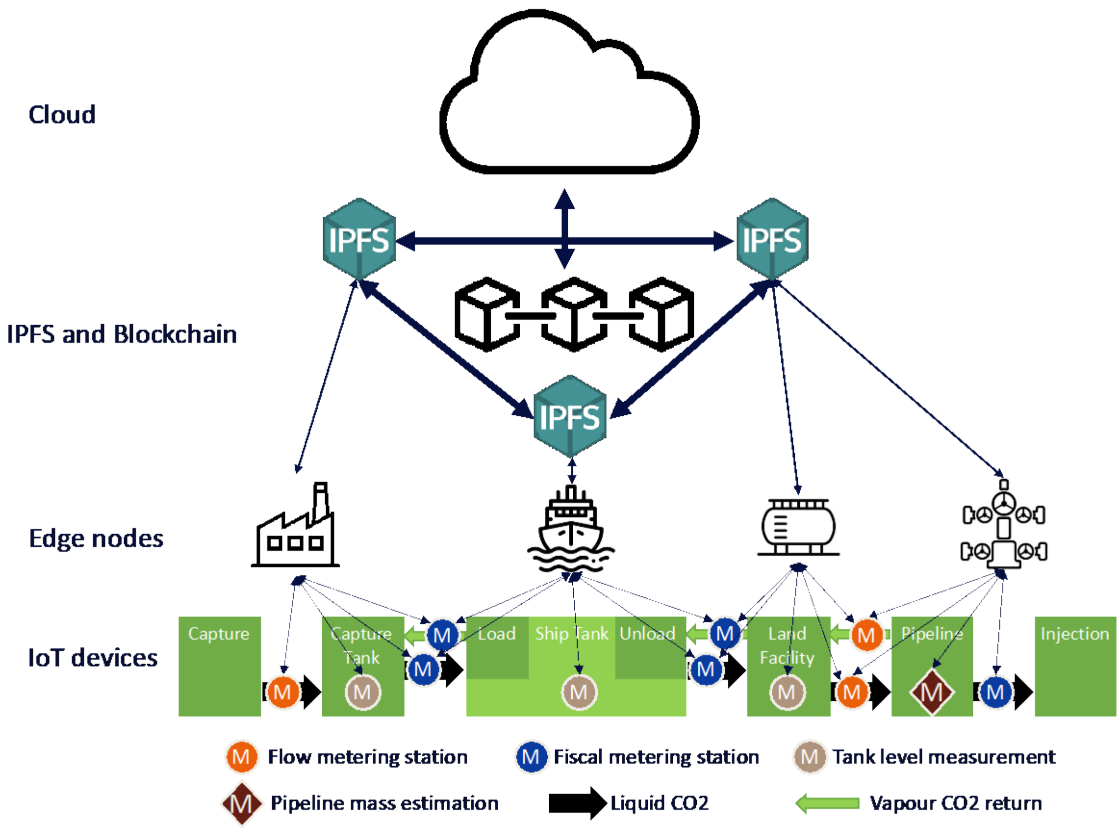

Figure 4. The technical architecture of CO_2-Echain, the Carbon Removal Credits Management digital framework for a full-scale Carbon Capture and Storage chain

3. THE TECHNICAL FRAMEWORK OF CO_2-ECHAIN

The CO_2-Echain, designed specifically for CRCs management in full-scale CCS projects, complies with the guidelines laid out in Section 2.4. As depicted in Figure 4, CO_2-Echain integrates an edge-to-cloud architecture that spans from the edge of the network, where data is generated, to the cloud, where it is authorized accessible from anywhere.

In this setup, Internet of Things (IoT) devices generate raw data that is then processed in real time by edge computing, reducing the volume of data that requires storage and distribution through the InterPlanetary File System (IPFS). The system also leverages blockchain to record metadata. This information is synchronized on a cloud platform, rendering it readily accessible to authorized users from CCS partners and third-parties.

In the following sections, we will introduce each technology and discuss the benefits and challenges for establish the proposed CO_2-Echain.

3.1 *Internet of Things (IoTs)*

An efficient IoT-based strategy is crucial for real-time monitoring of large-scale CCS projects, measuring CO_2 flow from capture sites to permanent storage locations. Recent advancements in IoT technology have led to a digital transformation process aimed at intelligent and advanced management of industrial process systems [13]. Implementing IoT solutions enables effective monitoring methods for CO_2 transportation in extensive CCS projects. Chawla *et al*. [14] proposed a roadmap for monitoring and controlling CCS processes using IoT devices.

