A Distributed Blockchain Framework for Real-Time Traceability and Transparency in the Voluntary Carbon Market

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**Abstract.** In real-world business operations, the Voluntary Carbon Market (VCM) enables businesses to offset their carbon emissions by buying and exchanging carbon credits. Nevertheless, there are several issues with the conventional VCM, including its lack of transparency, fragmented registries, and vulnerability to double counting. This paper proposes a conceptual blockchain-based framework to address these issues by leveraging smart contracts, tokenization, and real-time data indexing tools. The proposed system supports and manages a decentralized carbon credit lifecycle, from proposal submission and validation to issuance, trading, and retirement while embedding metadata that aligns with specific carbon standards and project attributes. The Graph Protocol, which enables resilient, real-time data retrieval from the blockchain to a decentralized application’s frontend is also incorporated into the framework. Besides, it also examines the potential advantages of combining decentralized finance (DeFi) with blockchain infrastructure while acknowledging related risks and considerations of DeFi adoption in decentralized systems by including enhanced market accessibility, stronger policy alignment through transparent and verifiable digital assets, and increased stakeholder trust.

# Introduction

Carbon credit is now a crucial tool in combating climate change because they ensure the welfare of future generations while protecting the environment. The organization provides financial incentives for projects that reduce greenhouse gas emissions by allowing programs to earn and trade the right to emit a certain amount of greenhouse gases measured as credits. Once they emit less than their limit, they can sell the extra credits to others. By doing so, the financial rewards contribute to reducing emissions and ensure other companies limit their pollution via carbon. Other organizations can reduce their emissions and contribute to the attainment of broader climate objectives by selling excess credits on carbon markets. However, the current structure of carbon markets is still rather fragmented, as the reason different countries operate distinct exchanges, such as the European Union Emissions Trading System (EU ETS) and Malaysia's Bursa Carbon Exchange (BCX), is that each is governed by a different set of rules. While these regulatory differences make it difficult to establish a unified global platform and create significant challenges for market interoperability. In addition, the lack of standardization across platforms increases the risk of carbon credit double counting, where the same credit may be claimed by multiple entities. As a result, the integrity of carbon offset claims is compromised, as well as undermining trust in the system too. To improve transparency, traceability, and regulatory alignment with voluntary carbon markets (VCMs), this paper proposed a framework that implements decentralized technologies by incorporating mechanisms such as tagging compliance attributes, timestamping credit lifecycles, and engaging independent verification agents. The framework aims to establish a more trustworthy, efficient, and interoperable system for carbon credit issuance, trading, and retirement.

# LITERATURE REVIEW

We analyzed three interrelated domains in this session, which are the Voluntary Carbon Market (VCM), the use of blockchain technology within environmental solutions, and the application of Decentralized Finance for environmental sustainability. This analysis identifies persistent problems within the VCM, including a lack of transparency, trust, and traceability. Building upon these issues, this analysis also explores how environmental and financial solutions built with blockchain technology could address these challenges. Collectively, this analysis supports the theoretical proposal of a distributed framework for real-time traceability in the VCM.

## The Voluntary Carbon Market

To voluntarily offset greenhouse gas (GHG) emissions globally, the Voluntary Carbon Market (VCM) conducted emission-reducing projects to enable individuals as well as organizations to purchase carbon credits. Unlike the Compliance Carbon Market (CCM), which is regulated by the government, the VCM is not driven by regulations from any nation. Instead. it is primarily motivated by corporate sustainability goals, investor expectations, and reputational concerns [1]. For instance, carbon credits within the VCM are generated by buyers contracting carbon project developers to implement and verify climate projects. Besides, while participation is open to public, the financial cost associated with offsetting serves as an incentive for reducing emissions. As such, the VCM promotes inclusive participation in global climate action and accommodates diverse project types that may not receive funding through compliance systems.

