computers

MDPI

Article

Beyond Opacity: Distributed Ledger Technology as a Catalyst for Carbon Credit Market Integrity

Stanton Heister [1,*], Felix Kin Peng Hui [2], David Ian Wilson [2] and Yaakov Anker [2,3,4]

[1] The School of Business, Portland State University, 1825 SW Broadway, Portland, OR 97201, USA
[2] Renewable Energy and Energy Efficiency Group, Department of Infrastructure Engineering, Melbourne School of Engineering, The University of Melbourne, Melbourne, VIC 3010, Australia; kin.hui@unimelb.edu.au (F.K.P.H.); diwilson@unimelb.edu.au (D.I.W.); kobia@ariel.ac.il (Y.A.)
[3] Department of Chemical Engineering, Ariel University, Ariel 40700, Israel
[4] Department of Environmental Research, Eastern R&D Center, 65 Ramat HaGolan Street, Ariel 40700, Israel
* Correspondence: heister2@pdx.edu

Abstract

The 2015 Paris Agreement paved the way for the carbon trade economy, which has since evolved but has not attained a substantial magnitude. While carbon credit exchange is a critical mechanism for achieving global climate targets, it faces persistent challenges related to transparency, double-counting, and verification. This paper examines how Distributed Ledger Technology (DLT) can address these limitations by providing immutable transaction records, automated verification through digitally encoded smart contracts, and increased market efficiency. To assess DLT's strategic potential for leveraging the carbon markets and, more explicitly, whether its implementation can reduce transaction costs and enhance market integrity, three alternative approaches that apply DLT for carbon trading were taken as case studies. By comparing key elements in these DLT-based carbon credit platforms, it is elucidated that these proposed frameworks may be developed for a scalable global platform. The integration of existing compliance markets in the EU (case study 1), Australia (case study 2), and China (case study 3) can act as a standard for a global carbon trade establishment. The findings from these case studies suggest that while DLT offers a promising path toward more sustainable carbon markets, regulatory harmonization, standardization, and data transfer across platforms remain significant challenges.

Keywords: blockchain; distributed ledger technology; DLT; carbon credit; carbon credit market; United Nations Sustainable Development; sustainable development; carbon credit case study; clean development methodologies; global carbon market

check for updates

Academic Editor: Paolo Bellavista

Received: 21 May 2025
Revised: 5 September 2025
Accepted: 15 September 2025
Published: 22 September 2025

Citation: Heister, S.; Hui, F.K.P.; Wilson, D.I.; Anker, Y. Beyond Opacity: Distributed Ledger Technology as a Catalyst for Carbon Credit Market Integrity. *Computers* **2025**, *14*, 403. https://doi.org/10.3390/computers14090403

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

The carbon credit market has long been plagued by issues of transparency, accessibility, and standardization [1]. However, the emergence of Distributed Ledger Technology (DLT), commonly known as blockchain, offers a promising solution to these challenges. DLT, with its inherent features of decentralization, immutability, and transparency, can modify the way carbon credits are traded and verified. By securely digitizing carbon credits as tokenized carbon credits and recording them on a blockchain network, the ecosystem can become more transparent, accessible, and liquid, enabling seamless transactions between various stakeholders, including energy companies, project verifiers, and concerned citizens [2].

Carbon credit transitions have exceeded 100 million events per month over multiple platforms [3]. The implementation of DLT-based carbon credit systems can help ensure

compliance with existing Clean Development Mechanism methodologies and reduce the risks associated with traditional carbon credit trading [4]. Furthermore, the use of digitally encoded and signed assets that are executed by laws through designated organizations [2], can automate the distribution and management of carbon credits, reducing the burden on regulatory authorities and enhancing the overall efficiency of the system [5,6]. Standardization of alternate blockchain networks can enable digital carbon credit exchange within New Market Mechanisms, on a local and multinational level. Global partnerships will be nurtured by providing a platform with embedded fiduciary instruments to areas having limited digital infrastructure [4]. This approach can also contribute to the United Nations Sustainable Development Goals by promoting transparency and integrity in carbon credit transactions [7].

Global carbon markets, both compliance and voluntary, have emerged as key instruments in the fight against climate change, with the total market value exceeding USD 850 billion in 2023 [8]. These markets enable the trading of carbon credits, representing verified greenhouse gas emission reductions or removals, which can be used to offset emissions elsewhere. Despite their potential, carbon markets face persistent challenges that undermine their effectiveness, including a lack of transparency, double-counting of credits, high transaction costs, and difficulties in verification [9].

Distributed Ledger Technology (DLT), the foundation of blockchain systems, may remove these challenges through its core properties of immutability, decentralization, and cryptographic security [10]. Recording transactions on a distributed ledger that cannot be altered retroactively can provide transparency and traceability for carbon credits throughout their lifecycle, from issuance to retirement. Emerging regulatory frameworks for greenhouse gas (GHG) emissions accounting can work synergistically with DLT to enhance transparency and credibility, specifically in voluntary carbon markets, which have historically suffered from fragmentation and inconsistent standards [11]. This integration is becoming increasingly important because voluntary carbon markets are playing a larger role in climate mitigation. However, environmentally sound technologies (ESTs) face a recognition barrier, which prevents them from being fully incorporated into mandatory global carbon credit markets [12]. Their recognition is a barrier because, without clear standards or acceptance in compliance markets, they cannot generate certified carbon credits, limiting investment and large-scale adoption.

The main aim of this paper is to evaluate the strategic potential of DLT adoption for leveraging its benefits in carbon markets and beyond. It is estimated that mastering sustainability requires a convergence of technology, finance, and human capabilities, highlighting the importance of a holistic approach that DLT can enable. The question is how DLT can transform carbon credit markets by addressing existing limitations and enabling new functionalities. A comparative analysis of three DLT-based carbon trading platforms enables evaluating DLT applicability for Global Carbon Market integration. A comparative analysis should evaluate these technical architectures in real-world application performance and assess the potential for integration with global compliance markets. Following the comparative assessment, the key limitations, including technical development challenges, integration, and scalability of public and private blockchain networks, as well as user interface design challenges, must be acknowledged and overcome to enable effective ownership data control while ensuring transparency and inclusivity for all stakeholders. Current and future trends in governance should also be discussed, as for the role of prosumers in the carbon market.

2. Background

Since the ultimate motivation behind a carbon credit economy is to eventually reduce GHG emissions to mitigate global climate change, several trading architectures are applied to some extent, with hindrances such as a lack of transparency and correlation between platforms and trading networks motivating the need for more educated carbon credit trading platforms.

2.1. DLT Architectures for Carbon Credit Trade and Registration

Three predominant DLT architectures are already employed for carbon credit markets (Figure 1). The first, a public blockchain approach, utilizes existing networks like Bitcoin (BTC), Litecoin (LTC), or Ethereum Classic (ETC) to tokenize carbon credits, enabling broad market participation but facing scalability constraints and high energy consumption [12]. Many of these first-generation systems often employ a Proof-of-Work (PoW) consensus mechanism, which, while secure, is energy-intensive. Proof-of-work blockchains can have an infinite number of miners (verifiers) participating in the validation and creation of blocks. Each one of these mining nodes is represented by a powerful processor that consumes high volumes of energy [13]. For example, Kazakhstan has nearly 90,000 crypto mining nodes that are consuming over eight percent of the country's energy usage. Although this has represented a windfall for the economy, it has also introduced significant financial risks. As a result of the increase in energy consumption, there has been a spike in fuel prices, which has resulted in political instability. This instability resulted in the temporary shutdown of the Bitcoin mining system for more than six days, which reportedly cost Bitcoin miners and the economy over USD 20 million [14]. Although due to its architecture, decentralization, and massive number of verifiers (also known as miners), the PoW systems are highly secure, but with risks and sustainability issues that should be carefully considered when developing a blockchain solution.

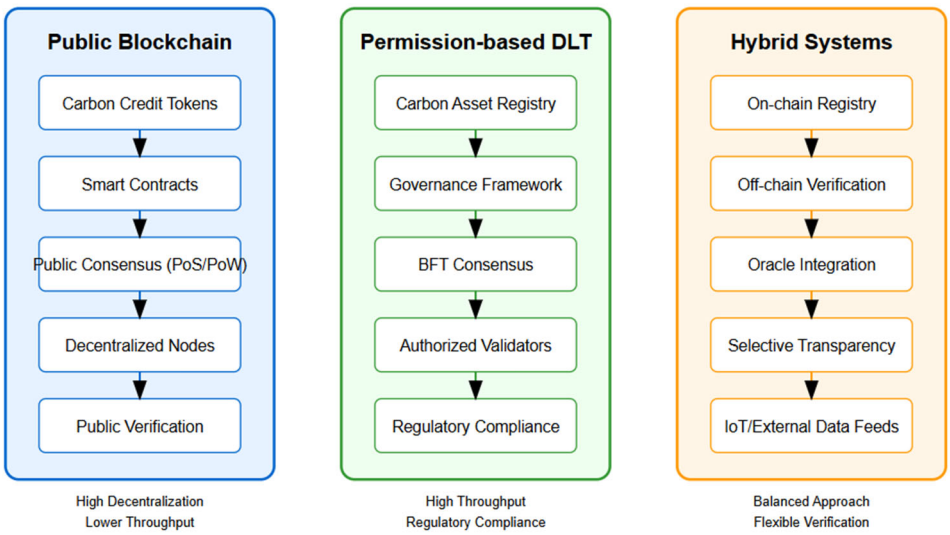


Figure 1. Architectural Comparison of DLT Systems for Carbon Credits [Diagram showing three DLT architectures: public blockchain, permission-based DLT, and hybrid systems, with their key components and data flows].

