

Review

Blockchain for the carbon market: a literature review

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Abstract

The increasing urgency of climate change demands innovative solutions to reduce the environmental impact of human activities. While carbon credits have become a pivotal tool in reducing greenhouse gas emissions, their effectiveness is hindered by challenges such as lack of transparency, inefficiencies, and governance issues in carbon markets. This article uniquely explores how blockchain technology addresses these gaps by automating processes like verification and validation through blockchain-based smart contracts. Unlike previous reviews, our work focuses on platform interoperability and the integration of blockchain within the “3D’s” of decentralization, decarbonization, and digitization, providing a structured analysis of its potential to transform carbon markets. This comprehensive review synthesizes findings from academic papers, international reports, and technical documents, showing that blockchain technology improves transparency, reduces fraud, and ensures compliance with regulatory standards for the carbon market. However, interoperability between platforms and governance issues remain a challenge.

Keywords climate change · carbon market · blockchain

1 Introduction

The escalating impacts of climate change have underscored the urgent need for innovative mechanisms to mitigate greenhouse gas emissions [1]. Carbon markets, particularly carbon credits, have emerged as critical tools in incentivizing emission reductions. However, these markets face significant barriers, such as lack of transparency, inefficiencies in verification and validation processes, and governance challenges, which undermine their potential to drive global decarbonization efforts [2–5].

Blockchain technology has been widely recognized as a disruptive innovation that addresses these issues. Its inherent characteristics, like decentralization, immutability, and automation, offer unique opportunities to enhance the transparency, efficiency, and reliability of carbon markets [6]. For instance, blockchain-based smart contracts can automate verification and validation, enabling broader participation from smaller emitters and fostering trust among stakeholders. Despite these promising applications, the adoption of blockchain in carbon markets remains in its infancy, with several unresolved questions regarding interoperability, scalability, and cost-effectiveness [7].

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Existing research on blockchain and carbon markets has predominantly focused on isolated use cases or theoretical frameworks, leaving a critical gap in understanding how blockchain can transform these markets. This article addresses this gap by conducting a literature review to explore the intersection of blockchain and carbon markets. It investigates the key challenges and opportunities, synthesizes findings from diverse sources, and examines ongoing initiatives to provide actionable insights for researchers and practitioners.

A narrative literature review is used to summarize and discuss existing research on a topic in a clear and flexible way. This approach allows researchers to describe important ideas, trends, and gaps in the literature without strictly following a rigid systematic method [8]. By bridging this research gap, this study aims to contribute to the global effort to combat climate change through innovative and sustainable solutions. It highlights blockchain technology's transformative potential in overcoming current carbon market limitations and sets the stage for future research and development in this emerging field.

Finally, this document is structured as follows: the next section will address the literature review on blockchain and carbon credits, followed by the research findings, a discussion of key points raised, and recommendations for future work.

2 Theoretical framework

Carbon dioxide (CO₂) regulates the climate and maintains Earth's environmental balance. As one of the primary greenhouse gases, CO₂ helps to trap the sun's heat in the atmosphere, creating a natural effect that keeps the planet's temperature at levels suitable for life [9]. However, human activities such as burning fossil fuels for energy and transportation have dramatically increased CO₂ concentrations in the atmosphere, leading to an intensified greenhouse effect, global warming, and climate change [10].

In addition to its role in climate regulation, carbon dioxide is essential for photosynthesis, the process by which plants, algae, and some bacteria convert sunlight into chemical energy. During photosynthesis, plants absorb CO₂ from the atmosphere and produce glucose and oxygen together with water and sunlight. This process is important for plant growth, food production, and the release of oxygen, which is essential for the respiration of animals and humans [11].

Therefore, carbon dioxide is important in its dual role as a climate regulator and an essential nutrient for plant life. However, the imbalance caused by the increase in CO₂ emissions resulting from human activities poses a significant challenge to the planet's health. It underscores the urgent need for actions to reduce carbon emissions and mitigate the impacts of climate change [10].

2.1 Emissions trading system - ETS

The Emissions Trading System (ETS) is a policy instrument designed to efficiently reduce GreenHouse Gas (GHG) emissions. It operates by establishing a maximum limit of allowable emissions and issuing emission permits equivalent to that amount. Companies that exceed their emissions can purchase additional permits from other companies that have exceeded their allocations or have implemented reduction measures beyond what is required. This creates a market for emission permits, where the price is determined by supply and demand [12].

2.2 Carbon offsets and carbon credits

Carbon offsets and carbon credits are mechanisms designed to neutralize or reduce greenhouse gas emissions. Although often used interchangeably, they differ in scope. Carbon offsets specifically refer to initiatives to compensate for an organization's emissions by funding projects that remove or reduce carbon dioxide from the atmosphere [13]. On the other hand, carbon credits represent tradable certificates that verify the reduction or avoidance of emissions and can include a broader range of initiatives, such as innovations in sustainable energy or industrial processes.

2.3 Voluntary carbon markets

Voluntary carbon markets allow organizations to purchase and trade carbon offsets from projects designed to reduce or remove greenhouse gas emissions. Unlike compliance markets, these operate on a voluntary basis, enabling companies to contribute to climate goals beyond regulatory requirements [14]. They are important in financing emission reduction

initiatives and supporting carbon neutrality strategies, particularly in sectors where direct emission reductions are challenging to achieve.

2.4 Carbon market in the Paris agreement

The Paris Agreement represents a significant milestone in global climate action, establishing a framework for international carbon markets through Article 6. This article aims to promote transparency, cooperation, and accountability by enabling emissions trading between countries. It sets a foundation for robust accounting rules and introduces mechanisms to facilitate international collaboration in achieving emission reduction targets. These efforts are important for advancing global decarbonization and addressing the complexities of mitigating greenhouse gas emissions on a global scale [15].

2.5 Intensification of governmental involvement in voluntary markets

A growing trend highlights the increasing involvement of governments in shaping, moderating, and regulating voluntary carbon markets. These efforts aim to address the lack of standardization and safeguards in these markets, which often operate with limited rules enforcement. By introducing hybrid arrangements that blend private and public sector initiatives, governments seek to enhance credibility, transparency, and efficiency in voluntary markets [16].

2.6 Carbon credit markets and mechanisms

Carbon credit markets are systems designed to incentivize emission reductions by allowing organizations to trade certified emission reductions (CERs) or offsets. These credits are generated through verified projects that reduce or avoid greenhouse gas emissions and can be traded in compliance or voluntary markets. Mechanisms such as the Clean Development Mechanism (CDM) are important in facilitating the creation and trade of credits, providing a structured framework for emission reductions in both developed and developing countries [17].

2.7 How carbon credits regulation works

The regulation of carbon credits ensures the credibility and effectiveness of mechanisms designed to reduce greenhouse gas emissions. At the international level, the United Nations Framework Convention on Climate Change (UNFCCC) oversees the development and implementation of market instruments, such as carbon credits, to achieve global climate goals [13].

Regulatory frameworks vary across jurisdictions. For instance, the European Union Emissions Trading System (EU ETS) is a cap-and-trade mechanism regulated by the European Commission to limit emissions across several sectors. Similarly, the United States Environmental Protection Agency (EPA) oversees various programs, including voluntary carbon offset initiatives, to regulate greenhouse gas emissions. These regulatory systems aim to provide transparency, accountability, and market efficiency, ensuring that carbon credits contribute meaningfully to emission reduction targets.

2.8 Carbon pricing: a key tool for emission reductions

Carbon pricing is a mechanism that assigns a monetary value to greenhouse gas emissions, incentivizing emission reductions by making polluters bear the cost of their environmental impact. Common approaches include cap-and-trade systems, with a limit on total emissions, and carbon taxes, which impose a direct cost on emissions. These tools play a critical role in driving investments in clean energy and promoting the transition to a low-carbon economy by internalizing the cost of carbon emissions into economic decision-making [18].