The integration of IoT devices in the Longship CCS project paves the way for real-time data collection and a higher degree of automation in the CCS process. By upgrading meters like Custody Transfer Measurement Systems to IoT devices, operators can ensure accurate and timely billing data to reduce human error. These meters can also be used to determine the exact amount of CO_2 transferred during the CCS process, contributing to the verifiable tracking of the CRCs.

3.2 Edge computing

Edge computing is a distributed information technology architecture in which client data is processed at the periphery of the network, as close to the originating source as possible. In a CCS chain, these edge nodes, can be found in various locations such as capture sites, transport infrastructures, and storage sites.

In the context of CO_2-Echain, edge computing devices gather raw data - including parameters like CO_2 flow rate, concentration, pressure, and volume - from IoT devices. These devices then utilize standardized methodologies to calculate the CRCs according to a predefined workflow. This real-time data processing also enhances other functions, such as real-time immediate leak detection, contributing to more efficient and reliable operations.

Edge computing, bolstered by IoT devices, provides numerous operational benefits. It enables real-time data processing by minimizing latency, facilitating immediate computations on-site. Furthermore, by processing data locally rather than transmitting it over long distances to centralized servers or cloud infrastructures, edge computing can also enhance energy efficiency for computations. In open infrastructures like Northern Lights, edge computing ensures scalability, allowing seamless addition of new IoT devices without taxing centralized resources. It guarantees system reliability and resilience, maintaining functionality despite network disruptions. Crucially, edge computing bolsters data security and privacy by locally processing and storing data, reducing interception risks during transmission. Finally, it aids in regulatory compliance by enabling local data processing, particularly beneficial in cross-border collaborations. Thus, edge computing offers substantial benefits across various domains.

However, with different types of devices and systems potentially being used at the edge of the network, ensuring the interoperability of these devices and system can be a challenge. To address this issue in the CO_2-Echain framework, we utilize the InterPlanetary File System (IPFS). The IPFS follows a standardized protocol for data storage and retrieval across different edge nodes, thereby facilitating seamless collaboration across various components of the system.

3.3 InterPlanetary File System (IPFS)

The IPFS is a decentralized and peer-to-peer protocol that facilitates distributed file storage, sharing, and retrieval among network nodes. With its ability to handle substantial data volumes and accommodate a large number of nodes, IPFS demonstrates excellent scalability and efficiency, making it suitable for expanding edge node systems.

CO_2-Echain utilizes the IPFS as a platform for storing the CRCs calculation procedures at different edge nodes. To enable recording on IPFS, the calculation procedure must first undergo serialization, transforming it into a format that is both storable and distributable, such as a binary file, which is well suited for complex data structures. This serialized data is then integrated into the IPFS through an IPFS client or library, a process that fragments the data into smaller blocks. Each block is assigned a unique hash, and the culmination of these hashes results in a unique CID that represents the entire dataset.

Considering the needs for long-term storage as required by third-party auditors in the CO_2-Echain, it's crucial to use a pinning service. Once the data is securely pinned, the CID is available for distribution. This allows for the retrieval of the recorded CRCs calculation procedures from any IPFS node that stores the data.

One important feature of IPFS is its use of content addressing. Each piece of data on IPFS is uniquely identified by a CID. This feature is essential in ensuring the integrity of the CRCs calculation procedures on the CO_2-Echain, as any changes to these procedures will immediately become apparent due to the resultant change in the CID.

IPFS relies on a decentralized network of nodes, but it does not include a built-in consensus mechanism. As a result, it is necessary to validate the CRCs calculation procedures from individual nodes to ensure adherence to commercial agreements and relevant regulations.

To address this issue, the CO_2-Echain framework leverages the strengths of both IPFS and blockchain technology, aiming to establish an efficient and compliant system for CRCs management.

3.4 Blockchain and Smart Contracts

Blockchain, recognized as a Distributed Ledger Technology (DLT), provides a secure, decentralized framework for data storage that is spread across multiple nodes. This technology is known for its transparency, decentralization, immutability, and robust security. Complementing blockchain, smart contracts are digital scripts that automatically executed when predefined conditions are met. These contracts enhance transaction efficiency and reduce manual errors, leveraging the transparency and immutability of blockchain.

The application of blockchain and smart contracts in carbon accounting and trading has been thoroughly explored in various research studies [15, 16, 17]. The integration of blockchain and smart contracts can create a more reliable, transparent, and efficient framework for carbon accounting and trading. This system can thereby contribute to more robust carbon markets and support global efforts to mitigate climate change.

While existing research indeed provides valuable insights into the application of blockchain and smart contracts in carbon accounting and greenhouse gas emission reduction activities, it primarily does not address their use in CCS, a key carbon removal approach. As discussed in Section 2, CCS projects often demand cross-border collaborations, thereby necessitating compliance with commercial agreements and regulations. The development of a digital framework for CRCs management in CCS projects is thus confronted with the challenge of establishing a system that is not only reliable and secure, but also flexible and adaptable to the diverse needs of various stakeholders and the regulatory landscapes they operate within.