Public blockchains such as Ethereum's second-generation blockchain (ETH) employ a different type of consensus mechanism to verify transactions cryptographically—Proof-of-Stake (PoS). In Proof-of-Stake consensus protocols, a more finite and smaller set of "miners" called "validators" participate in forming and validating new blocks on the chain. Because

a limited number of validators is employed, energy usage with PoS systems is lowered, and they become a greener option than the original PoW systems [15].

The second DLT architecture employs purpose-built, permission-based, or private DLT systems designed specifically for environmental assets, offering greater throughput and regulatory compliance. These permissioned systems often use consensus mechanisms like Proof-of-Stake (PoS) because of their energy efficiencies and the limited number of participants that make up these permissioned blockchains. Ethereum (ETH) is the largest PoS ecosystem when defined by its market capitalization and the number of decentralized applications (dApps) running on the platform. A limitation of the Ethereum network is the high transaction "Gas" cost. "Gas" is measured by the computational power needed to perform actions on the Ethereum network. These actions include exchanging the cryptocurrency (ETH) itself, executing smart contracts, or running dApps. Any of these transactions requires gas, and depending on the load of the transaction and the volume on the network, a total cost is determined and assigned to the user [16]. Cardano, Polkadot, and Solana are other well-known PoS blockchains that may offer participation on the network with lower gas fees than ETH.

The third DLT architecture approach uses hybrid systems that combine on-chain record-keeping with off-chain verification processes, balancing accessibility with operational efficiency [17]. Data in these systems can be stored directly on the blockchain or off-chain, in a traditional database or system, for example, whereby a hash or "locator" that represents the location of the data is then posted on the blockchain. The advantage here is gas/transaction cost savings and speed, as large files that are slow to execute on the blockchain can be accessed and executed more quickly when stored off-chain [18].

Among these architectures, permission-based systems demonstrated the highest transaction throughput (>1000 transactions per second) while maintaining the lowest energy footprint [19]. However, public blockchain implementations show superior resistance to centralized control, an important consideration for global markets spanning multiple jurisdictions [17].

2.2. Key Parameters for Carbon Credit Trade and Registration Architectures Applicability

2.2.1. Market Efficiency Gains

A decade ago, carbon credit markets were small, but they now constitute 70% of the governments' revenues from GHG compensation in 2022 (Figure 2). Carbon credit markets are evolving from carbon taxes as part of Emissions Trading Systems (ETSs). The rapid growth of demand for carbon credits has encouraged stakeholders to explore and leverage digital technologies, including blockchain, seeking to reduce transaction costs and improve transparency. Carbon tokens are created via a "bridging" process, where carbon credits are canceled or retired in a credit mechanism registry and reissued as blockchain-based crypto assets, thereby creating new sources of demand and improving market liquidity [20]. DLT suggests significant efficiency improvements across multiple dimensions owing to direct and transparent data exchange across the registry systems (Figure 3). Transaction costs are estimated to decrease by an average of 50% compared to traditional registry systems, primarily due to the elimination of intermediaries and streamlined verification processes [21]. Settlement times decreased from an average of 5–7 days to near-instantaneous finality, enhancing market liquidity [22]. To improve processing speed and efficiency, trade-related applications use self-executing (smart) contracts with the terms directly written into code—automated key processes for accrediting and identifying clients and suppliers [22]. This approach enables real-time certification that allows credit issuance, transfer of ownership, and retirement certification. This automation reduced administrative

overhead by approximately 50% while decreasing error rates by 83% compared to manual processes [23].

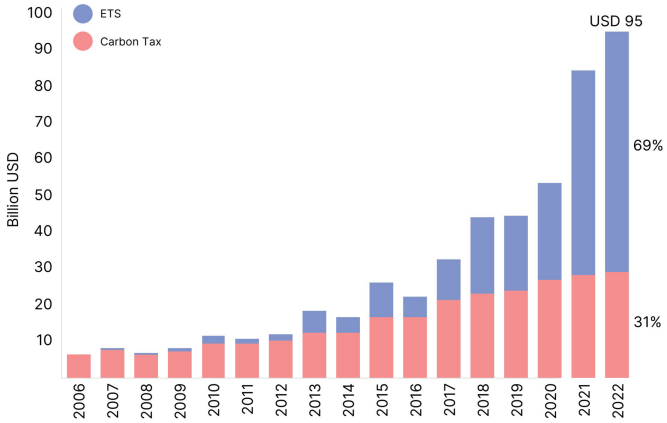


Figure 2. Evolution of global revenues from carbon [20].

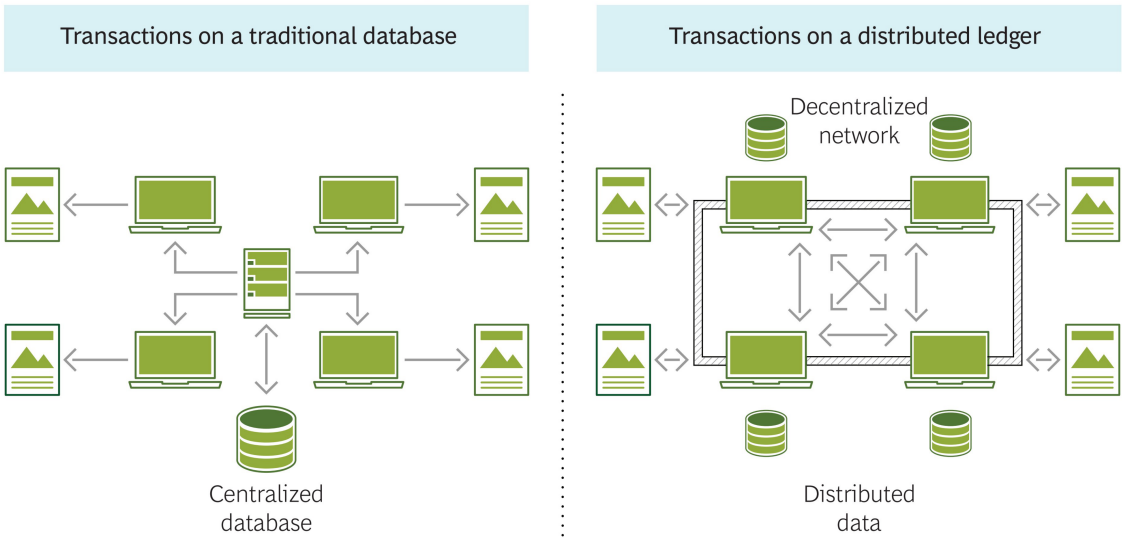


Figure 3. Comparison Between Traditional and Distributed Ledgers [21].

2.2.2. Stakeholder Perspectives

In some industries or cases, such as track and trace, DLT adoption has reached maturity and, in some cases, the scalability necessary to result in large-scale implementations. Carbon market developers are beginning to understand these advantages, but the industry, as late as 2024/25, is still further from full-scale adoption, and perceptions of DLT solutions could be considered fragmented. DLT systems are nearing maturity and are more viable due to improved scalability, with transaction speeds having improved to over 100,000 transactions per second [24]. Additionally, the sustainability of second and third-generation blockchains employing Proof-of-Stake consensus protocols makes these systems more attractive. DLTs offer a level of sovereignty as no one person, entity, or state (unlike traditional database systems) controls the blockchain. This allows us to create a fully transparent and secure trading system for carbon credits, which helps attract institutional participants and ensures environmental integrity [25]. Momentum seems to be growing in the industry due to the potential cost savings that DLT systems can provide. Because the system is highly automated and smart contracts eliminate the need for the exchange of traditional contracts and the associated human-related administrative costs and errors, this makes DLT systems an attractive option in the carbon credit industry [26].

2.2.3. DLT Application in Carbon Trading Market

A review of blockchain technology in carbon trading markets shows that developers view DLT as a tool for credit traceability and secondary market creation, whereas regulators identify governance and compliance complexity as barriers [27]. However, DLT effectiveness, despite its efficiency and trust benefits, may be undermined by the consortium rules established to set up and operate the blockchain for a given carbon credit entity [28]. Additionally, governance can create friction and is perhaps the most critical aspect of a successful consortium. Stakeholders of and within the system must work together, even when there may be a competitive element among one or more members of the working entity. Partners can differ in their respective priorities, market strategies, business processes, etc. DLT can improve transparency and reduce transaction friction, but it also introduces complexity that may confuse participants unfamiliar with the technology, thus hampering trust in tokenized credits [27]. These potentially contentious discussions and decisions should be worked out well in advance of the buildout of the system to ensure there are no blockades that arise midway through development [28].