3 Overview of blockchain technology

Blockchain technology has become a disruptive tool with applications in various sectors, including finance, healthcare, logistics, and environmental sustainability. At its core, blockchain is a decentralized system for recording transactions that offer security, transparency, and immutability through a distributed network of computers [19–21].

The fundamental characteristic of blockchain is its ability to create a shared and verifiable digital ledger, where transactions are recorded in chained blocks chronologically. Each block contains a set of transactions validated by consensus across the network, and once added to the chain, it becomes immutable and tamper-proof [22]. This ensures data integrity and eliminates the need for intermediaries to validate transactions. Furthermore, blockchain technology utilizes advanced cryptographic algorithms to ensure information security and user privacy [23]. End-to-end encryption protects transactions and data stored on the network, making blockchain a reliable option for transferring digital assets and executing smart contracts [24].

Another aspect of blockchain is its decentralized nature, which means no central authority controls the network. Instead, transaction validation is carried out collaboratively by nodes in the network, ensuring transparency and fault tolerance [25]. This distributed architecture makes blockchain a resilient and reliable technology, capable of supporting a wide range of applications across various sectors.

The technology represents a significant innovation redefining how transactions are conducted and data is shared in the digital age. Its unique combination of security, transparency, and decentralization makes it a powerful tool for driving efficiency, trust, and innovation in various contexts, including carbon markets and environmental sustainability [26].

3.1 Consensus mechanisms

Consensus mechanisms are fundamental to the operation of blockchain networks. They ensure that all participants agree on the network's current state and the validity of transactions [27].

Proof of Work (PoW) is the consensus mechanism used initially by Bitcoin [28]. In PoW, participants (miners) compete to solve complex mathematical problems, and the first to find the solution is rewarded with creating new blocks on the blockchain. Although secure, PoW is known to be energy-intensive. In Proof of Stake (PoS), validators are chosen based on the cryptocurrency they hold and are willing to "stake" as collateral [29]. This eliminates the need for mining and significantly reduces energy consumption compared to PoW.

In the Proof of Authority (PoA) model, validators are recognized authorities who are granted permission to create new blocks [30]. PoA is often used in private blockchains, where validators' identities are known and trusted. In Delegated Proof of Stake (DPoS), cryptocurrency holders elect representatives to validate transactions. This model is known for its scalability and efficiency. Practical Byzantine Fault Tolerance (pBFT) is a consensus mechanism to reach agreement among network nodes, even when some are malicious [31]. It is often used in permissioned blockchains.

3.2 Smart contracts and oracles

Smart contracts and oracles, as they are known, play essential roles in the blockchain ecosystem. They enable the automation of agreements and the integration of real-world data into decentralized applications [32–34].

Smart contracts are self-executing programs stored on the blockchain that define and automatically execute the terms of an agreement when predefined conditions are met. They are written in specific programming languages and are immutable, transparent, and self-executing [35]. Smart contracts eliminate the need for transaction intermediaries, ensuring the reliable and transparent execution of digital contracts. Oracles, conversely, are services or mechanisms that connect smart contracts with external sources of real-world data. They bridge the blockchain and external information, such as weather data, financial asset prices, or sports event outcomes. Oracles provide smart contracts with access to external information for automated decision-making and execution of conditions based on real-world events [33].

The interaction between smart contracts and oracles creates more sophisticated and versatile decentralized applications [36]. Smart contracts ensure the reliable execution of agreements without the need for trust between parties. At the same time, oracles allow smart contracts to access and respond to external data, expanding their capabilities beyond the limits of the blockchain. It is important to consider the security and reliability of oracles when integrating them into smart contracts, as the accuracy and integrity of external data can directly impact the operation and security of decentralized applications [37]. The effective combination of smart contracts and oracles has the potential to transform various sectors, from finance and supply chains to insurance and governance, through the automation and transparency provided by blockchain technology.

3.3 Tokens and cryptocurrencies

Tokens and cryptocurrencies are fundamental digital assets in the blockchain ecosystem, each with characteristics and distinct functions [38].

Tokens are digital assets issued on a blockchain representing a wide range of assets, such as utility, security, physical assets, or non-fungible tokens (NFTs) [39]. They can be created and managed centralized or decentralized, depending on the project and the blockchain on which they are issued. Tokens are often associated with specific use cases, such as access to services, participation in voting, representation of physical assets, or digital collectibles. There are different types of tokens, including security, utility, asset-backed, and non-fungible (NFTs).

Cryptocurrencies are a form of digital money that operates on a specific blockchain and is used as a medium of exchange, store of value, or unit of account [40]. Cryptocurrencies are decentralized and based on blockchain technology, which means a central authority, such as a government or central bank, does not control them. Popular examples of cryptocurrencies include Bitcoin, Ethereum, and Litecoin, each with its characteristics and specific use cases. Cryptocurrencies are traded on specialized exchanges and can be used for transactions, investments, or payments in various sectors [41].

While tokens and cryptocurrencies share the characteristics of being blockchain-based digital assets, they have distinct purposes and functionalities. While tokens represent a variety of assets and have specific use cases within blockchain ecosystems, cryptocurrencies are primarily used as forms of digital money and a medium of exchange.

4 Methodology

This study conducts a narrative literature review [8] to examine the applications of blockchain technology in carbon markets. A narrative literature review is used to summarize and discuss existing research on a topic in a clear and flexible way. This approach allows researchers to describe important ideas, trends, and gaps in the literature without strictly following a rigid systematic method [8]. For instance, Green et al. [42] explain that narrative reviews are helpful for organizing a wide range of studies into a coherent story, making it easier to understand the evolution of knowledge in a field. Additionally, Grant and Booth [43] highlights that narrative reviews can offer valuable insights when a comprehensive view of the literature is needed, especially in areas that are complex or not yet fully explored.

The objective is to synthesize existing knowledge on how blockchain enhances transparency, efficiency, and accountability in carbon emissions trading. Unlike systematic reviews, which follow predefined protocols, this study adopts a **flexible and integrative approach**, incorporating insights from academic papers, industry reports, and policy documents.

The literature search was conducted using databases such as **Frontier, Scopus, Web of Science, ACM Digital Library, and IEEEExplore**, with keywords including “*blockchain*”, “*carbon markets*”, and “*carbon credits*”. The selection focused on publications from **2022 to 2024**, prioritizing studies that provide empirical or conceptual insights into the intersection of blockchain and carbon emissions. Reports from key industry stakeholders, such as DAO IPCI,¹ the Toucan Protocol,² and Climate Impact X,³ were also reviewed to understand real-world applications.

To ensure relevance, studies were included based on the following criteria:

- **Scope:** The study explicitly discusses blockchain applications in carbon markets.
- **Focus:** It provides insights into governance, scalability, or transparency improvements.
- **Methodology:** The research includes empirical data, conceptual frameworks, or case studies. Studies that only briefly mention blockchain without substantial analysis were excluded.

Additionally, this session outlines the literature search and screening process, detailing the criteria and methodology used to identify relevant studies. Following this, the chapter presents a structured synthesis of blockchain-based use cases, highlighting how companies and organizations utilize this technology to track, trade, and offset carbon emissions in an advanced and transparent manner. Notable examples include platforms developed by DAO IPCI, the Toucan Protocol,

¹ DAO IPCI - Blockchain technology for carbon markets: <https://ipci.io>

² Toucan - The first liquid market for biochar credits: <https://toucan.earth>

³ Climate Impact X - Carbon credits that deliver real impact: <https://www.climateimpactx.com>

and the Energy Web Foundation,⁴ illustrating this technology's transformative potential. Moreover, major companies like Rabobank⁵ are adopting blockchain-based solutions to drive the transition to a more efficient and sustainable global carbon market. Finally, the research questions guiding this investigation are presented, providing a structured framework for analyzing blockchain integration in carbon markets.

4.1 Search and screening process

To ensure a structured and comprehensive literature review, this study follows a narrative literature review approach to synthesize existing knowledge on blockchain applications in carbon markets. Unlike systematic reviews, which adhere to predefined methodologies for study selection and analysis, this review adopts a flexible approach, integrating insights from academic research, industry reports, and policy documents.