For one, the VCM relies on multiple interdependent actors to operate properly. Project developers are responsible for designing and executing carbon-reducing initiatives. Third-party auditors verify that emission reduction claims are met. Carbon credit buyers such as corporations and individuals purchase verified credits to compensate for their carbon footprints. On the other hand, regulatory bodies such as Verra and Gold Standard, establish the requirements for credit issuance to maintain market credibility. Furthermore, the carbon credit market has seen rapid growth due to supportive policies that stemmed from rising climate awareness. According to MarketsandMarkets [2], the global carbon credit market is projected to grow from USD 414.8 billion in 2023 to USD 1,602.7 billion by 2028 (CAGR 31.0%). Similarly, Precedence Research [3] estimates an increase from USD 933.23 billion in 2025 to USD 16,379.53 billion by 2034 (CAGR 37.68%). This substantial growth highlights the need for transparent, standardized platforms to manage credits effectively and reinforce market trust. However, current carbon credit systems face several challenges that negatively impacts credibility and large-scale adoption. Notably, there is a lack of transparency and standardization within the VCM, where many project documents are missing or mislabelled across registries [4,5]. For instance, Wyburd and Defrasne [4] reportedly found 444 missing documents across 140 projects. Consequently, the missing documents make it difficult for stakeholders to verify climate and social benefits. Another concern is double counting, where the same credit is claimed multiple times, either accidentally or deliberately. In their study, Ma and Duan [5] estimated that undocumented and overcounted reductions could exceed reported reductions by 0.9 to 1.3 times between 2021 and 2030. As such, these pending issues must be resolved to preserve the environmental integrity of carbon markets.

## Carbon Credits and Trading Standards in the Voluntary Carbon Market (VCM)

A carbon credit is the reduction or removal of one metric ton of CO₂ or similar greenhouse gasses (GHGs). Environmentally responsible initiatives create credits that can be used to offset emissions, aligning with frameworks like the Kyoto Protocol and the Paris Agreement. To assess project quality, the AVID+ framework (Additional, Verifiable, Immediate, Durable, plus co-benefits) was introduced by Sterman [6], promoting integrity and impact in carbon offsetting efforts. Within the VCM, several independent standards govern the issuance and verification of carbon credits:

* **Verra’s Verified Carbon Standard (VCS)**: It is the most widely adopted, issuing over one billion credits globally. Its dynamic methodologies, especially in REDD+ projects, align with evolving climate policy and scientific developments. While studies by Pauly et al. [7] support VCS’s accuracy in baseline deforestation estimates, others like West and Haya [8] raise concerns over inconsistent methodologies, calling for continued refinement
* **The Gold Standard (GS)**: Established by the WWF and NGOs, GS emphasizes sustainable development and requires projects to contribute to at least three UN SDGs. GS avoids REDD+ certification due to baseline reliability issues [4,8], focusing instead on clean technologies. While Gill-Wiehl et al. [9] questioned emissions reductions from cookstove projects, GS defended its metered methodologies, citing consistent reductions supported by studies [10,11,12].
* **Shariah-compliant standards**: In parallel, efforts to align Islamic finance with carbon markets have led to the emergence of Shariah-compliant standards. Habibullah [13] proposed integrating Maqasid Al-Shariah with green finance to support ethical, sustainable investing. Notably, Malaysia’s Bursa Carbon Exchange (BCX) is the world’s first Shariah-compliant carbon exchange [14], and XTCC has launched a Shariah-compliant ecosystem certified by Mufti Ismail Desai [15]. Furthermore, Razali et al. [16] and Hosen [17] have underscored how Islamic finance instruments like the SRI-linked Sukuk can fund projects while meeting both ethical and environmental objectives.

## Blockchain Technology Within Environmental Solutions

Blockchain technology has become a popular alternative to traditional solutions in recent years due to its characteristics such as enhanced efficiency, transparency, and traceability within environmental sectors. In the context of carbon credit systems, these features are crucial for enhancing their credibility. For instance, Siemens’ Estainium uses decentralized trust to track and offset supply chain emissions [18]. Moreover, the use of consensus mechanisms preserves data integrity by ensuring data recorded on-chain cannot be modified without agreement from the network. As a result, blockchain helps with carbon accounting and prevents issues such as double counting or fraud. These capabilities are increasingly being leveraged in practical applications, as summarized in Table 1.