2.2.4. Transparency and Market Integrity

DLT implementation substantially enhances transparency in carbon credit markets, addressing the critical issue of double-counting, which reduces the real impact to half of what is accounted [11]. By recording all transactions on an immutable ledger, DLT systems provide a verifiable chain of custody for each credit from issuance to retirement [29]. The transparent nature of DLT also facilitated improved stakeholder confidence. The BNY Mellon digital asset custody platform serves U.S. clients, initially supporting Bitcoin and Ether. Its market participants (n = 217) survey results indicated a 47% increase in trust levels following migration to DLT-based systems, with 79% citing improved transparency as the primary factor. This demonstrates that DLT implementation can significantly improve market credibility by creating an immutable audit trail that allows for independent verification of claims and retirement status [11]. Traditional databases that may house this information provide four functions so that database administrators can

- Create a record;
- Read a record;
- Update a record;
- Delete a record.

This is functionally known by its acronym, CRUD, which leaves an opening for potential bad actors to erroneously change or delete records. DLT systems only allow the first two functions—creating or reading a record, thereby making it almost impossible for this type of fraud to exist. This is particularly valuable in addressing common criticisms of voluntary carbon markets regarding the legitimacy of offsetting claims.

2.3. Potential Carbon Credit Platform Infrastructures

Several operational DLT-based carbon credit platforms aim to address issues like transparency, market fragmentation, and inefficiencies in the carbon credit lifecycle. The key initiatives to enhance carbon trading activities in the voluntary carbon market were assessed against real-world performance:

1. **CarbonChain**: A permission-based platform focusing on compliance markets in the EU and Canada, which has processed over 8.2 million carbon credits representing 8.2 $MtCO_2e$. The platform reduces verification times by 80% and decreases transaction costs by 58% [30].

2. **CarbonBlocks**: A public blockchain implementation on Ethereum focused on voluntary carbon markets with an emphasis on nature-based solutions. The platform has tokenized 3.4 million carbon credits but faces scalability challenges during high-demand periods.
3. **Distributed Carbon Ledger (DCL)**: A hybrid system combining on-chain record-keeping with off-chain Measurement, Reporting, and Verification (MRV). DCL demonstrated superior scalability and regulatory compliance but requires greater centralization.
4. **TransparenTerra**: A consortium-based DLT platform focused on land-use change and forestry credits in tropical regions. The system's smart contract-based verification reduced fraudulent credits by an estimated 92% compared to previous registry systems [31].
5. **Carbonex:** This enterprise uses blockchain to create a transparent and efficient global market for trading carbon credits. The platform aims to simplify the carbon credit lifecycle, ensure compliance, and integrate with existing Emissions Trading Systems (ETSs). It plans to have nodes in all countries that ratified the Paris Agreement, with limited write access for entities like the UNFCCC and local governments while maintaining open read access for public accountability.
6. **IBM Energy Blockchain Labs**: IBM, in partnership with Energy Blockchain Labs, has developed a carbon asset development platform using blockchain technology. This platform automates carbon quota calculations through smart contracts, enhancing transparency, information sharing, and regulatory monitoring. It uses Hyperledger Fabric to securely store environmental data and facilitate emissions tracking for participants.
7. **ClimateTrade**: This online service provider uses DLT to track and sell carbon credits, ensuring that all transactions are visible to platform users. ClimateTrade links to projects verified by major standards like CDM, VCS, and the Gold Standard, allowing users to offset emissions, calculate carbon footprints, and prepare sustainability reports.
8. **Nori**: Nori focuses on carbon removal through regenerative farming practices. It uses blockchain to create a market for carbon removals, issuing Ethereum-based tokens representing one ton of CO_2 removed from the atmosphere for at least ten years. The process involves farmers, independent verifiers, and buyers, with all data stored on a blockchain to prevent double-counting.
9. **Moss.Earth**: Moss is an environmental fintech company that sells carbon credits linked to projects in the Amazon rainforest, such as the Ituxi and Juma projects. Using Ethereum, Moss provides a digital platform for individuals and companies to buy, store, and use carbon credits, aiming to combat deforestation and climate change.

These initiatives demonstrate the potential of DLT to revolutionize the voluntary carbon market by improving transparency, efficiency, and accountability in carbon trading activities. Nonetheless, the data collected is limited to the DLT-based carbon platforms and initiatives included in the case studies. While these platforms provide valuable insights, they may not be fully representative of all DLT applications in carbon markets. Additionally, the study focuses primarily on the technological aspects of DLT implementation. Further research is needed to explore the social, economic, and policy dimensions of DLT adoption in carbon markets [12].

2.4. Regulatory Frameworks and Standards

International regulatory standards and frameworks are necessary for establishing and maintaining agreed-upon practices, processes, and procedures amongst industry players and across international borders. Article 6 in the Paris Agreement is an example of work

being performed in this field to ensure consistency and compliance when capturing and reporting carbon credits on an international scale. Specifically, Articles 6.2 and 6.4 address international market-based cooperation, guidance, and mitigation processes for the transfer of carbon credits through the use of a protocol called Internationally Transferred Mitigation Outcomes (ITMOs). Interlinkages of registries and implications for functions and structures in the context of Paris Agreement Article 6 underscore the necessity of an international framework, specifically for industry's needs [32]. For global trades such as the airline industry, it becomes imperative to have some mechanism (in this case, ITMOs) to ensure fair capture, reporting, and transfer of carbon credit-related data from region to region.

Digitizing monitoring, reporting, and verification (MRV) processes can help to initiate work and, moreover, create scale and confidence in carbon market development using DLT. Digital MRV (dMRV) frameworks make it possible to standardize workflows, such as origination processes, manufacturing systems, and product definitions. Standardization builds credibility, attracts investors, and ensures the reliability of outcomes [33]. While DLT systems reduce the probability of double-counting due to their secure architecture, if tokens from different blockchains do not share cryptographically linked audit trails for MRV, it is difficult to prove the authenticity of a set of tokenized transactions that span different DLT ledgers. The InterWork Alliance (IWA) has coordinated with the Global Blockchain Business Council's (GBBC) Interwork Alliance group in 2023 and 2024 to develop a digitized framework that addresses these issues from an industry and business perspective. It has created technical specifications for developers to ensure consistency across various development entities, which are open-source and available on GitHub. Additionally, IWA and GBBC have produced a digital asset (Fact Card) that provides a snapshot of definitions and types of carbon markets, key entities, quality standards, certification standards, MRV Process flows, tokenization descriptions, and how organizations can engage in the dMRV framework [33].

The GBBC has also performed work on mapping global standards over the past few years. Their goal with these standards is to advance the work in the areas of sustainability and sustainable blockchains, including those in the carbon market space. These mapping reports include a taxonomy of sources of authority in the industry, such as various legislation or legislative bodies, guidance, regulations, including documentation around the Paris Agreement (Article 6), EU Green Deal, and EU Emissions Trading System, US SEC Climate disclosures, the International Carbon Disclosure Project, and many other industry stakeholders [34]. Regulatory and institutional analysis for carbon market development has been in process for several years and seemingly continues to gain momentum. These initiatives and future frameworks, regulations, and institutions can act as a catalyst and drive scale within the industry through the adoption of DLT solutions. Future research in this area could focus on how these developments have impacted or failed to impact the development of carbon markets using blockchain solutions.

2.5. Conflicts Between Decentralized Systems and Decentralized Systems

There are traditional database systems in place in the carbon capture and reporting industry. Verra and Gold Standard are two that seem to have gained much of the momentum in terms of development or use to date. DLT systems, for reasons discussed in this paper, are challenging these traditional centralized approaches. As this dichotomy unfolds, it is important to understand some of the potential conflicts that could arise.

Notable potential conflicts include the following:

1. Control over issuance and authenticity in the MRV processes;
2. Governance;
3. Double-counting or fraud.

Control over issuance and authenticity in the MRV Processes

- Centralized systems require projects to make use of strict methodologies in order to issue credits, and central registries and people within those entities control the issuance and certification of credits. In these systems, third-party audits and manual field inspections are often necessary, which can create credibility questions.
- Decentralized systems make use of tokenization and smart contracts to auto-issue credits in the system. Consortia members, rather than a central entity, create the rules and establish the methodology for verifying transactions in the system.

The conflict here is trust, whereby centralized systems believe their way of issuing and authenticating is more trustworthy than decentralized systems because some believe DLT systems can allow "junk" credits to enter the system, since there is, in many cases, no "human" intervention in assessing the validity of the issuance. As discussed in the previous section, tokens from different blockchains should share cryptographically linked audit trails for MRV to prevent erroneous addition of credits to prevent such occurrences.

Proponents of decentralized cite the lack of credible human verifiers that can lead to inaccuracies or fraud. For example, because of untrustworthy issuance, "In January 2023, the Guardian, together with Die Zeit, reported that 94% of the carbon credits from rainforest protection projects certified by the largest registry in the VCM, Verra, were 'worthless'" [35].

Governance

Governance and decision-making in centralized carbon credit systems are performed by technical committees, supervisory boards, or based on scientific research. Often referred to as "Credit Registries", which can be international, national, or private, such as the Gold Standard for Global Goals (GS4GG) [32]. The proliferation of registries can lead to cross-communication issues and data inconsistency. Additionally, much of the work is performed by individuals, where human error or poor intention can compromise the data and undermine confidence in the system. Interoperability also becomes a concern as differing technologies or input processes can cause inaccuracies or an inability to communicate in the same terms.

In terms of validation and verification, common practice, in some carbon market systems, relies on project management entities hiring third-party auditors, which may have a vested interest in ensuring the project succeeds, which can lead to inaccuracies or fraud. The current iteration of the ICVCM (Integrity Council for the Voluntary Carbon Market) lacks provisions for future iterations to advance beyond this existing verification model [36].