4.1.1 Search strategy

The literature search was conducted using a set of carefully selected keywords, including "blockchain", "carbon market", and "carbon credits", to capture a broad spectrum of relevant studies. Searches were performed across multiple recognized academic databases, including Frontier, Scopus, Web of Science, ACM Digital Library, and IEEEExplore, ensuring access to high-quality, peer-reviewed literature. These databases were strategically selected due to their interdisciplinary coverage, spanning technological advancements and conceptual frameworks related to carbon markets.

In addition to academic sources, reports from international organizations (e.g., the World Bank, United Nations Framework Convention on Climate Change - UNFCCC) and technical documents were included to provide a more applied perspective on blockchain implementations in carbon trading. This holistic approach examines theoretical foundations and real-world applications, offering a comprehensive understanding of the topic.

4.1.2 Eligibility criteria

A structured eligibility protocol was implemented to refine the selection process and ensure the relevance of reviewed studies. Table 1 summarizes the inclusion and exclusion criteria applied:

4.1.3 Screening process

After retrieving the initial set of studies, duplicate entries were removed, and a two-step screening process was conducted:

1. **Title and Abstract Screening:** The first filtering stage removed studies that did not explicitly address blockchain applications in carbon markets.
2. **Full-Text Review:** The remaining studies were reviewed in detail to assess their methodological rigor, contribution to the field, and applicability to this research.

4.1.4 Diversity of sources

Including academic articles, institutional reports, and technical documents provided a broad and diversified perspective on the intersection between blockchain and carbon credits.

1. Academic articles provided theoretical foundations and methodological insights.
2. Institutional reports (e.g., UNFCCC, World Bank) provided policy trends and regulatory frameworks relevant to carbon markets.
3. Technical documents contributed detailed information on blockchain implementations, practical use cases, and challenges in adoption.

⁴ Energy Web Foundation: <https://www.energyweb.org>

⁵ Rabobank - We embrace innovation, growth, and sustainability: <https://www.rabobank.com>

Table 1 Search Parameters

| Category | Inclusion criteria | Exclusion criteria | Justification |
|------------------|-------------------------------------|--|--|
| Language | Portuguese and English | Anything other than Portuguese and English | Local language and the most commonly used in global academia |
| Search Fields | Title, abstract, and keywords | Other fields | Fields for effective search |
| Publication Year | From 2022 to March 2024 | Before 2022 | Searching for the latest information |
| Publication Type | Review papers and academic articles | Other types | Reviewed research provides greater accuracy |
| Availability | Full-text available | Full-text not available | Necessary conditions for review |
| Subject | Blockchain and carbon market | Not related to both topics together | Narrowing down the study to be specific |
| Context | Carbon market and carbon credits | Not related to carbon | Limiting the study to carbon |

^aSource: Author's own

This multi-source strategy enabled a comprehensive and contextualized analysis, balancing theoretical rigor with practical insights. By integrating diverse perspectives, this review captures both the opportunities and challenges in leveraging blockchain for carbon markets.

4.2 Use cases of Blockchain for carbon emissions

The blockchain technology has been widely explored by various companies and organizations as an innovative tool to transform the carbon market, offering advanced and transparent solutions for tracking, trading, and offsetting carbon emissions, as can be seen in figures 1 and 2. Companies like DAO IPCI are developing blockchain-based platforms to facilitate the trade of carbon credits, enabling secure and transparent transactions in specific and non-specific carbon markets. The Toucan Carbon Pools [44] is another prominent example, providing a blockchain infrastructure to streamline

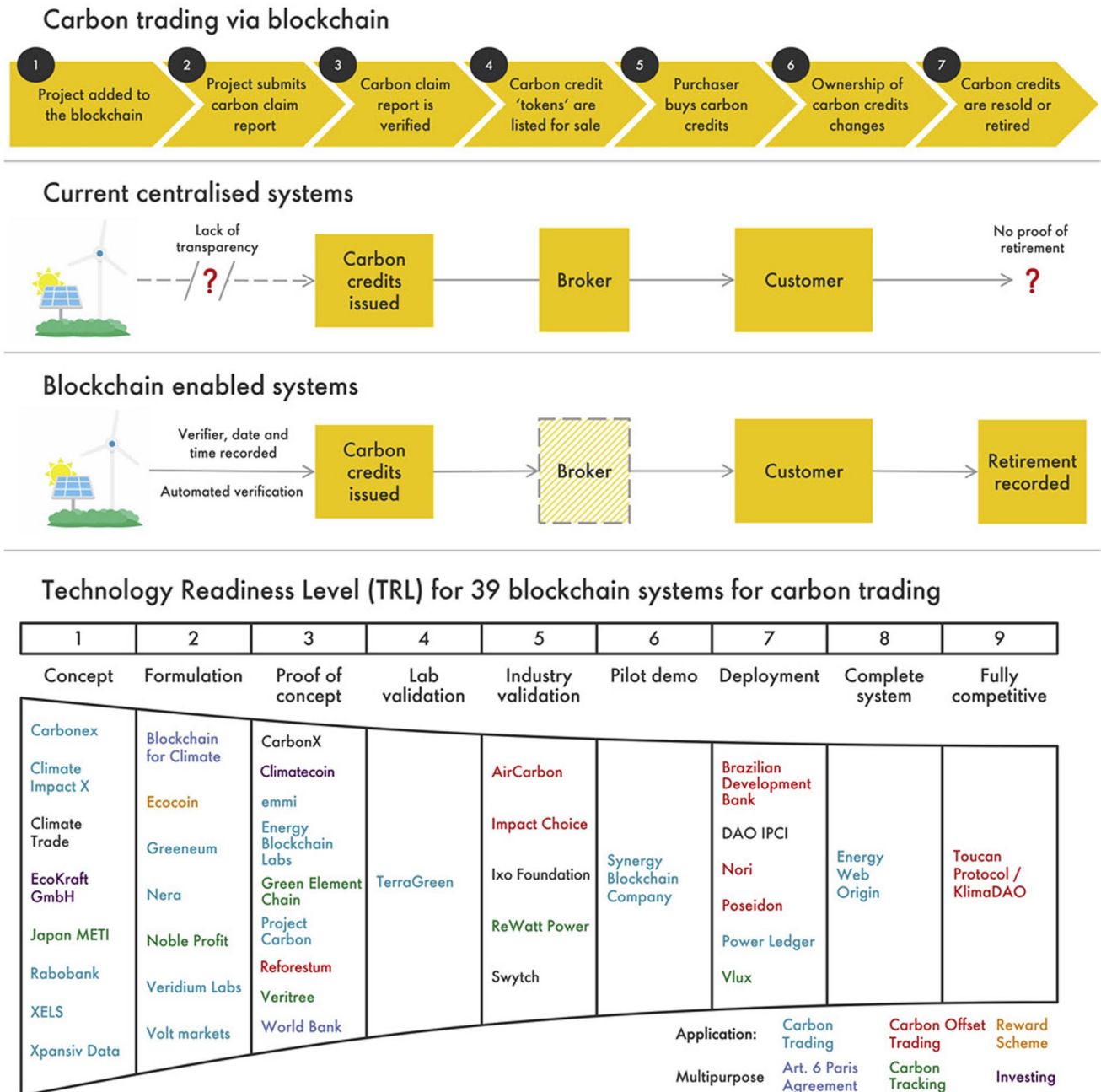


Fig. 1 Schematic view of blockchain-based carbon trading versus a centralized platform. Source: [45]