**TABLE 1**. Functional capabilities of blockchain in environmental applications

|  |  |  |  |
| --- | --- | --- | --- |
| Functionality | Description | Use Case | Source |
| Automated Compliance Enforcement | Smart contracts automatically verify and ensure adherence to environmental regulations. | Real-time maritime environmental compliance monitoring with MARPOL standards. | Quigley et al. [19] |
| Transparent Environmental Reporting | Ensures immutable and transparent recording of environmental data. | Recording and verification of sustainability information of building materials during the design process. | Cheng et al. [20] |
| Greenwashing Prevention | Provides immutable audit trails to verify environmental claims. | Automated controls that detect and prevent greenwashing in corporate environmental disclosures. | Gu et al. [21] |
| Efficient Energy Management | Optimizes energy consumption and distribution through automated controls. | Energy consumption management in electric vehicles (EV) without sacrificing user comfort. | Hijjawi et al. [22] |
| Incentivization of Sustainable Practices | Facilitates reward systems for environmentally sustainable behaviors. | Incentivization of regenerative agriculture through data-driven reward systems. | Chainlink [23] |
| Fraud Detection and Carbon Traceability | Utilizes blockchain-based data visualization to detect credit overclaiming. | Identification and monitoring of malicious behavior in transactions through interactive blockchain visualization | Tsai [24] |

## Leveraging DeFi for Environmental Sustainability

Decentralized Finance (DeFi) is a blockchain-based alternative to traditional finance that enables peer-to-peer (P2P) financial services without intermediaries such as banks or brokers [25]. By separating traditional banking services, like lending, borrowing, and trading from central authorities, DeFi provides financial services in the form of smart contracts to empower individuals to interact directly with these services [25]. At its core, DeFi replaces centralized systems with decentralized models, so financial services are not gatekept by any central authority. Besides, it also improves financial inclusion by allowing anyone with an internet connectivity to access it, regardless of their location or economic status [26].

Decentralized Finance (DeFi) and Traditional Finance (TradFi) are two different approaches to financial transactions. In TradFi, entities like banks are responsible for processing transactions and enforcing compliance, while DeFi replaces them with smart contracts, allowing peer-to-peer (P2P) interactions and reducing the need for third-party monitoring [27]. Consequently, the lack of intermediaries also affects transaction costs. For instance, fees in TradFi accumulate due to intermediary services such as account management and loan processing. Rahman et al. [28] found that these layers significantly raise costs in emerging economies. In contrast, DeFi allows automated transactions through smart contracts, which results in lower transaction costs [29] and establishes outstanding performance for the system's accessibility, as TradFi often excludes underserved populations due to fees, documentation requirements, or lack of local infrastructure. According to the World Bank [30], billions remain financially underserved; instead, DeFi allows anyone with internet access and a digital wallet to participate. For instance, Vasishta et al. [31] highlighted the role of DeFi in improving access to financial services via decentralized lending, digital wallets, and blockchain-based transactions, especially in remote or low-income regions. In summary, DeFi has the potential to reform financial systems by eliminating intermediaries, reducing costs, and enhancing accessibility.

## The Role of DeFi in Reforming Voluntary Carbon Markets

The voluntary carbon markets (VCMs) revolutionized blockchain technology integrated with DeFi on a wider scale [32, 33, 34]. By enabling the retirement of carbon credits in form of cryptocurrencies, the technology introduces enhanced transparency, efficiency, and accessibility with the support from institutions like the UN and World Bank [30]. However, the technology falls short of facing several challenges, such as poor interoperability and limited support for high-liquidity trading.