In blockchain or DLT, governance is much more automated, relying not on individuals but on smart contracts or computer code to govern how the system reports and verifies information. Governance rules are established by people or organizations who are a part of the overall consortia of the system—stakeholders who play a direct role or have a vested interest in a given carbon capture project. Stakeholders in DLT systems determine decision rights and technically enact accountability through the creation of Decentralized Autonomous Organizations (DAOs), where consensus mechanisms and smart contracts drive dMRV processes rather than direct human interaction [37]. DAOs offer advantages over centralized carbon capture systems by increasing transparency and traceability as transactions are recorded openly and immutably. This architecture serves as an important tool in monitoring dMRV progress when implementing the Nationally Determined Contributions under the Paris Agreement [38].

Though there are clear advantages to governing under DLT systems, there are challenges that must be avoided or overcome. For example, governance of data and rules of the system must be well defined before the system begins the process of collecting data. Con-

sortia members bear the responsibility of determining how data will be defined, and which type of data will be recorded and managed over its lifecycle [39]. Moreover, it must also determine how data interacts with other DLT and potentially non-DLT systems. Perhaps the most concerning challenge of DLT systems is the workings of the consortia themselves. Despite the potential for the benefits of DLT systems, forming and operating consortia that may involve many entities with differing goals may require members to agree to terms that challenge long-held belief systems or foundational business models. Participants may find they must incorporate changes to business models or even incorporate strategies to meet the needs of the consortia as a whole [28].

3. Methodology

The initial stage of research included Scopus and Web of Science Databases surveys for the terms "blockchain", "Carbon Markets", and "Case Studies". Using "blockchain" alone resulted in a very large number of papers (>42,000). Adding the term "carbon markets" reduced this to just 44 papers (Web of Science) and 241 papers (Scopus), and then "case studies" resulted in just 8 papers (Web of Science) and 32 papers (Scopus). Those latter papers enabled us to gain enough information to develop a theoretical framework (Figure 4). A comparative case study approach was used to develop architecture (Figure 4) following Eisenhardt's methodology [40], which enabled the use of cross-case synthesis to identify patterns, similarities, and differences in DLT applications across three markets. The case studies represented different levels of market maturity and DLT utilization for carbon credits booking and trading.

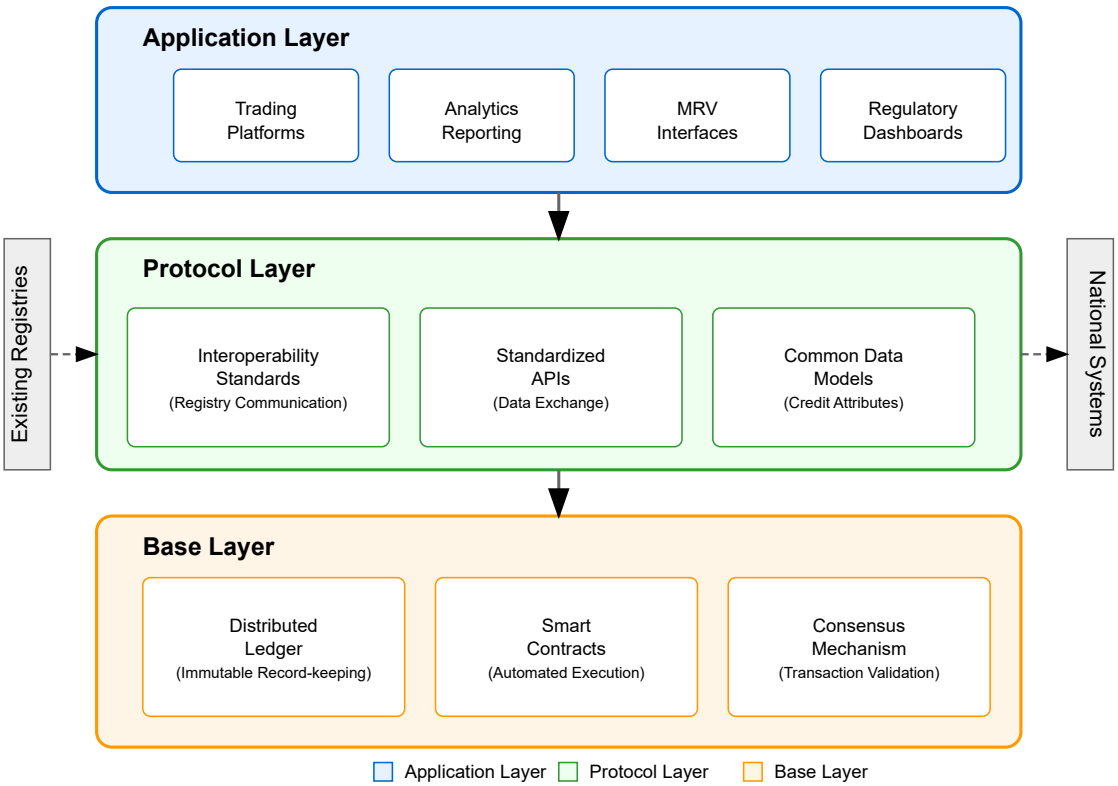


Figure 4. Proposed Three-tier Architecture for Global Carbon Market Integration [Diagram illustrating base layer, protocol layer, and application layer components for integrating DLT with compliance markets].

In accordance with Eisenhardt's methodology [40], three independent case studies were used to develop an architectural structure for a blockchain 3.0 application [41] in

carbon markets. The case studies evaluated DLT application in carbon markets of Europe, Australia, and China, providing, through the three scenarios, an example of the potential application of DLT to carbon markets [34]. The first paper analyzed was an Emissions Trading Case Study from the European Union [42], the second, a case study from the Australian Carbon Market [30], and the third, a case study from the Shanghai Environment and Energy Exchange [3].

Case Study Design

All three studies employed case study methodology focused on specific carbon trading systems:

- EU ETS Study: European Union Emissions Trading System: As the world's largest and most mature market, this case provides insight into DLT integration within an established regulatory framework.
- Australian Study: Australia's Emissions Reduction Fund (ERF): This case represents a developed economy with an evolving carbon market, offering perspectives on transitioning to DLT-based systems.
- China, Shanghai Study: Shanghai Environment and Energy Exchange (SHEE): As part of China's emerging national carbon market. This case illustrates the DLT application in a rapidly developing economy with significant emission reduction targets.

These cases were selected to provide a comprehensive view of DLT implementation across different regulatory environments, market structures, and stages of development. Each case study employs comparable background strategies, whereas the comparison is performed for application parameters that are most relevant for industrial emission credit trade [41]. The EU case study examines EU ETS: Legal and regulatory documents, policy literature, and historical EU ETS data [42]. The Australian case study applied a systematic literature review, identifying four blockchain carbon market models that are suitable for the Australian market [43]. The China, Shanghai case study also applies a peer-reviewed literature and gray literature that are publicly available information to decipher potential DLT strategies suitable for the Chinese market [3].

All studies compared current centralized systems against proposed blockchain implementations:

- EU ETS: Centralized vs. decentralized system comparison;
- Australian: Traditional carbon market vs. blockchain-enabled market;
- Shanghai: Pre-blockchain vs. post-blockchain market performance.

The comparison parameters selection criteria were choosing parameters that indicate the applicative viability of each system and included: user authentication, system stability, and economic design [41]. Once these parameters were deciphered from the literature, they were sent into a comparative table (Table 1), which highlights the integrative difference from one case study strategy to the others.

Table 1. Market benefits presented by each system.

STUDY	EFFICIENCY GAINS	COST REDUCTIONS	PROCESSING SPEED
EU ETS	Automated compliance, reduced admin burden	>EUR 5 billion fraud prevention	Smart contract automation
AUSTRALIA	Reduced CSP reliance, automated MRV	Lower transaction costs	Instant vs. 6-week ACCU issuance
CHINA	15% transaction cost reduction	Lower regulatory costs	40% transaction speed increase

4. Comparative Analysis Results

Having outlined our comparative case study methodology in Section 3, we now turn in Section 4 to a detailed examination of each case study—beginning with the EU's Emissions Trading Scheme—to explore how blockchain might inform or enhance their experience with carbon market operations. Generalized Market Performance evaluation is presented in Table 1.

4.1. EU Carbon Market Case Study

The EU Emissions Trading Scheme (ETS) was launched in 2005, the world's largest and most mature cap-and-trade program, covering approximately 40% of the EU's greenhouse gas emissions. The case study does not incorporate DLT; it describes the evolution of the carbon market trading system, the challenges that it faces, and the lessons learnt. It operates by setting a declining cap on total emissions and enabling the trading of emission allowances (EUAs) among regulated entities [28]. The system has evolved over multiple phases, introducing improvements such as centralized allocation, expanded sectoral coverage, and increased auctioning. To address the persistent oversupply of allowances that led to low carbon prices, the EU implemented a "backloading" measure in 2014, which temporarily withheld 900 million allowances from auction. This was followed by the introduction of the Market Stability Reserve (MSR) to more systematically adjust supply. Despite initial design flaws, the EU ETS has contributed significantly to achieving the Union's emission reduction targets and remains central to its strategy for climate neutrality by 2050.