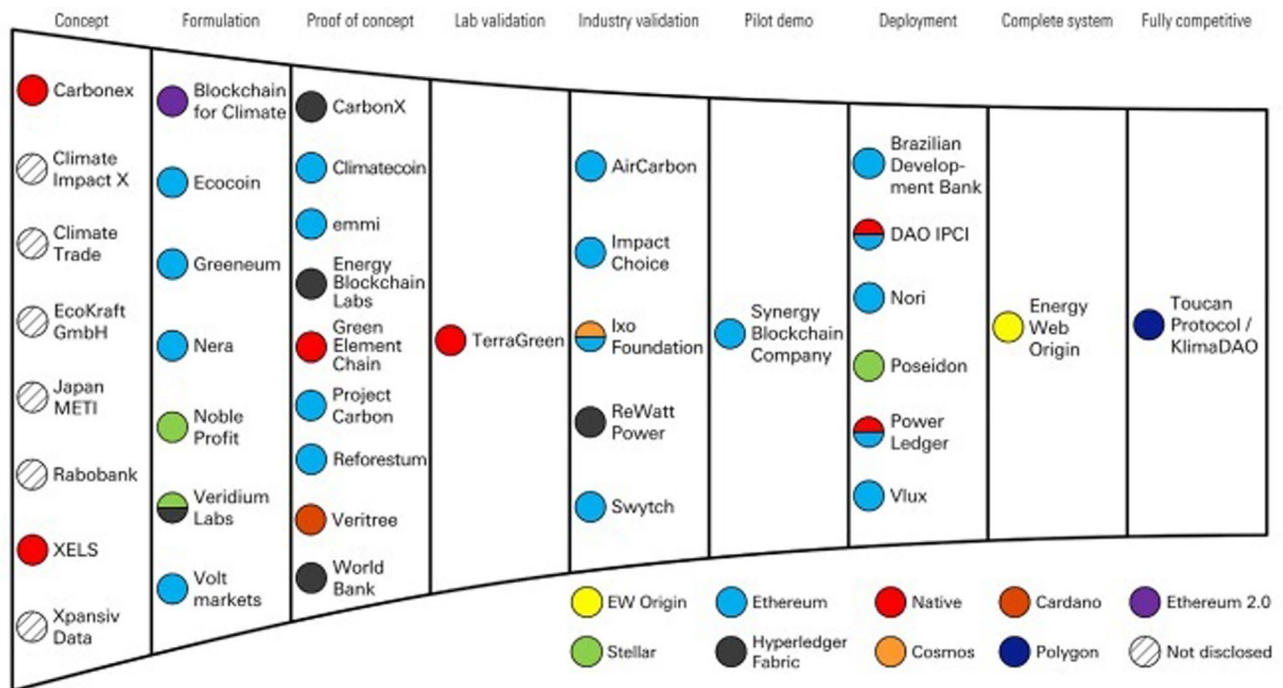


Fig. 2 Characteristics of the funding source and the technology used for blockchain solutions in carbon markets, adapted from [45]

the carbon offsetting process and ensure the authenticity of transactions. The Energy Web Foundation has stood out by using blockchain to enhance the tracking of carbon offsets across supply chains, promoting transparency and transaction reliability. Additionally, KlimaDAO⁶ has innovated by linking carbon credits to tokens that increase in value through staking, offering a unique approach to the carbon market.

Significant companies like Rabobank, Climate Impact X, and Project Carbon⁷ are also adopting blockchain-based solutions to drive the transition to a more efficient and sustainable global carbon market. These use cases demonstrate the transformative potential of blockchain technology in the carbon sector, emphasizing the importance of innovation and collaboration in addressing the challenges of climate change and promoting more sustainable and transparent business practices.

4.3 Research questions

The questions formulated in this study were designed to address identified gaps and challenges in carbon markets and explore the role and impact of blockchain technology in this context. The first question aims to identify the key unresolved issues in carbon markets, focusing especially on emission trading schemes and carbon offset projects. This question is important for understanding system deficiencies and guiding future improvement and development initiatives. The second question investigates how blockchain technology aligns with the principles of the “3D’s” - decentralization, decarbonization, and digitalization - within the context of carbon markets. Exploring this intersection is fundamental to understanding how blockchain can contribute to the positive transformation of these markets by providing greater transparency, efficiency, and reliability. Finally, the third question aims to identify the potential benefits and challenges of implementing blockchain technology in carbon markets, emphasizing sustainability and efficiency. Understanding these aspects is essential for assessing the impact and feasibility of blockchain adoption in this context and informing future strategic and policy decisions. These questions provide a comprehensive framework for analyzing and investigating carbon markets and blockchain technology topics.

⁶ KlimaDAO - Real world assets driving real-world impact <https://www.klimadao.finance>

⁷ Project Carbon - alliance between CIBC, Itaú Unibanco, National Australia Bank, and NatWest Group aiming to use blockchain to provide tracking of carbon credits - <https://carbonplace.com>

- What are the main unresolved issues in carbon markets, especially in emissions trading schemes and carbon offset projects?
- How does blockchain technology fit into the concept of the "3D's" of decentralization, decarbonization, and digitization in the context of carbon markets?
- What are some potential benefits and challenges of implementing blockchain in carbon markets for sustainability and efficiency?

5 Results

This research provides valuable insights into the key unresolved carbon market issues, especially emission trading schemes and carbon offset projects. The identified challenges include insufficiently low carbon prices in many Emissions Trading Systems (ETS), resulting in a lack of incentive to reduce emissions actively, as well as issues related to the distribution of emission allowances and carbon leakage. The review also highlights the importance of ensuring the quality and credibility of carbon offset projects to avoid greenwashing and preserve the integrity of carbon markets.

The analysis of blockchain technology demonstrates how it fits into the "3D's" of decentralization, decarbonization, and digitization in carbon markets. Blockchain provides a decentralized ledger that enhances transparency and trust in carbon transactions, simplifies administrative processes, and promotes sustainable practices. Additionally, blockchain technology offers a range of potential benefits, such as transparency, automation, decentralization, and data immutability, which can enhance the efficiency and sustainability of carbon markets. However, blockchain technology faces significant challenges like scalability, energy consumption, regulatory issues, and privacy concerns. Addressing these challenges will be important to harness the full potential of blockchain technology in transforming carbon markets and mitigating climate change.

The articles and documents reviewed in this research, as shown in Table 2, cover a wide range of topics related to blockchain technology, carbon markets, sustainability, and environmental policies.

- "Blockchain for sustainability: A systematic literature review for policy impact" provides a comprehensive overview of the use of blockchain technology to promote sustainability, including its application in carbon markets.
- "Blocked chains of governance: Using blockchain technology for carbon offset markets?" explores the potential of blockchain technology for carbon offset markets, examining its challenges and opportunities.
- "Carbon emission and cost of blockchain mining in a case of peer-to-peer energy trading" investigates the environmental impact of blockchain mining in peer-to-peer energy trading scenarios.
- "Research on carbon flow traceability system for distribution network based on blockchain and power flow calculation" proposes a blockchain-based system for carbon flow traceability in energy distribution networks.
- "Blockchain's Scope and Purpose in Carbon Markets: A Systematic Literature Review" examines the role and scope of blockchain technology in carbon markets through a systematic literature review.
- "State and Trends of Carbon Pricing" and "Voluntary carbon markets, a review of global initiatives and evolving models" provide insights into the current state and trends of carbon markets and carbon pricing.
- Reports from CSIS (Center for Strategic and International Studies) may address policies and strategies related to sustainability and carbon markets.
- Journalistic articles, such as those from The Guardian, can provide information on specific issues related to carbon offset certification and its effectiveness.
- "Blockchain solutions for carbon markets are nearing maturity" can offer a perspective on the current stage of blockchain-based solutions for carbon markets.
- "Applying blockchain technology for building energy performance measurement, reporting, and verification (MRV) and the carbon credit market: A review of the literature" explores the application of blockchain technology in measuring, reporting, and verifying energy performance in buildings and the carbon credit market.
- "Blockchain technology in the energy sector: A systematic review of challenges and opportunities" investigates the challenges and opportunities of blockchain technology in the energy sector.
- "Blockchain for Cities - A Systematic Literature Review" examines the use of blockchain technology in urban contexts, which may include sustainability and carbon emission reduction initiatives.