Addressing these requirements, CO_2-Echain capitalizes on the strengths of blockchain and smart contracts in conjunction with IPFS to streamline the documentation and validation of CRCs calculation procedures, ensuring their compliance with commercial agreements and regulatory standards.

Specifically, IPFS serves as a decentralized storage system for detailed CRCs calculation procedures, as outlined in Section 3.3. In synchrony with IPFS, blockchain technology is leveraged to securely record the CIDs and metadata of these IPFS files. This recording occurs once the CRCs calculation procedures have been validated against a set of predefined consensus rules, which are agreed upon by multiple nodes within the network. For instance, other validators in the network are tasked with confirming whether the standardized CRCs calculation methodologies have been correctly applied, verifying that the CO_2 sender has an adequate balance to fulfill the transfer, ensuring that the same quantity of CO_2 has not been transferred multiple times (i.e., avoiding a 'double-spend' scenario), and assessing the compliance of transactions with other commercial agreements and regulatory standards. In contrast, if the validation fails, the CRCs calculation procedures will be unpinned from the IPFS system and eventually be eliminated.

Smart contracts are a powerful tool that can be utilized to facilitate interaction between a blockchain and IPFS. This process encompasses the storage of IPFS file CIDs and metadata on the blockchain, the regulation of access rights to the respective blocks, and the retrieval of data from IPFS. Meanwhile, it can maintain an auditable record of access to IPFS files.

This collaborative process benefits from the security and transparency of blockchain, the efficient and decentralized storage capability of IPFS, the efficient execution of Smart contracts. Altogether, this integrated approach offers a transparent, secure, and efficient method for managing CRCs, ensuring compliance with the commercial agreements and regulations.

3.5 Cloud computing

Access in a private blockchain is limited to a selected consortium, yielding greater control over the network, faster transactions, and improved privacy. However, the nature of CCS projects mandates a certain degree of transparency and interoperability with third-party services, such as verifiers, auditors, public registries, and financial services.

To address this requirement, CO_2-Echain seeks to synchronize the private blockchain with a cloud platform, enhancing the blockchain's functionality and providing the adaptability necessary to meet evolving needs. The scalable nature of cloud platforms accommodates the expansion of the blockchain, thereby allowing the framework to adjust and grow in response to changing needs. This adaptability is particularly beneficial in the rapidly evolving field of CCS, where market conditions and regulatory requirements may shift.

Furthermore, the suite of tools and services offered by cloud platforms simplifies the development and deployment of integrations with other platforms or third-party services, reducing the time and effort needed for their creation and maintenance.

For instance, in the EU ETS context, carbon removal certifications should be verified by accredited third-party verifiers for accuracy and compliance. As showing in Figure 5, by integrating these verify services into our proposed framework, verifiers are granted specific access permissions to interact with the data stored on the blockchain and IPFS via the cloud platform. This facilitates efficient verifying while ensuring transparency and preventing tampering, as each interaction with the data is blockchain-recorded.

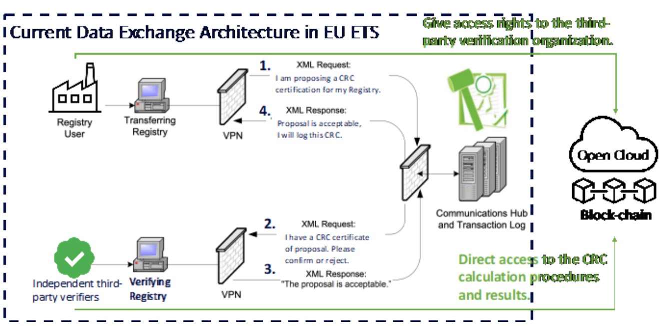

Figure 5. An illustration of the interaction between the third-party verifier and the CO_2-Echain under the EU ETS through the cloud platform.

3.6 An overview of CO_2-Echain

The CO_2-Echain framework enables the CRCs management in the full-scale CCS chain by guaranteeing integrity, transparency, and efficiency. Catering to both CCS service companies and third-party users, it uses IoT devices, edge computing, IPFS, and blockchain technology to facilitate secure collaboration within the same CCS project. Additionally, it synchronizes the blockchain with a cloud platform to enable third-party access, enhancing interoperability with other platforms.