While the EU ETS does not currently use blockchain technology for trading or registry operations, the potential for its application is being explored. Trading continues through traditional platforms such as the European Energy Exchange (EEX) and the Intercontinental Exchange (ICE), with allowances tracked via the centralized Union Registry. Although blockchain offers theoretical advantages in transparency, traceability, and decentralization, the EU has opted for the robustness and regulatory certainty of its existing infrastructure. Nevertheless, blockchain is being piloted in voluntary carbon markets and may play a future role in enhancing data integrity and auditability within compliance markets like the EU ETS.

Benefits of Distributed Ledger for Carbon Trading

The integration of carbon markets globally presents significant opportunities for creating a more efficient and consistent price on carbon. Connecting these markets can promote greater confidence, stimulate investment, and foster new technology development through enhanced financial flows. However, the challenge lies in the legal and regulatory fragmentation of individual carbon markets [44].

Distributed Ledger (DL) or blockchain technology offers a promising "bottom-up" solution to this challenge. Its key benefits include the following:

1. Interoperability: DL can facilitate connections between different carbon markets without requiring complete legal and regulatory standardization [45].
2. Transparency and Trust: The distributed database with public/private key encryption provides a transparent and secure environment for transactions.
3. Decentralized Infrastructure: This aligns well with the prosumer model, allowing for more direct participation in carbon trading.
4. Innovative Data Sharing: DL enables novel approaches to managing and sharing data, crucial for accurate carbon accounting across different markets.
5. Flexible Transaction Management: This feature is particularly beneficial for prosumers who may engage in smaller, more frequent transactions.

As for user authentication, the EU ETS registry utilizes a two-factor authentication system, requiring both email/password and a QR code generated by a registered phone number (Table 2). The central authentication service allows access to various commission services with a single email and password, and can incorporate second-factor verification methods [46]. System stability through the EU ETS is considered a mature and stable carbon market, having been in operation since 2005. The Market Stability Reserve (MSR) is a key mechanism for regulating allowance supply and demand, enhancing the market's resilience to shocks. It is suggested that the market functions in an orderly manner, comparable to other financial markets, without widespread market manipulation [38]. The EU ETS economic design is a mature cap-and-trade system covering a wide range of sectors and gases. Emission allowances are classified as financial instruments, subject to financial market rules and oversight. The EU ETS has proven effective in driving emission reductions, particularly in the power sector, and generates substantial revenue for green transition initiatives [47].

Table 2. Case study comparison by three key parameters.

PARAMETER	CHINA (DLT-BASED)	AUSTRALIA (DLT-ENABLED)	EUROPEAN UNION (ESTABLISHED DLT)
USER AUTHENTICATION	Focused on legal entities, potential for future offshore access; emphasis on data quality and security measures	Advocates for secure API access and robust security measures like multi-factor authentication	Robust two-factor authentication system with a central authentication service
SYSTEM STABILITY	Younger market, increasing stability, but still more volatile compared to the EU ETS; fewer price stabilization mechanisms	Evolving market with reforms to enhance transparency and integrity; rising ACCU prices indicate increasing stability	Mature and stable market with a proven track record; Market Stability Reserve (MSR) effectively manages supply and demand
ECONOMIC DESIGN	Mandatory ETS and voluntary CCER scheme; initially, intensity-based allocation with free allowances; aiming to incentivize low-carbon practices	Combines ACCU projects with the Safeguard Mechanism; ACCUs treated as financial products; emphasis on broad economic coverage and sectoral linkages	Mature cap-and-trade system with wide sectoral coverage; allowances classified as financial instruments; effective in driving emission reductions and generating revenue for green transition

4.2. Australian Carbon Market Case Study

Australian carbon market DLT application case study [43] specifically focuses on retrofitting DLT into the existing Australian National Registry of Emissions Units (ANREU). Through detailed document analysis of legislation, registry protocols, Clean Energy Regulator governance, and project workflows, they derive system requirements compatible with Australia's Emissions Reduction Fund and ANREU framework. They propose a permissioned DLT model under regulator control, embedding smart contracts to automate credit issuance, transfers, and compliance processes—thereby enhancing transparency, preventing double-counting, and reducing administrative friction. Key anticipated benefits include operational efficiency, improved equity through broader market participation, and integrity upheld within a hybrid governance structure aligned to legal mandates.

In the context of emerging prosumer participation—households or small entities that both generate and consume carbon-offsetting energy—DLT can facilitate peer-to-peer (P2P) trading of carbon allowances and energy, allowing prosumers to influence pricing and participate in decentralized markets directly [48]. In such P2P frameworks, prosumers upload their surplus renewable energy generation or carbon reduction data, receive and trade carbon credits within the DLT system, and thereby gain a more equitable share of market opportunities. This aligns with the case design principles, offering a future pathway for Australia's carbon registry to support decentralized carbon energy exchanges while preserving regulatory oversight [43].

The integration of DLT in carbon trading, as evidenced by the Australian case study, offers the following significant benefits:

1. Market Access: DLT can lower barriers to entry, allowing smaller-scale prosumers to participate more easily in carbon markets.
2. Accurate Accounting: The transparent and immutable nature of DLT addresses the challenge of accurately tracking emissions and credits for decentralized energy producers.
3. Cross-Market Participation: As prosumers may operate across different jurisdictions or markets, the interoperability offered by DLT systems is particularly valuable.
4. Trust in Decentralized Systems: DLT's ability to establish trust without centralized authorities aligns well with the decentralized nature of prosumer energy production and consumption.
5. Policy Adaptation: As demonstrated in the Australian case, DLT can help existing markets adapt to the changing landscape brought about by prosumers.

The emergence of prosumers in the energy sector presents both challenges and opportunities for carbon markets. Blockchain and DLT offer promising solutions to these challenges by providing a flexible, transparent, and efficient platform for carbon trading. The potential benefits, as highlighted in the Australian case study and the broader analysis of DL applications, suggest that blockchain could play a crucial role in adapting carbon markets to the prosumer era. This adaptation is essential for creating more inclusive, efficient, and effective carbon trading systems that can accommodate the complex dynamics of modern energy production and consumption while effectively managing carbon emissions on a global scale.

As for user authentication, carbon market participants, including brokers and digital marketplaces, advocate for secure API access to the registry for efficient analysis and trading (Table 2). There is support for multi-factor authentication, data protection, and encryption, indicating a focus on robust security for user authentication and access. With over a decade of national carbon markets experience, system stability action is focused on enhancing transparency and integrity. The Safeguard Mechanism, a key policy, requires large emitters to reduce their emissions or offset them with Australian Carbon Credit Units (ACCUs). The market is evolving, and ACCU prices are expected to rise, suggesting increasing stability and confidence [49]. Australian carbon market economic design combines ACCU Scheme projects (generating credits) with the Safeguard Mechanism (requiring large emitters to manage their emissions).

ACCUs are considered financial products, and organizations engaging in the market must adhere to Australian Financial Services License obligations. The market design emphasizes broad economic coverage and aims to link sectoral transition plans for accelerated decarbonization [43].

4.3. Shanghai Energy Exchange Case Study

China, the world's largest emitter of greenhouse gases, has set ambitious targets for achieving carbon neutrality by 2060. The nation is actively exploring innovative approaches to manage its carbon footprint and drive sustainable economic growth. DLT, particularly blockchain, is emerging as a critical tool in this endeavor, offering unique solutions for enhancing transparency, efficiency, and trust within China's developing carbon market. A case study of a successful blockchain implementation for carbon trading in the Shanghai Energy Exchange [3] provides a review of how blockchain affected carbon trading prices.

Monitoring the effect of six events on carbon prices since carbon trading began on the Shanghai Energy Exchange in 2022 included the following: certification of asset trading, research on DLT applications, an international standard on blockchain and carbon trading, a demonstration of carbon trading on carbon neutral management, integration

with international carbon markets, and a regulatory framework to support long-term blockchain applications in carbon trading. The Cathay Pacific trading data statistical analysis concluded that the market reacted positively to these events, showing that blockchain technology changes elevated carbon prices in the short term. It was also concluded that blockchain technology was positive for the carbon trading market and had significant potential for innovation and improvement. However, blockchain also created challenges to the market, such as increased costs, elevated energy consumption, transaction delays, and higher learning costs for participants. To address these challenges, selecting more efficient and cost-effective blockchain platforms and considering environmentally friendly consensus mechanisms, such as Proof-of-Stake, was recommended.

While impacts and benefits included enhanced transparency through immutable records, allowing for easier auditing and verification, and automated compliance verification through smart contracts streamlines operations, reducing transaction time and costs. The challenges and limitations involve high initial costs for DLT implementation, both in infrastructure and for market participants' learning investment, increased energy consumption in reference to the current database system, and transaction delays. As DLT improves efficiency in some areas, the processing speed of some networks may lead to transaction delays. In the future, as suggested in the Shanghai case study, China is expected to continue integrating DLT into its carbon market, aiming to further enhance its efficiency and integrity, contributing to fraud risk reduction and increased market trust. The Shanghai Market Structure impacts involve facilitated cross-regional and international cooperation, standardized international trading processes, and sustained market confidence seeking to leverage technology for climate action.

As for user authentication, the CCER registration system is limited to legal entities registered within China. The government has expressed intentions to open up the market to offshore investors in due course. There is also a strong emphasis on data quality management, multi-level review, and intelligent early warning systems, potentially influencing user authentication protocols. User authentication for individual carbon accounts at the local level and within company systems involves methods like email and specialized applications, sometimes using QR codes for login and transaction signing (Table 2).