Table 2 Reviewed articles and documents

| Refs. | Title | Source | Authors | Link |
|-------|--|--|--|---|
| [46] | Blockchain for sustainability: A systematic literature review for policy impact, 2023 | Elsevier | Catherine Mulligan et al. | https://doi.org/10.1016/j.telpol.2023.102676 |
| [47] | Blocked chains of governance: Using blockchain technology for carbon offset markets? 2022 | Frontiers | Christopher Round and Ingrid Visseren-Hamakers | https://doi.org/10.3389/fbloc.2022.957316 |
| [48] | Carbon emission and cost of blockchain mining in a case of peer-to-peer energy trading, 2022 | Frontiers | Kevin Coutinho et al. | https://doi.org/10.3389/fbuil.2022.945944 |
| [49] | Research on carbon flow traceability system for distribution network based on blockchain and power flow calculation, 2023 | Frontiers | Heyang Sun et al. | https://doi.org/10.3389/feng.2023.1118109 |
| [50] | Blockchain's Scope and Purpose in Carbon Markets: A Systematic Literature Review, 2023 | MDPI | Arsenii Vilkov and Gang Tian | https://doi.org/10.3390/su15118495 |
| [18] | State and Trends of Carbon Pricing, 2023 | 2023 International Bank for Reconstruction and Development | The World Bank | https://openknowledge.worldbank.org/handle/10986/39796 |
| [16] | Voluntary carbon markets, a review of global initiatives and evolving models, 2023 | CSIS - Center for Strategic and International Studies | Allegra Dawes et al. | https://www.csis.org/analysis/voluntary-carbon-markets-review-global-initiatives-and-evolving-models |
| [51] | The Guardian. Revealed: more than 90% of rainforest carbon offsets by biggest certifier are worthless, analysis shows, 2023 | The Guardian | Patrick Greenfield | https://www.theguardian.com/environment/2023/jan/18/revealed-forest-carbon-offsets-biggest-provider-worthless-verra-aoc |
| [52] | State and Trends of Carbon Pricing: International Carbon Markets (English), 2023 | 2023 International Bank for Reconstruction and Development | The World Bank | http://documents.worldbank.org/curated/en/099703112082335476/IDU09668a0c0165a04c150a7b80f749ed369c2 |
| [45] | Blockchain solutions for carbon markets are nearing maturity, 2022 | One Earth | Adam Siphthorpe et al. | http://www.scopus.com/inward/record.url?partnerID=HzOxMe3b&scp=85134335253&origin=inward |
| [53] | Applying blockchain technology for building energy performance measurement, reporting, and verification (MRV) and the carbon credit market: A review of the Literature | Elsevier | Junghoon Woo et al. | https://doi.org/10.1016/j.builenv.2021.108199 |
| [54] | Blockchain technology in the energy sector: A systematic review of challenges and opportunities | Elsevier | Merlinda Andoni et al. | https://doi.org/10.1016/j.rser.2018.10.014 |
| [55] | Blockchain for Cities - A Systematic Literature Review, 2018 | IEEE Access | Charles Shen et al. | https://ieeexplore.ieee.org/document/8531608 |
| [56] | Blockchain Technology in Carbon Trading Markets: Impacts, Benefits, and Challenges-A Case Study of the Shanghai Environment and Energy Exchange, 2024 | MDPI | Zhang, G. et al. | https://www.mdpi.com/1996-1073/17/13/3296 |
| [57] | The Role of Blockchain in Finance Beyond Cryptocurrency: Trust, Data Management, and Automation, 2024 | IEEE Access | H. Chen et al. | https://ieeexplore.ieee.org/document/10516318 |

³Source: Own authorship

These articles and documents contribute to a deeper understanding of the challenges and opportunities of applying blockchain technology in carbon markets and promoting environmental sustainability.

With a solid foundation of reviewed literature, we can now explore the answers to this research's central questions. Let's analyze the key challenges faced in carbon markets, the role of blockchain technology in decentralizing, decarbonizing, and digitizing these markets, and the potential benefits and challenges of implementing blockchain for sustainability and efficiency.

5.1 Global implementation and challenges of emissions trading systems (ETS)

The ETS has been implemented in various regions and countries worldwide, as Fig. 3 depicts. The European Union Emissions Trading System (EU ETS) is the largest and oldest example. The EU ETS covers several industrial sectors, such as energy, industry, and aviation, aiming to reduce CO₂ emissions across the European Union [58].

In addition to the EU, other countries and regions, such as California, the USA, China, and South Korea, have also adopted emissions trading systems to combat climate change [59]. Each system has its own characteristics and specific objectives, but they all share the basic principle of limiting emissions and creating incentives for reduction.

Proponents of the ETS argue that it provides an efficient and flexible mechanism for reducing emissions by allowing the market to determine the price of emissions and incentivizing innovation and the adoption of cleaner technologies [12]. However, critics point out potential flaws, such as the initially overly generous allocation of permits, which can lead to low prices and reduce the incentive for emission reduction [60].

Despite the controversies, the ETS continues to be an important tool in the fight against climate change, and many countries are considering or already implementing emissions trading systems as part of their GHG mitigation strategies [61].

5.2 Trends, challenges, and opportunities in voluntary carbon markets

Voluntary carbon markets have been the subject of heated debate over time. These markets allow buyers to acquire and trade offsets from emission reduction or removal projects [14]. Some advocates argue they are essential for increasing climate financing and helping companies achieve carbon neutrality goals. However, critics argue that such agreements are elaborate mechanisms of "greenwashing", masking the true extent of emissions.

By early 2023, increasing companies sought to adopt carbon neutrality strategies, contributing to a growing market [62]. Developing countries also showed interest, planning to use revenues from credits generated by domestic forest projects to boost their economies [63, 64]. New initiatives emerged to address credibility issues, such as the

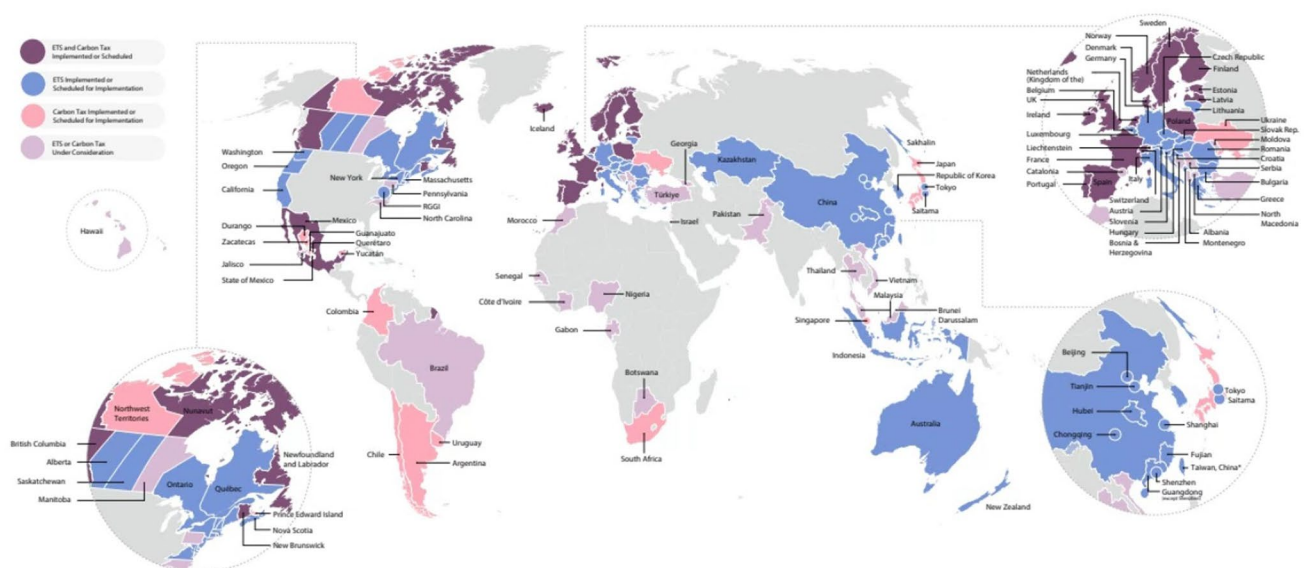


Fig. 3 Map of Carbon Prices and ETSs, adapted from [18]

“Science-Based Targets Initiative” and the “Voluntary Carbon Market Integrity Initiative”, strengthening confidence in the potential growth of the voluntary carbon credit trade [15].