Here's a high-level overview of the process:

a) **Deployment of IoT Devices**: Install IoT devices at various nodes within the CCS chain to collect essential data for calculating carbon removal credits.

b) **Standardized Methodologies**: Design standardized methodologies and workflows for calculating carbon removal credits. These will be deployed in edge devices to ensure accurate and consistent computations.

c) **Edge Device Processing**: The edge devices, equipped with pre-established models and workflows, will process the collected data. This allows for real-time processing and minimizes the need for transmitting raw data to a centralized location.

d) **Results Generation**: Edge devices will generate results, including transported CO_2 volumes at different nodes and carbon removal credits, alongside necessary metadata based on the computations performed.

e) **Storage on IPFS**: The collected data, computational models, workflows, and results will be stored on IPFS. Each component will be assigned a unique Content Identifier (CID) for efficient identification and retrieval.

f) **Smart Contracts on the Blockchain**: Smart contracts on a blockchain platform will facilitate interactions between IPFS and the blockchain. These contracts can store IPFS hashes and associated metadata on the blockchain, control access, facilitate retrieval, and maintain an auditable record of access to IPFS files.

g) **Cloud Integration**: The blockchain will be synchronized with a cloud platform to enable authorized third-party users to access authorized CIDs on the blockchain. Depending on their permissions and requirements, these users can retrieve corresponding files from IPFS.

The CO_2-Echain framework is an innovative solution designed to address the design criteria listed in Section 2.4. This framework successfully fulfils the defined criteria through the integration of advanced technologies

This process creates a system that enables real-time, automated monitoring across the entire CCS chain. It provides a comprehensive framework encompassing all aspects of Carbon Removal Certification—from data gathering to carbon credit computation. It is also promotes consensus and trust among stakeholders, and accommodates of third-party auditors. It significantly enhances transparency and auditability throughout the Carbon Removal Certification process.

However, this CO_2-Echain framework also presents several potential disadvantages. Installing and configuring IoT devices across various points in the CCS chain, along with setting up edge computing, IPFS, blockchain, and cloud technologies, is a complex task. This complexity could pose challenges in deployment, maintenance, and troubleshooting. The implementation of these advanced technologies requires significant financial resources, not only for initial setup but also for ongoing maintenance, upgrades, and potential transaction costs, particularly with blockchain. Seamless integration between IPFS, blockchain, and cloud platforms is critical for the system's operation. Given the sensitive nature of the data handled, the system requires robust security protocols to protect against potential cyber threats.

However, many of these disadvantages can be mitigated with careful planning, technical expertise, and robust system design. With the right resources and management, the advantages could very well outweigh the disadvantages.

4. CONCLUSIONS

The European Union Emissions Trading System (EU ETS) utilizes a market-based approach to regulate and curtail Greenhouse Gas (GHG) emissions. The escalating carbon prices have stimulated EU ETS participants to explore carbon removal technologies for cost mitigation. Nevertheless, the existing EU ETS framework lacks provisions for certifying and trading Carbon Removal Credits (CRCs), undermining the potential for Carbon Capture and Storage (CCS) practices.

This paper proposes, a comprehensive digital framework, CO_2-Echain, that manages CRCs across the full-scale CCS chain. It can also be used to interoperate with EU ETS.

Drawing on studies examining the integration of CRCs into the EU ETS, the challenges of a full-scale CCS chain, and current regulations, we defined five design criteria for the CO_2-Echain: 1) Data Integrity and Security, 2) Transparency and Auditability, 3) Compliance, 4) Alignment with Existing Infrastructure and Workflow, 5) Flexibility, and Scalability, and 6) Operational Efficiency.

To fulfil the above criteria, the proposed CO_2-Echain uses an edge-to-cloud architecture linking distributed Internet of Things (IoTs) and edge nodes via the InterPlanetary File System (IPFS) system and blockchain networks, synchronized with a cloud to enable third-party services, such as auditing and finance. This solution offers comprehensive CRCs management, from data collection, carbon credit calculation, data storage, and data trivial. In addition, the framework heightens transparency and audibility by including third-party auditors, fostering stakeholder consensus.

Despite these advantages, potential hurdles should not be ignored, such as the complexity of deploying advanced technologies, the substantial financial investment, and the need for robust security protocols to guard sensitive data.

The decision to adopt this framework should balance these challenges against benefits, considering factors like budget, current workflow, technological infrastructure, and regulatory environment. If well-implemented and potential issues are proactively mitigated, the benefits of this system could outweigh the challenges.

In summary, the CO_2-Echain, characterized by its decentralized and transparent design, offers a potential digital framework for managing CRCs in a full-scale CCS chain and for integrating with the EU ETS. Enhancing transparency and trust in the carbon credit market could stimulate further investment in CCS technologies and projects. Given the critical need for climate change mitigation, the implementation of such comprehensive solutions could have a significant impact.

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DECLARATION OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. All authors read and approved the final manuscript.

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