The young Chinese national carbon market demonstrates increasing system stability and vibrancy. While it is designed to unlock emission reduction potential and is projected to become the world's largest carbon market, compared to the EU, China's ETS is considered less mature and more volatile due to fewer price stabilization mechanisms and smaller sectoral coverage [50]. The national carbon market economic design includes both a mandatory ETS and a voluntary CCER scheme, which are interconnected. While the ETS is initially intensity-based, with free allowance allocation, potentially impacting near-term decarbonization incentives, it aims to raise awareness that "emissions come at a cost and reductions yield benefits," encouraging low-carbon practices and technological adoption [48].

5. Discussion

5.1. Integration with Global Compliance Markets

The integration of DLT with existing compliance markets represents both a significant opportunity and a challenge. Our analysis suggests that a phased approach is most feasible, beginning with parallel operation of DLT systems alongside traditional registries, followed by gradual integration through standardized APIs and common data models.

The Paris Agreement's Article 6, which establishes mechanisms for international cooperation on climate mitigation, provides a framework for this integration. Specifically, Article 6.2's cooperative approaches and the Article 6.4 mechanism could benefit from

DLT's ability to track Internationally Transferred Mitigation Outcomes (ITMOs) and prevent double-counting across jurisdictions [51].

We propose the following three-tier architecture (Figure 4) for integrating DLT with global compliance markets: (1) a base layer providing immutable record-keeping and basic transaction functionality; (2) a protocol layer implementing standardized interfaces for interoperability between different registries; and (3) an application layer enabling market-specific functionality such as trading platforms and verification systems.

Our findings indicate that DLT can significantly enhance the integrity and efficiency of carbon markets, though several challenges must be addressed to realize its full potential.

5.2. Challenges and Limitations

Despite its promise, DLT faces several challenges in carbon market applications. First, the PoW energy consumption consensus mechanisms conflict with the carbon market environmental goals. While newer consensus mechanisms like PoS (Proof-of-Stake) have substantially reduced energy requirements, they introduce different trade-offs regarding security and decentralization [52].

Second, the "oracle problem"—reliably connecting on-chain systems with off-chain data—remains significant for carbon markets, which depend on accurate Measurement, Reporting, and Verification of physical emissions. Hybrid systems using IoT devices, satellite data, and AI for verification show promise but require further development [53]. For instance, combining DLT with artificial neural networks can enhance the ability to monitor and mitigate adverse environmental effects within the digital economy, creating a more holistic approach to sustainability.

The "oracle problem" in blockchain technology presents a significant challenge in obtaining and providing reliable, real-time, real-world data in a trustworthy and secure manner. This issue is crucial because blockchains operate in a decentralized environment where data reliability and trust are paramount. While blockchain has demonstrated effectiveness in supply chain traceability [54,55] and has the potential to address counterfeiting issues [56], the integration of external data remains a complex hurdle.

The implementation of blockchain in business processes, as seen in cases like TraceThai, shows promise in enhancing trust between new business partners. It can serve as a signaling mechanism for suppliers to demonstrate trustworthiness through brand credibility, third-party verified information, and transparent information sharing. However, its impact may be limited in well-established relationships where trust has already been developed through long-term interactions [57].

Governments can play a role in incentivizing the deployment of blockchain technology, potentially addressing some aspects of the oracle problem [56]. However, the challenge remains in ensuring that the data fed into the blockchain from external sources maintains the same level of reliability and trustworthiness as the blockchain itself.

It is important to note that while blockchain can enhance traceability and trust in certain contexts, it is not a universal solution to all data reliability issues. The oracle problem highlights the ongoing need for developing robust mechanisms to bridge the gap between blockchain's internal environment and external data sources, especially in applications that require real-time, real-world information.

Third, regulatory fragmentation across jurisdictions creates significant barriers to the global adoption of DLT-based carbon markets. Harmonizing regulations, particularly regarding the legal status of tokenized carbon credits, will be essential for realizing DLT's full potential [58]. In emerging carbon markets, regulatory frameworks must also be designed with technological integration in mind to maximize transparency benefits while ensuring market stability [59].

Blockchain as a new global resource faces immense challenges in stewardship or governance, which involves regulating behavior, including meting out punishments [60]. Governance is needed at different levels of implementation, i.e., at the platform level, application level, and ecosystem level. From a supply chain perspective, blockchain is an emerging technology and supply chain enabler with a lot of promise, but its adoption is also fraught with difficulties in mismatched expectations of technology adopters, as well as slow learning cycles [54]. Technology adopters normally come with a set of prioritized goals that will include financial goals, operational costs, system and efficiency, return on investments, trust, and end-to-end integration, i.e., flexibility of use with partners (both nationally and internationally).

Businesses are expected to align with and support their governments' commitments to the Paris Agreement. However, this alignment can be challenging due to differing priorities between businesses and governments. Additionally, businesses often lack the capacity or incentive to track emissions across their entire supply chain, leading to fragmentation and potential gaps in carbon accounting. This situation creates obstacles in efficiently managing carbon assets and meeting climate objectives. The implementation of standardized methods for emissions tracking and the integration of carbon markets could help address these challenges, but significant hurdles remain in achieving comprehensive and consistent carbon management across business operations [61]. The use of blockchain and its feasibility for use at scale is constrained by the fact that different industries as diverse as agriculture, finance, mining, and manufacturing, have different types of assets, standards, and regulations [62].

5.3. Prosumers in Blockchain-Based Carbon Trading

The concept of prosumers has become increasingly relevant in the context of blockchain applications for carbon trading [48]. Prosumers, individuals or entities that both produce and consume a product or service, are reshaping traditional market dynamics, particularly in the energy sector and carbon markets.

In the realm of carbon trading and energy management, prosumers play a crucial role. The global energy sector is undergoing a significant transformation driven by the emergence of prosumers who generate and consume energy. These individuals utilize decentralized energy sources like solar panels and wind turbines, enhancing energy independence by producing their own energy and selling surplus back to the grid [63].

The importance of the prosumer perspective in blockchain-based carbon trading can be understood through the following seven key points:

1. Decentralization and Market Dynamics: Prosumers contribute to the decentralization of energy production and carbon management. This shift aligns well with blockchain's decentralized nature, potentially creating more dynamic and responsive carbon markets.
2. Accurate Emissions Tracking: As both producers and consumers of energy, prosumers present unique challenges in accurately tracking carbon emissions. Blockchain technology can offer a solution by providing a transparent and reliable Measurement, Reporting, and Verification (MRV) system [64].
3. Equitable Pricing Mechanisms: The dual role of prosumers necessitates the development of fair and equitable pricing mechanisms in carbon trading. Blockchain-based platforms can facilitate peer-to-peer (P2P) trading of carbon allowances [63].
4. Enhanced Participation in Carbon Markets: By enabling more accurate tracking and trading of carbon credits, blockchain technology can help the building sector and individual prosumers participate more effectively in carbon credit markets [64].

5. Regulatory Challenges: The prosumer model introduces new regulatory challenges in carbon trading. Blockchain's transparency and immutability can aid in creating more effective regulatory frameworks.
6. Data Management and Privacy: Prosumers generate significant amounts of data related to energy production and consumption. Blockchain can provide secure and transparent management of this data while addressing privacy concerns.
7. Market Access and Democratization: Blockchain-based systems can potentially democratize access to carbon markets, allowing smaller-scale prosumers to participate alongside larger entities.

In practical applications, the prosumer perspective is crucial for several reasons:

1. It drives innovation in energy management and carbon trading systems.
2. It encourages more widespread adoption of renewable energy sources.
3. It necessitates the development of more sophisticated and flexible carbon trading platforms.
4. It challenges traditional market structures, potentially leading to more efficient and responsive carbon markets.

6. Implications and Future Directions

The findings of this study have several important implications. DLT has the potential to significantly enhance the efficiency, transparency, and integrity of carbon credit markets. By reducing transaction costs, automating processes through smart contracts, and providing immutable records, DLT can increase market participation and improve trust among stakeholders. The strategic potential of DLT adoption is crucial for leveraging its benefits in carbon markets and beyond. Furthermore, DLT can facilitate innovative financial mechanisms such as pay-for-outcome models in sustainable agriculture, further driving environmental benefits. The intersection of Web3 and climate is fostering the growth of regenerative finance, which seeks to align financial incentives with positive environmental outcomes.

Our findings point to several promising directions for future development. First, the integration of DLT with emerging technologies such as Internet of Things (IoT) sensors and artificial intelligence could further automate verification processes, reduce costs, and enhance accuracy. Hybrid systems using IoT devices, satellite data, and AI for verification show promise but require further development. Furthermore, combining DLT with artificial neural networks can enhance the ability to monitor and mitigate adverse environmental effects within the digital economy, creating a more holistic approach to sustainability. Second, the development of interoperability protocols could enable seamless exchange between different carbon credit platforms and traditional registries, increasing market liquidity and efficiency. Third, programmable DLT carbon credits could enable new market mechanisms that automatically adjust prices based on environmental outcomes or time-based parameters.