Despite these positive signs, the previous year was challenging for voluntary carbon markets. Credit prices fell across all categories throughout the year, and major corporate buyers reduced their carbon credit purchases amid growing concerns about “greenwashing” [65].

5.3 Progress, challenges, and innovations in carbon markets under the Paris Agreement

Will international carbon markets finally comply with the rules and processes of the Paris Agreement for a public international carbon market? Article 6 was approved at the 26th Conference of the Parties to the United Nations Framework Convention on Climate Change (COP 26) three years ago, but few government agreements have been reached since then [66]. Meanwhile, the media has exposed alarming deficiencies in fragile private voluntary carbon markets, while companies face increasing legal challenges for offset claims. Can Article 6 finally help the public carbon market achieve its climate and nature objectives?

The Paris Agreement establishes a robust and ambitious foundation for using international markets and reinforces the Parties’ international goals, transparency, and accountability [15]. Recognizing the importance of international carbon markets, Article 6 of the agreement allows Parties to use international emissions trading to help achieve emission reduction targets, establishes a framework for common robust accounting rules, and creates a new and more ambitious market mechanism. The article provides a comprehensive overview of the complexities of international cooperation on greenhouse gas emissions mitigation, as outlined. It discusses establishing a public carbon market, primarily under Article 6.2, where carbon credit agreements are made between governments. However, progress in this domain has been slow, with only a few bilateral agreements, mainly involving developed and developing countries, as shown in Fig. 4.

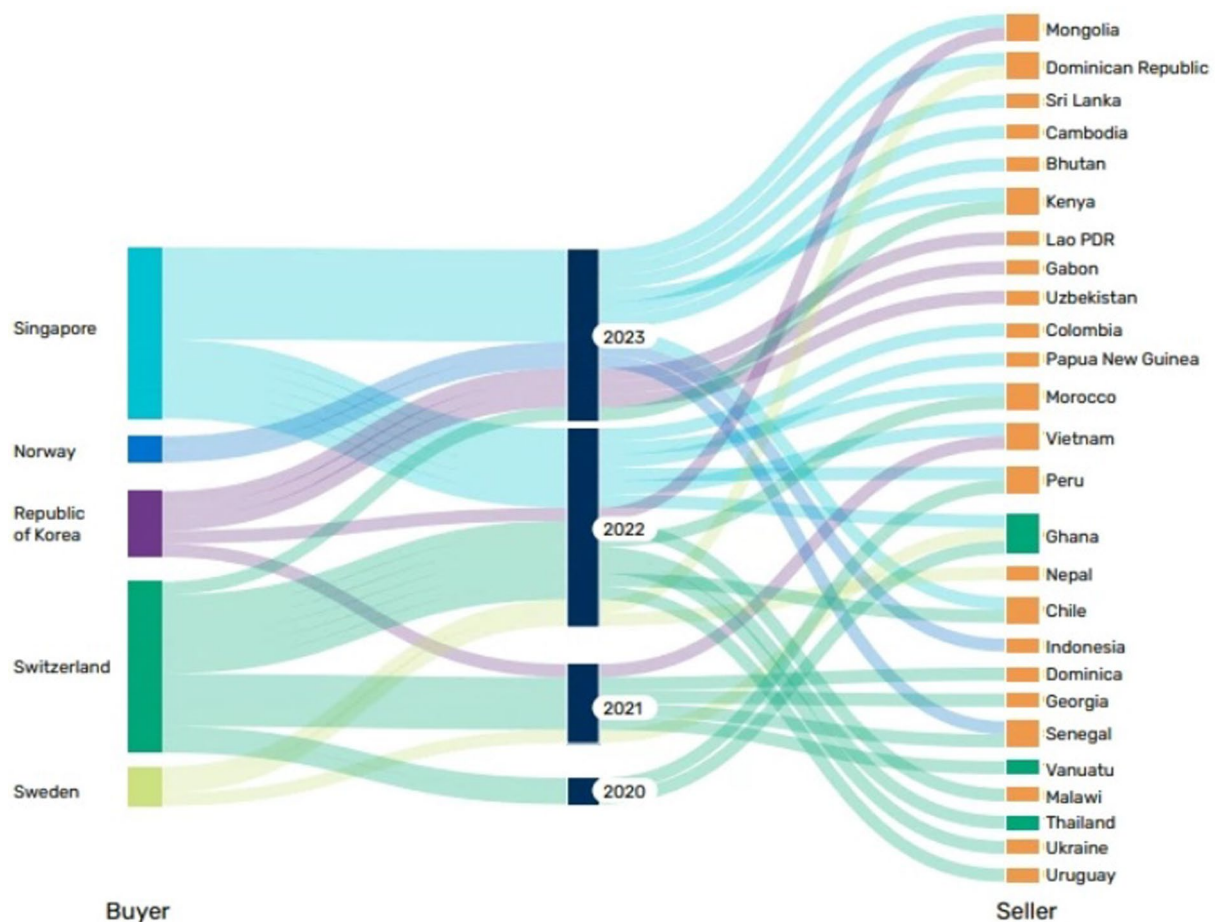


Fig. 4 Bilateral Cooperation Agreements under Article 6.2 of the Paris Agreement, 2020–2023, adapted from [18]

Furthermore, private carbon markets face challenges, such as concerns about the credibility and effectiveness of voluntary carbon credits. Recent controversies and legal actions have overshadowed these markets, leading to declining private-sector investments [67].

Additionally, the role of Article 6.4 in setting standards and guidelines for carbon markets and credits is discussed, addressing the supervisory body's efforts to tackle critical issues such as additionality and permanence, which are important for maintaining the integrity of carbon offset programs.

Article 6.8 emerges as a potential avenue for innovative forms of international climate cooperation, including technology transfer and debt-for-climate swaps. These initiatives aim to address the interconnected challenges of debt, climate change, and biodiversity loss, offering new pathways for climate action financing.

5.4 Intensification of governmental involvement in voluntary markets

A long-term trend is emerging in which governments play more prominent roles in the design, moderation, and, to some extent, regulation of voluntary markets. A survey published by the CSIS (Center for Strategic and International Studies) [16] analyzed some of these market arrangements that incorporate elements of governmental involvement in voluntary markets. Globally, several governments are working to establish domestic voluntary market initiatives. In Japan, for example, the GX League plays a central role in the country's energy transition goals; over 600 companies, representing 40% of domestic emissions, have joined the league, committing to reduce and offset their remaining emissions [68]. These hybrid arrangements can assist in regulating demand in the voluntary market and setting expectations for the supply side [68, 69].

While the outcomes of these efforts remain uncertain, there is a growing recognition that voluntary markets need some safeguards [70]. Voluntary markets resemble the "Wild West", a territory where rules are loosely enforced or absent. The past year has highlighted increasing corporate caution in the face of potential risks arising from claims unsupported by credible emissions reductions. While a global carbon price may not emerge soon, many companies are genuinely interested in reducing emissions and achieving carbon neutrality. Additionally, there is a growing recognition of the critical importance of funding energy transition and climate change mitigation in developing countries [71, 72]. The central challenge is establishing an infrastructure that provides more information about projects, credit quality, and buyer credit goals [73]. These emerging initiatives, aimed at improving market supply-side regulation and demand-side organization, can help reshape voluntary markets in a more promising direction.