To effectively support a proposed development, [33] demonstrate how blockchain can encourage participation and secure transactions in VCMs. However, it is noted that they also face issues like market maturity and user retention, thus highlighting the need for regulatory clarity and technical standards [32]. Furthermore, Burgoyne and Olexiuk [34] has stressed that while tokenization is promising, success depends on strong design, regulation, and adaptability through their analysis. As such, DeFi introduces risks that must be addressed for sustainable application in carbon markets despite its potential. Besides, scalability is poor in blockchain solutions, where network congestion and limited parallel processing slow transactions and raise costs [35,36]. Moreover, blockchain solutions has unwanted complexity due to regulatory ambiguity, with cross-border legal inconsistencies discouraging adoption [37,38]. Additionally, DeFi’s lack of regulations from authorized parties can increase market misconduct. To give substance to a claim, Xiong et al. [39] demonstrated how actors exploit features like flash loans and transaction transparency to execute front-running and price manipulation through the bZx incident. However, these views have since been challenged by recent research from Universiti Putra Malaysia [40]. Other than that, AI is collaborated for demonstrating how blockchain could enhances transparency and accountability in green finance once they explored the potential risk of DeFi. Thus, their findings suggest this combination leads to more precise investment strategies and sustainable outcomes. In sum, DeFi holds considerable promise for reforming carbon markets.

# proposed System Architecture

To enable key stakeholders to participate in the voluntarys carbon credit lifecycle, the proposed architecture is designed on a decentralized application (dApp) ecosystem. By ensuring traceability, accountability, and auditability are achieved, the smart contracts, blockchain-based data storage, and real-time indexing are collaborated on to improve the performance. The backbone of this design is the use of an indexing tool, The Graph Protocol, which enables real-time retrieval of blockchain token data and proposal information for integration into the dApp interface. In addition, it supports dynamic user queries, ensures metadata transparency, and facilitates seamless interaction between the frontend and backend. Figure 1 illustrates the overall system architecture, highlighting the interactions among users, smart contracts, and indexing services.

## Stakeholders and Roles

With clearly defined key stakeholders, the functionality is permissioned based on specific roles, making the proposed architecture both distinctive and robust:

* **Developer**: Developers initiate the carbon offset process by submitting detailed project proposals through the platform. These proposals include key information aligned with recognized carbon standards and project goals. Upon receiving approval from an authorized auditor, developers are allowed to issue carbon credit tokens, which are then listed on the marketplace for trading. Thus, this stage allows all people to ensure the carbon credit supply is verifiable and compliant on the grounds of traceability for each transaction to its originating developer.
* **Auditor**: Carbon credit auditors are instrumental in preserving the legitimacy and consistency of carbon credits. They assess the proposal independently to ensure accuracy, compliance, and the effectiveness of internal controls through carbon credit supplements. In proposed architecture, the auditors are able to retrieve the on-chain proposal and submit their assessment by evaluating certain guidelines, like global carbon standards or Islamic finance precepts, to ensure the traceability of the auditing report for future enhancement. Once the proposal has been approved, a non-fungible token (NFTs) of carbon credit would embed together with verified metadata and then issued to developer.
* **Buyer**: By this method, the developer can be referred to as the seller to sell the credit(s) in the marketplace. Each available token on the platform is traceable and embedded with rich metadata that includes project purpose, carbon standard, and geographical origin. Thus, buyers are enabling informed decision-making to purchase or exchange the carbon credits for offsetting purposes or investment. In this manner, the marketplace of the proposed architecture did provide mutual benefit for both parties by promoting a trustworthy and user-friendly trading environment.
* **Public/NGO/Government**: Moreover, due to the transparency of the proposed architecture, external stakeholders are qualified to access the platform to verify the authenticity and integrity of carbon credit projects. Due to immutable ledger implementation, publicity is allowed to use any available blockchain tools and interfaces, such as dApps and blockchain explorers, for inspecting audit credit status and reviewing project metadata to ensure reliability. This public layer reinforces transparency, enhances trust in the voluntary carbon market, and supports regulatory oversight or third-party certification processes.

A diagram of a diagram

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**FIGURE 1**. Overall System Architecture

## Smart Contract Modules

To improve code reusability and maintain complex contract logic more effectively, there are three smart contract modules: proposal, token, and marketplace are designed in this proposed architecture.

Firstly, the proposal contract serves as the initial point of interaction for project developers. It handles the logic of carbon offset project proposal submission by developers. Additionally, it also captures essential details required for evaluation and only allows authorized auditors to manage and update submission status—whether pending, approved, or rejected.