Future developments in carbon markets should consider the potential of regenerative finance models enabled by Web3 technologies to drive more sustainable and equitable outcomes. Further research should investigate the long-term strategic implications of DLT adoption for carbon markets, considering factors such as competitive advantage and market disruption. Ultimately, realizing sustainability goals necessitates not only technological advancements but also financial innovation and a deep consideration of human agency in driving change. Further research should explore the integration of DLT with pay-for-outcome financing models to enhance the effectiveness of sustainable agriculture projects.

Future Research

Academic research on the use of DLT in capturing and tracking carbon credits is not new, as several researchers have successfully published in this area, including as recently as 2025. However, because of large-scale implementations or long-running use cases, longitudinal research options are limited at the time of publication of this research. As the industry becomes less fragmented and more successful implementations can be studied, many opportunities for research will begin to emerge.

- *Social Impact*: As more data begins to emerge regarding cost savings, accuracy, and transparency of recording and tracing tokenized carbon credits, automated features through the use of smart contracts, etc., researchers could begin to assess how these advantages and others affect local and regional communities and parts of the world. If positive results are revealed, this could add momentum to the carbon capture and credit industry as a whole and have a positive impact on global sustainability.
- *Governance Strategies*: Traditional governance in the carbon credit industry typically makes use of centralized entities like Verra, Gold Standard, UN Clean Development, etc., for decision-making and regulation. This approach can result in picking winners and losers (unfair assessments), clouded or confused or slow decision-making processes, a lack of public trust, and high administrative and transaction costs [65]. Blockchain systems allow for the creation of Decentralized Autonomous Organizations (DAOs), which are digital governance models whereby the DAO operates via the use of smart contracts (computer programs and logic) that drive governance decisions and actions. These automated systems can offset or mitigate many of the aforementioned concerns or limitations of traditional models of governance. If designed and implemented successfully, these governance systems can improve speed, reduce cost, increase transparency, reduce unfair decision-making, and thereby increase public confidence. Researchers should be able to conduct longer-range studies that assess improvements or risks, potentially enhancing these systems in the future.
- *Impact Assessments*: As industries begin the digitization of processes, decision-making procedures, and administrative functions, researchers have an opportunity to verify the effectiveness of the change in quantitative terms. Industry studies from reputable sources such as the World Economic Forum or The Organization for Economic Co-operation and Development (OECD) make broad statements regarding improved efficiencies, reduced administrative costs, faster decision-making but the reports by in large, avoid citing concreate or specific quantitative results perhaps due to the lack of time production systems have been in place or a simple lack of successful cases to study. Future research should be able to uncover accurate statistics, which can lead to more confidence in those in the process of using a DLT approach to improve their carbon reporting systems.

Author Contributions: Conceptualization, S.H. and Y.A.; methodology, D.I.W. and Y.A.; Case Studies, F.K.P.H.; validation, D.I.W. and F.K.P.H.; formal analysis, S.H. and Y.A.; investigation, D.I.W.; writing—original draft preparation, Y.A. and S.H.; writing—review and editing, D.I.W.; visualization, Y.A.; supervision, S.H. All authors have read and agreed to the published version of the manuscript.

Funding: No funding by the author institutions was provided.

Data Availability Statement: Data available on request due to restrictions (e.g., privacy, legal or ethical reasons). The data presented in this study are available on request from the corresponding author due to copywrite protection.

Acknowledgments: This paper acts as a background to the impact maximization work package (8), in the Israeli Science Foundation Planning and Budgeting Committee, Waste to Energy Research Hub (Grant No. 0605408961).

Conflicts of Interest: There are no conflicts of interest.

References

1. Hasselknippe, H. Systems for Carbon Trading: An Overview. *Clim. Policy* **2003**, *3*, S43–S57. [CrossRef]
2. Saraji, S.; Borowczak, M. A Blockchain-Based Carbon Credit Ecosystem. *arXiv* **2021**, arXiv:2107.00185. [CrossRef]
3. Zhang, G.; Chen, S.C.I.; Yue, X. Blockchain Technology in Carbon Trading Markets: Impacts, Benefits, and Challenges—A Case Study of the Shanghai Environment and Energy Exchange. *Energies* **2024**, *17*, 3296. [CrossRef]
4. Dunkel, S. *How a Blockchain Network Can Ensure Compliance with Clean Development Mechanism Methodology and Reduce Uncertainty About Achieving Intended Nationally Determined Contributions*; Elsevier Inc.: Amsterdam, The Netherlands, 2018; ISBN 9780128144480.
5. Xu, Z. Research on The Path of China's Green Finance to Support the Development of Low-Carbon Economy. *Front. Bus. Econ. Manag.* **2022**, *5*, 133–136. [CrossRef]
6. Kim, S.K.; Huh, J.H. Blockchain of Carbon Trading for UN Sustainable Development Goals. *Sustainability* **2020**, *12*, 4021. [CrossRef]
7. Yao, X.; Broca, S. *Sustainable Development—17 Goals to Transform Our World*; FAO: Rome, Italy; United Nations: New York, NY, USA, 2015.
8. Martinez, R.; Gregorie, J.; Val, S. The World Needs Carbon Markets. Here's How to Make Them Work Better. *Deloitte Insights*. 2023. Available online: https://www.deloitte.com/us/en/insights/industry/financial-services/future-of-carbon-market.html (accessed on 11 September 2025).
9. Narassimhan, E.; Gallagher, K.S.; Koester, S.; Alejo, J.R. Carbon Pricing in Practice: A Review of Existing Emissions Trading Systems. *Clim. Policy* **2018**, *18*, 967–991. [CrossRef]
10. Swan, M. *Blockchain Blueprint for A New Economy*; McGovern, T., Ed.; O'Reilly: Sebastopol, CA, USA, 2015; ISBN 9781491920497.
11. Manarte, B.M.C. Challenges and Opportunities in the Voluntary Carbon Market: How Can Emerging Regulatory Frameworks and Blockchain Technology Enhance Transparency and Credibility in the Market. Master's Thesis, Nova School of Business and Economics, Carcavelos, Portugal, 2022; Volume 4.
12. Scott, N.; Nellore, S.; Marke, A. DLT and the Voluntary Carbon Markets. In *Governing Carbon Markets with Distributed Ledger Technology*; Marke, A., Mehling, M.A., Correa, F.d.A., Eds.; Cambridge University Press: Cambridge, UK, 2022; pp. 115–136, ISBN 9781108919166.
13. Heister, S. Enterprise Blockchain Explained. *Pathw. Res.-Bus.* **2022**, 1–11. Available online: https://about.ebsco.com/sites/default/files/acquiadam-assets/Pathways-to-Research-Business-Sample-Enterprise-Blockchain-Explained.pdf (accessed on 11 September 2025).
14. Volpicelli, G.M. As Kazakhstan Descends Into Chaos, Crypto Miners Are at a Loss. Available online: https://www.wired.com/story/kazakhstan-cryptocurrency-mining-unrest-energy/ (accessed on 14 April 2025).
15. Sriman, B.; Ganesh Kumar, S.; Shamili, P. Blockchain Technology: Consensus Protocol Proof of Work and Proof of Stake. In *Intelligent Computing and Applications (Advances in Intelligent Systems and Computing)*; Dash, S.S., Das, S., Panigrahi, B.K., Eds.; Springer Nature: Singapore, 2020; pp. 395–406.
16. Coinmetro Gas Fees Explained: Why Ethereum Transactions Can Be Expensive. Available online: https://www.coinmetro.com/learning-lab/gas-fees-explained (accessed on 14 April 2025).
17. Zhang, S.; Lee, J.H. Analysis of the Main Consensus Protocols of Blockchain. *ICT Express* **2020**, *6*, 93–97. [CrossRef]
18. Chainlink Hybrid Smart Contracts Explained | Chainlink. Available online: https://chain.link/education-hub/hybrid-smart-contracts (accessed on 14 April 2025).
19. Khan, D.; Jung, L.T.; Hashmani, M.A.; Cheong, M.K. Empirical Performance Analysis of Hyperledger LTS for Small. *Sensors* **2022**, *22*, 915. [CrossRef]
20. World Bank. *State and Trends of Carbon Pricing 2023*; World Bank: Washington, DC, USA, 2023.
21. Choudhury, R.; Jhanji, K.; Samd, H.; Gleeson, S.; Bennett, S.; Nirgudkar, N.; Boston Consulting Group (New York). *Impact of Distributed Ledger Technology in Global Capital Markets*; AFME: London, UK, 2023.
22. Mohan, P. DLT in Securities Settlement, Potential Impact and Challenges of Implementation. Master's Thesis, Johann Wolfgang Goethe-Universität Frankfurt, Frankfurt am Main, Germany, 2020; Volume i.
23. BJÖRN FONDÉN. *Making Net Zero Possible*; BJÖRN FONDÉN: Genève, Switzerland, 2023.
24. Pons, J.R.D. *Trust Creation with Blockchain and Distributed Ledger Technology (DLT) for Carbon and Biodiversity Credit Management*; 2025. Available online: https://www.researchgate.net/publication/390466525_Trust_Creation_with_Blockchain_and_Distributed_Ledger_Technology_DLT_for_Carbon_and_Biodiversity_Credit_Management (accessed on 11 September 2025).