5.5 Trends, challenges, and growth opportunities in carbon credit markets

In 2022, carbon credit markets experienced a slowdown after two years of rapid growth [74]. The supply of new credits and the demand from end users decreased slightly, reversing the substantial increases observed in 2021. Although independent crediting mechanisms are still predominant, there has been an increase in emissions from the Clean Development Mechanism (CDM), and more countries are considering establishing domestic credit mechanisms [17]. Compliance demand is gaining importance. Challenging macroeconomic conditions have also affected carbon credit markets. These challenges have been exacerbated by public criticism of the integrity of some carbon credits and ongoing uncertainty about the effective use of carbon credits by companies for voluntary purposes [75]. Despite these difficulties, carbon credit markets continue to evolve, with new investors, financial products, technological platforms, and service providers contributing to a potential decade of significant growth. The implementation of international cooperation under Article 6 of the Paris Agreement is progressing, with several new bilateral agreements and the first projects to generate authorized emission reductions.

5.6 Regional and national approaches to carbon credits regulation

National and regional frameworks for regulating carbon credits play a critical role in shaping the effectiveness of carbon markets. For example, Brazil's recent legislative developments, including Bill No. 412 of 2022, signify its commitment to formalizing its emission reduction market. Approved by the Brazilian Federal Senate in 2023, this bill establishes guidelines for carbon credit trading and amends existing environmental laws to align with international practices [76].

In the European Union, the EU ETS is a model for cap-and-trade systems, offering lessons on scalability and market efficiency. Meanwhile, the United States relies on the Environmental Protection Agency (EPA) to regulate various carbon

offset programs, emphasizing flexibility and voluntary participation. These examples highlight the diverse regulatory landscapes that govern carbon credits and the need for harmonization to support global decarbonization efforts.

5.7 Current situation and trends in carbon pricing in 2023

The “State and Trends of Carbon Pricing 2023” report [18] highlights several significant findings and trends in carbon pricing and international carbon markets. The report underscores the substantial investment needed to achieve the goals of the Paris Agreement, with estimates ranging from US\$ 3 to US\$ 6 trillion annually until 2050 in emerging markets and developing economies. There has been a notable increase in global investments in clean energy, with US\$ 1.8 trillion invested in 2023, representing a 40% increase from 2020. Carbon finance, where buyers pay for verified emissions reductions, is highlighted as a tool to mobilize capital for climate action, especially in emerging markets and developing economies. The report emphasizes the importance of transitioning to a low-carbon energy system to achieve net-zero emissions, focusing on expanding renewable energy generation, particularly in regions like Africa. Carbon markets are recognized as a proven tool for channeling private sector investment into mitigation activities, supporting the mobilization of resources for climate action. The report acknowledges challenges, such as concerns about environmental integrity and uncertain government policies, while highlighting initiatives to build integrity and certainty in carbon markets. These findings and trends underscore the importance of carbon pricing and international carbon markets in driving climate action, mobilizing resources for sustainable development, and accelerating the transition to a low-carbon economy.

5.8 What are the main unresolved issues in carbon markets, especially in emission trading schemes and carbon offset projects?

Carbon prices in many ETS have been insufficiently low to incentivize companies to invest in emission reduction technologies or projects. This can result in a lack of incentive for companies to reduce their emissions actively.

The mechanism for allocating carbon emission allowances is important for effectively and economically reducing greenhouse gases (GHG). Issues arise when allowances are distributed for free or through auctions, which can harm new or growing companies. Auctions may raise concerns about fairness and competitiveness.

Carbon leakage occurs when companies or industries transfer their production facilities to countries with less stringent environmental regulations, potentially increasing global emissions. This issue is particularly relevant in Joint Implementation (JI) projects and the Clean Development Mechanism (CDM) under the Kyoto Protocol.

Ensuring the quality of carbon offset projects is essential for their credibility and effectiveness. Challenges include establishing baseline and measurement criteria, ensuring verifiability and transparency, demonstrating additionality, and addressing potential co-benefits and carbon leakage within projects. The decline in the viability of CDM projects due to low Certified Emission Reduction (CER) prices has raised concerns about the sustainability and commercial viability of these projects, highlighting the need for reassessment and improvement.

Companies involved in carbon offset projects without clear contributions to climate change mitigation risk greenwashing, where their environmental efforts are exaggerated or misleading. This undermines the credibility of carbon offset projects and the overall integrity of carbon markets. Addressing these outstanding issues is important to improving the effectiveness, transparency, and integrity of carbon markets, ETS, and carbon offset projects in the global effort to combat climate change.

5.9 How does blockchain technology fit into the concept of the “3D’s” of decentralization, decarbonization, and digitalization in the context of carbon markets?

Blockchain enables a distributed and decentralized ledger technology, allowing multiple participants in the carbon market to access and verify transactions without the need for a central authority. This decentralization enhances transparency, trust, and efficiency by providing a shared and immutable record of carbon-related data. By facilitating transparent tracking of carbon credits, emission data, and offset projects, blockchain technology supports decarbonization efforts in carbon markets. It provides a secure platform for monitoring and verifying carbon reduction activities, ensuring the integrity of carbon trading, and promoting sustainable practices.

Blockchain digitizes and automates the recording and verification of carbon-related transactions, making processes more efficient and secure. In carbon markets, digitalization through blockchain simplifies the issuance, trading, and retirement of carbon credits, reducing administrative burdens and enhancing the effectiveness of emission reduction

initiatives. It also operates on a decentralized ledger, meaning that data is stored across a network of computers (nodes) rather than in a central database. This decentralized nature ensures that no single entity controls the entire system, promoting transparency and reducing the risk of manipulation or fraud.

Transactions on a blockchain network are conducted directly between participants (peers) without intermediaries. This peer-to-peer structure eliminates reliance on centralized authorities, such as banks or clearinghouses, simplifying processes and reducing transaction costs. Blockchain networks validate and confirm transactions using consensus mechanisms, such as Proof of Work (PoW) or Proof of Stake (PoS). These mechanisms rely on distributed nodes reaching agreement on the validity of transactions, ensuring trust and security in a decentralized manner. Smart contracts are self-executing contracts with predefined rules and conditions encoded on the blockchain. These contracts automatically execute and enforce agreements between parties without intermediaries, further enhancing transaction decentralization and efficiency.

The immutability of blockchain data ensures that once information is recorded on the ledger, it cannot be altered or deleted. This feature enhances trust and transparency in decentralized systems, as all participants have access to a tamper-proof record of transactions. Blockchain also enables transparent and secure tracking of carbon emissions, offsets, and credits throughout their lifecycle. By providing a decentralized and immutable ledger, blockchain ensures the integrity of carbon-related data, facilitating monitoring and verification of emission reduction efforts.

Blockchain can optimize the management of carbon offset projects by automating processes such as verification, issuance, and trading of carbon credits. This efficiency reduces administrative burdens and encourages the development and implementation of more sustainable projects aimed at decarbonization. Blockchain incentivizes organizations to adopt sustainable practices and invest in emission reduction initiatives by providing a transparent and auditable platform for carbon-related transactions. This shift towards sustainability aligns with the decarbonization goal and contributes to mitigating climate change.

5.10 What are some potential benefits and challenges of implementing blockchain in carbon markets for sustainability and efficiency?

We can observe benefits in providing a transparent and immutable ledger of carbon-related transactions, increasing trust and accountability in carbon markets. This transparency can help reduce fraud and ensure the integrity of carbon credits and offsets. By automating processes such as verification, validation, and trading of carbon assets through smart contracts, blockchain can streamline operations in carbon markets. This automation reduces administrative burdens and transaction costs, improving overall efficiency. The decentralized nature of blockchain eliminates the need for intermediaries in carbon trading, enabling direct peer-to-peer transactions. This decentralization promotes inclusion and reduces reliance on centralized authorities. The immutability feature of data in blockchain ensures the integrity and security of carbon-related information. This feature helps prevent data manipulation and ensures that carbon credits and offsets are recorded and verified accurately.