On approval by an auditor, the token contract is triggered to mint a unique non-fungible token (NFT) representing the carbon credit. At once, the verified metadata that includes the carbon standard, project description, environmental benefits, and country of origin is embedded in the minted NFT. The immutability and uniqueness of the NFT ensure secure traceability and prevent duplication.

Finally, the marketplace contract facilitates the decentralized trading of carbon credits in a peer-to-peer manner. It enables buyers to browse, filter, and purchase tokens based on metadata attributes such as standard compliance or geographical origin. Pricing mechanisms and exchange logic are handled on-chain, promoting transparency, efficiency, and trust in the voluntary carbon credit market.

## Token Design

To achieve the robust and user-driven development of the decentralized application (dapp), the chosen token design is dominant based on its available capabilities and suitability for the intended use case.

By the proposed method, each carbon credit is represented as a non-fungible token (NFT) to allow a unique and immutable digital identity for every issued credit. Nonetheless, the structure of NFTs enables them to carry embedded metadata that has been verified and approved during the proposal validation process by authorized auditors. This metadata includes key attributes such as the carbon standard (e.g., Gold Standard, Islamic-compliant certifications), project description, environmental and community benefits, and country of origin.

By tightly coupling this set of variables with the token itself, the design guarantees full traceability and enhances the credibility of each credit. Besides, it allowed differentiation between credits based on quality, impact, and compliance requirements. This design not only prevents double issuance or misuse but also enables buyers and verifiers to interact with transparent and trustworthy data directly on-chain, further reinforcing the legitimacy of the voluntary carbon market through verifiable digital representation.

# discussion

Due to the reliance on centralized registries, manual verification, and limited public access in conventional systems, the proposed architecture applies blockchain technology to ensure verifiable, tamper-proof records of carbon credit issuance, transfer, and retirement. By introducing programmatic trust, automated validation, and real-time transparency through smart contracts and tokenization, the proposed blockchain-based framework significantly improves the performance compared with traditional voluntary carbon market systems.

Furthermore, to allow public users, NGOs, and regulators to independently audit any credit via decentralized applications, the Graph Protocol is integrated by providing real-time data querying from on-chain. These enhancements collectively address key issues such as double counting, opaque validation processes, and audit delays. Table 2 highlights the core differences between traditional and blockchain-based systems, illustrating improvements in trust, transparency, and operational efficiency.

**TABLE 2.** Comparative analysis between traditional and blockchain-based carbon credit systems

|  |  |  |
| --- | --- | --- |
| Aspect | Traditional Registries | Proposed Blockchain Architecture |
| Traceability | Hard to audit due to centralized logs | Immutable ledgers allow transparent audit trails and proposal status. |
| Fraud Risk | Potential risk of double counting and fake credits | On-chain tokenization ensures 1-to-1 issuance and safe minting. |
| Interoperability | Country-specific registries | Cross-border accessibility via public blockchain |
| Data Access | Delayed and inconsistent | Real-time data retrieved via The Graph protocol |
| Trust & Verification | Opaque for NGOs/public | Publicity of metadata and token history for anyone |

# conclusion

In conclusion, by highlighting critical gaps in traceability, transparency, and trust across carbon credit issuance and trading standards, this study systematically reviewed the current challenges in the Voluntary Carbon Market (VCM). The existing infrastructure is examined and aligned with environmental and financial innovations to lay the foundation for a blockchain-based solution. Besides, conceptual architecture was presented by integrating technology of smart contracts, decentralized data storage, and real-time indexing through The Graph Protocol. The framework also encompasses key user roles, modular smart contracts, and token design that ensures the uniqueness and verifiability of each carbon credit. A cross-analysis also gives a demonstration regarding auditability, automation, and stakeholder engagement in this paper on how our approach outperforms traditional registries.

However, several areas remain open for future exploration. These include performance testing of the system under real-world transaction loads, assessing cross-chain interoperability for international carbon standards, integrating privacy-preserving mechanisms (e.g., zk-SNARKs) for sensitive compliance data, and evaluating the socio-political acceptance of DeFi components in regulated carbon markets. Further pilot implementations and stakeholder feedback will be crucial in validating the feasibility and scalability of the proposed framework in operational VCM platforms.

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