25. Parhamfar, M.; Sadeghkhani, I.; Adeli, A.M. Towards the Net Zero Carbon Future A Review of Blockchain-enabled peer-to-peer carbon trading. *Energy Sci. Eng.* **2024**, *12*, 1242–1264. [CrossRef]
26. Abiodun, T.P.; Nwulu, N.I.; Olukanmi, P.O. Application of Blockchain Technology in Carbon Trading Market: A Systematic Review. *IEEE Access* **2025**, *13*, 5446–5470. [CrossRef]
27. Tian, H.; Zhao, T.; Wu, X.; Wang, P. The Impact of Digital Economy Development on Carbon Emissions-Based on the Perspective of Carbon Trading Market. *J. Clean. Prod.* **2024**, *434*, 140126. [CrossRef]
28. Kaufman, M.; Heister, S.; Yuthas, K. Consortium Capabilities for Enterprise Blockchain Success. *J. Br. Blockchain Assoc.* **2021**, *4*, 34–42. [CrossRef] [PubMed]
29. Fuessler, J.; Braden, S.; Owen Hewlett, M.G.I. *Navigating Blockchain and Climate Action*; Climate Ledger Initiative (CLI): Zurich, Switzerland, 2020.
30. CarbonChain. Carbon Accounting Software for Manufacturers, Commodity Traders and Their Banks. Available online: https://www.carbonchain.com/ (accessed on 20 September 2025).
31. TransparenTerra. Available online: https://transparenterra.com/ (accessed on 21 March 2025).
32. Michaelowa, A.; Ahonen, H.-M.; Juliana Keßler, A.S.D. *Carbon Market Mechanism Working Group*; Perspectives Climate Group: Freiburg, Germany, 2023.
33. Interwork Alliance. *V2 Digital Measurement, Reporting & Verification Framework-Interwork Alliance*; Interwork Alliance: Washhington, DC, USA; Geneva, Switzerland, 2023.
34. Global Blockchain Business Council. Token Taxonomy Framework (TTF). 2025. Available online: https://www.gbbc.io/interwork-alliance/token-taxonomy-framework (accessed on 11 September 2025).
35. Greenfield, P. Revealed: More than 90% of Rainforest Carbon Offsets by Biggest Certifier Are Worthless, Analysis Shows. *Guardian* **2023**, *18*, 2023.
36. Kessler, J.; Ahonen, H.-M.; Schmid, A.; Frey, C. *Analysis of the ICVCM's Core Carbon Principles and Assessment Framework Analysis of the ICVCM's CCPs and Assessment Framework*; Integrity Council for the Voluntary Carbon Market (ICVCM): Freiburg, Germany, 2024.
37. Flourentzou, P. *Decentralised Sustainability: Integrating Climate Action into Digital Asset Management on Distributed Ledger Technology (DLT)*; Blockchain & Climate Institute: London, UK, 2025.
38. Mandaroux, R.; Dong, C.; Li, G. A European Emissions Trading System Powered by Distributed Ledger Technology: An Evaluation Framework. *Sustainability* **2021**, *13*, 2106. [CrossRef]
39. *ISO/TS 23635:2022*; ISO Blockchain and Distributed Ledger Technologies—Guidelines for Governance. ISO: Geneva, Switzerland, 2022; Volume 2022.
40. Eisenhardt, K.M. What Is the Eisenhardt Method, Really? *Strateg. Organ.* **2021**, *19*, 147–160. [CrossRef]
41. Kubler, S.; Renard, M.; Ghatpande, S.; Georges, J.P.; Le Traon, Y. Decision Support System for Blockchain (DLT) Platform Selection Based on ITU Recommendations: A Systematic Literature Review Approach. *Expert Syst. Appl.* **2023**, *211*, 118704. [CrossRef]
42. Zolla, M.; Marke, A.; Mehling, M.A. DLT and the European Union Emissions Trading System. In *Governing Carbon Markets with Distributed Ledger Technology*; Cambridge University Press: Cambridge, UK, 2022; pp. 98–114. [CrossRef]
43. Hartmann, S.; Thomas, S. Applying Blockchain to the Australian Carbon Market. *Econ. Pap.* **2020**, *39*, 133–151. [CrossRef]
44. Jackson, R.B.; Friedlingstein, P.; Andrew, R.M.; Canadell, J.G.; Le Quéré, C.; Peters, G.P. Persistent Fossil Fuel Growth Threatens the Paris Agreement and Planetary Health. *Environ. Res. Lett.* **2019**, *14*, 121001. [CrossRef]
45. Jackson, A.; Lloyd, A.; Macinante, J.; Hüwener, M. Networked Carbon Markets: Permissionless Innovation With Distributed Ledgers? Permissionless Innovation With Distributed Ledgers? In *Transforming Climate Finance and Green Investment with Blockchains*; Academic Press: Cambridge, MA, USA, 2018; pp. 255–268. [CrossRef]
46. EU Login-European Commission Authentication Service-Erasmus+ & European Solidarity Corps Guides-EC Public Wiki. Available online: https://wikis.ec.europa.eu/spaces/NAITDOC/pages/33529367/EU+Login+-+European+Commission+Authentication+Service (accessed on 22 August 2025).
47. EU Emissions Trading System (EU ETS)-European Commission. Available online: https://climate.ec.europa.eu/eu-action/carbon-markets/eu-emissions-trading-system-eu-ets_en (accessed on 22 August 2025).
48. Yang, Y.; Xu, X.; Pan, L.; Liu, J.; Liu, J.; Hu, W. Distributed Prosumer Trading in the Electricity and Carbon Markets Considering User Utility. *Renew. Energy* **2024**, *228*, 120669. [CrossRef]
49. CMI. *A National Carbon Market Strategy for Australia*; CMI: Singapore, 2024.
50. DeGrandpré, J.; Zhang, N.; Marquardt, M. *Navigating CBAM in China: Exploring Policy Pathways for Guangdong Province*; NewClimate Institute: Cologne, Germany; Berlin, Germany, 2025.
51. UN. *The Paris Agreement*; United Nations Framework Convention on Climate Change (UNFCCC): Bonn, Germany, 2016; p. 60.
52. Sedlmeir, J.; Buhl, H.U.; Fridgen, G.; Keller, R. The Energy Consumption of Blockchain Technology: Beyond Myth. *Bus. Inf. Syst. Eng.* **2020**, *62*, 599–608. [CrossRef]

53. World Bank. *Blockchain and Emerging Digital Technologies for Enhancing Post-2020 Climate Markets*; World Bank: Washington, DC, USA, 2018.
54. Hastig, G.M.; Sodhi, M.M.S. Blockchain for Supply Chain Traceability: Business Requirements and Critical Success Factors. *Prod. Oper. Manag.* **2020**, *29*, 935–954. [CrossRef]
55. Groenfeldt, T. IBM and Maersk Apply Blockchain to Container Shipping. Forbes. 2017. Available online: https://www.forbes.com/sites/tomgroenfeldt/2017/03/05/ibm-and-maersk-apply-blockchain-to-container-shipping/ (accessed on 11 September 2025).
56. Pun, H.; Swaminathan, J.M.; Hou, P. Blockchain Adoption for Combating Deceptive Counterfeits. *Prod. Oper. Manag.* **2021**, *30*, 864–882. [CrossRef]
57. Yavaprabhas, K.; Pournader, M.; Seuring, S. Blockchain and Trust in Supply Chains: A Bibliometric Analysis and Trust Transfer Perspective. *Int. J. Prod. Res.* **2024**, *63*, 5071–5098. [CrossRef]
58. UNFCCC. *Draft CMA Decision on Guidance on Cooperative Approaches Referred to in Article 6, Paragraph 2, of the Paris Agreement*; Proposal by the President; DT.DD.CMA3.i12a.v4; UNFCCC: New York, NY, USA, 2021; Volume 15, pp. 1–13.
59. Maya Zaynetdinova Dentzel. The Future of Climate Finance: Analysis of the Regenerative Finance Community at the Intersection of Web3 and Climate. Master's Thesis, University of California, Los Angeles, CA, USA, 2023; Volume 13.
60. Tapscott, D.; Tapscott, A.; Tapscott, D.; Tapscott, A. *Blockchain Revolution*; Portfolio/Penquin: New York, NY, USA, 2016; pp. 1–368.
61. Basu, P.; Deb, P.; Singh, A. Blockchain and the Carbon Credit Ecosystem: Sustainable Management of the Supply Chain. *J. Bus. Strategy* **2024**, *45*, 33–40. [CrossRef]
62. Carson, B.; Romanelli, G.; Walsh, P.; Zhumaev, A. Blockchain beyond the Hype: What Is the Strategic Business Value? *McKinsey Q.* **2018**, *2018*, 118–127.
63. Boumaiza, A.; Maher, K. Leveraging Blockchain Technology to Enhance Transparency and Efficiency in Carbon Trading Markets. *Int. J. Electr. Power Energy Syst.* **2024**, *162*, 110225. [CrossRef]
64. Woo, J.; Fatima, R.; Kibert, C.J.; Newman, R.E.; Tian, Y.; Srinivasan, R.S. Applying Blockchain Technology for Building Energy Performance Measurement, Reporting, and Verification (MRV) and the Carbon Credit Market: A Review of the Literature. *Build. Environ.* **2021**, *205*, 108199. [CrossRef]
65. Hoopes, J., IV; Lerner, A.; Mezzatesta, M.; Anna, H.; Cheikosman, E.; Dentzel, M.; Llyr, B. *Blockchain for Scaling Climate Action*; World Economic Forum (WEF): Geneva, Switzerland, 2023.

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.