We observe that blockchain networks may face scalability challenges when dealing with large transactions, especially in carbon markets with numerous participants and complex commercial activities. Scaling blockchain solutions to meet increasing demand can be a technical challenge. Proof of Work (PoW) consensus mechanisms in some blockchain networks require significant energy consumption for mining activities. This energy-intensive process may raise concerns about the environmental impact of blockchain technology on carbon markets. The regulatory landscape for blockchain in carbon markets is still evolving, with uncertainties surrounding compliance requirements and legal frameworks. Ensuring that blockchain implementations comply with relevant regulations and standards can be a challenge for market participants. Although blockchain offers transparency, the public nature of some blockchain networks may raise concerns about data privacy and confidentiality in carbon markets. Balancing transparency with data protection requirements poses a challenge for implementing blockchain solutions.

While blockchain technology holds promise for enhancing sustainability and efficiency in carbon markets, addressing these challenges will be important to realizing its full potential and ensuring the successful integration of blockchain for carbon trading and offset projects.

5.11 Practical implications of the study

This study provides actionable insights for governments, private companies, and non-governmental organizations aiming to enhance carbon markets' transparency, efficiency, and scalability using blockchain-based solutions. By leveraging the

most suitable frameworks, these stakeholders can address key challenges such as data integrity, governance, interoperability, and automation.

For regulated carbon markets, *Hyperledger Fabric*⁸ and *Corda*⁹ offer permissioned architectures that ensure compliance with Know Your Customer (KYC) and Anti-Money Laundering (AML) regulations. These frameworks enable controlled access to transaction data, making them suitable for regulatory oversight while maintaining privacy. In voluntary carbon markets, *Polygon*,¹⁰ *Hedera*,¹¹ and *Algorand*¹² provide transparent and immutable records, enhancing trust and auditability. Their smart contract capabilities enable automated verification and trading, reducing the risk of double counting and fraud. For hybrid approaches, *Climate Action Data Trust (CAD Trust)*¹³ and *Hyperledger Besu*¹⁴ integrate on-chain and off-chain data, facilitating cross-sector interoperability. These frameworks bridge gaps between government-regulated emissions trading schemes and voluntary carbon offset programs, promoting global standardization.

By adopting these tailored blockchain frameworks, policymakers can develop regulatory frameworks that address data standardization, governance models, and integration challenges, facilitating large-scale blockchain implementation in carbon markets.

5.12 Theoretical implications of the study

This study contributes to blockchain and sustainable technology research by offering a structured framework for selecting the most appropriate DLT solutions in carbon markets. It advances the understanding of how decentralization, decarbonization, and digitalization intersect through blockchain technology.

While prior studies focused on general blockchain applications, this research differentiates frameworks based on their suitability for specific carbon market needs, such as permissioned vs. public blockchains. The findings highlight the scalability limitations of some frameworks and the need for interoperability between permissioned (*Hyperledger*, *Corda*) and public blockchains (*Polygon*, *Hedera*, *Algorand*) to facilitate cross-border transactions and market adoption. Additionally, this study lays the foundation for future research on regulatory compliance, exploring how frameworks like *CAD Trust* and *Hyperledger Besu* can help integrate carbon accounting, financial markets, and climate policies into a unified system.

By providing a comprehensive, framework-based perspective, this study strengthens academic discourse on blockchain for climate action and serves as a strategic guide for real-world implementation in carbon markets.

6 Discussion

Why was there a decline in credit trading in 2023? One significant reason was the growing concern among companies about potential reputation risks. Two highly publicized studies highlighted systemic issues with credits from nature-based projects. In January 2023, a report conducted by *The Guardian*, the German weekly magazine *Die Zeit*, and *SourceMaterial* evaluated credits certified by *Verra*, one of the leading carbon standards [51]. The research revealed that over 90% of forest credits did not represent real emission reductions. In August, a study published in *Science* pointed out that forest programs significantly overestimated their ability to prevent deforestation [77].

While these reports are not new, they come when companies are particularly vigilant about potential reputation risks associated with carbon neutrality strategies. Investment strategies guided by environmental, social, and governance (ESG) standards have recently become controversial. ESG funds have been criticized for prioritizing environmental goals over investor returns and have lost support due to the underperformance of some funds. Additionally, the legal implications of using carbon credits have also increased. In May 2023, a class-action lawsuit was filed in California against *Delta Air Lines*, alleging that the company misrepresented itself as carbon neutral based on problematic carbon offsets. This reflects a growing trend; between 2015 and 2022, 81 cases of “climate washing” globally were recorded against companies.

⁸ <https://www.hyperledger.org/use/fabric>

⁹ <https://www.r3.com/corda/>

¹⁰ <https://polygon.technology/>

¹¹ <https://hedera.com/>

¹² <https://www.algorand.com/>

¹³ <https://climateactiondata.org/>

¹⁴ <https://www.hyperledger.org/use/besu>

These challenges underscore issues in voluntary carbon markets' supply and demand sides. The fundamental question is ensuring carbon credits represent real, additional, and permanent emissions reductions. Most carbon credits are acquired through bespoke deals, with little contract standardization. Various independent standards organizations employ different methodologies to certify projects and credits, complicating efforts to certify projects and preventing buyers from having a clear view of the quality of credits.

Secondly, there is uncertainty about demand. How companies use credits to achieve carbon neutrality goals is important. While organizations like the Voluntary Carbon Markets Integrity Initiative (VCMII) advocate for buyers to use credits to complement overall decarbonization pathways, there is little guidance on how to use them and what claims can be made. The lack of transparency regarding using carbon offsets hampers efforts to improve the credibility of voluntary arrangements.

The challenges faced by voluntary markets currently are substantial; the landscape is characterized by a lack of organization, with significant information asymmetries among project developers, standardization organizations, certifiers, and buyers. Concerns about the reputation that companies face can dampen demand for offsets. The supply side will fail to deliver on its promises without high-quality credits. However, despite these hurdles, voluntary markets have room for improvement.

7 Final considerations

This study analyzed the transformative potential of blockchain technology in carbon markets, highlighting its role in enhancing transparency, efficiency, and reliability in carbon credit transactions and emissions trading systems. The findings indicate that blockchain can address fundamental challenges in these markets, such as fraud prevention, automated verification, and regulatory compliance, due to its decentralized, immutable, and automated nature. However, fully realizing these benefits depends on overcoming governance, interoperability, and scalability challenges in blockchain-based platforms.

From a practical perspective, the insights from this research provide interesting guidance for policymakers, market participants, and technology developers interested in integrating blockchain into carbon markets. Establishing clear regulatory frameworks is essential to standardizing and strengthening the governance of these technological solutions, ensuring greater trust and adherence to environmental regulations. In this regard, implementing regulatory sandboxes could be viable for testing and refining blockchain-based platforms in a controlled environment. The interoperability between different registers and blockchain platforms remains a significant obstacle, underscoring the need for hybrid solutions such as the Climate Action Data Trust (CAD Trust) and Hyperledger Besu, which can facilitate connections between voluntary and regulated markets. Additionally, scalability and transaction costs must be addressed to ensure the large-scale viability of blockchain adoption. Emerging technologies, including Layer-2 solutions and energy-efficient consensus mechanisms, should be explored to optimize blockchain implementation in carbon markets.

From a theoretical view, this research contributes to the literature on blockchain applications in environmental finance by presenting a conceptual framework for its adoption in these markets. The study reinforces the relevance of the principles of Decentralization, Decarbonization, and Digitalization (3D's), emphasizing the role of blockchain as a key enabler in building more efficient and transparent carbon markets. Furthermore, by categorizing different blockchain architectures-including public, permissioned, and hybrid models-this research approaches existing gaps in the literature by assessing their applications and limitations across various carbon trading mechanisms. To deepen these discussions, future studies should prioritize empirical case studies and experimental validations to assess the real-world impact of blockchain on emissions tracking, carbon credit trading, and sustainable finance.

While blockchain presents a disruptive opportunity to transform carbon markets, its successful adoption will depend on strategic collaboration between governments, the private sector, and academia. Only through coordinated efforts will it be possible to overcome technological and regulatory challenges, ensuring blockchain-based systems play a meaningful role in mitigating climate change. This research establishes a discussion for future investigations and practical implementations, fostering more transparent, efficient, and trustworthy carbon markets for a sustainable economy.

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