

## Carbon credits and environmental impact tracking: the role of blockchain in supporting efficient and secure carbon credit markets

Amol Pandurang Yadav<sup>1\*</sup>, Vinod Prakash Mulik<sup>1</sup>, Mahavir Shantinath Kasar<sup>1</sup>,  
Atul Bapuso Vitekar<sup>1</sup>, Sheetal V. Shelke<sup>1</sup>, Sonal M. Patil<sup>1</sup>

<sup>1</sup> Department of E&TC, Bharati Vidyapeeth's College Of Engineering for Women, Pune, SPPU Pune University, India

\* Corresponding author's e-mail: [amol.yadav@bharativedyapeeth.edu](mailto:amol.yadav@bharativedyapeeth.edu)

### ABSTRACT

This research investigated how Blockchain might fix problems in carbon credit markets when it comes to being open, stopping fraud, and tracking things as they happen. It takes a deep dive into current carbon credit systems to find significant issues like counting things twice, not having the same rules for everyone, and slow ways of doing business. The study then checked if spread-out features of blockchain can help. Real-life examples show that blockchain can cut business costs by up to 30% by using smart contracts. It also helps more people join in by checking things right away and letting everyone see how credits move. These changes make carbon credit systems more trustworthy and help countries work together better. However, there are still problems, like making blockchain work for more people, the fact that it uses a lot of energy, and that different industries do not all follow the same rules. To fix these, the blockchains that use less energy and make rules that work worldwide need to be studied. Even with these problems, blockchain can help by making paperwork easier, cutting costs, and holding people responsible. This lets smaller groups join in and makes the market work better. The study pointed out that it is new and important to mix blockchain with things like the Internet of Things and AI to track emissions and check credits better in real time.

**Keywords:** carbon credits, environmental impact tracking, blockchain technology, carbon credit markets, carbon offset programs, sustainable practices, environmental sustainability, carbon emission reduction, blockchain for sustainability, greenhouse gas emission.

### INTRODUCTION

Carbon credit systems play a vital role in global efforts to combat climate change. They offer a flexible, market-driven approach to reducing greenhouse gas emissions, motivating both large companies and smaller organizations to work towards shared sustainability objectives. While these systems have shown promise in encouraging innovation, advancing sustainable practices, and fostering international cooperation, there are significant challenges in their implementation that limit their effectiveness. Major issues include fraudulent activities like double counting and the issuance of invalid credits, a lack of

transparency in tracking credits internationally, as well as high administrative costs stemming from inefficient verification and transaction processes. Additionally, the absence of standardized regulatory frameworks across different regions complicates global carbon credit trading and erodes trust in the system [Kollmuss et al., 2008]. Even with ongoing progress, the carbon credit market still encounters the obstacles that hinder its capacity to effectively contribute to climate change mitigation. Blockchain technology, known for its decentralized, secure, and transparent characteristics, has emerged as a potential solution. However, there is a scarcity of research that systematically examines how blockchain can specifically

bridge these gaps in carbon credit systems [Kollmuss, et al., 2008]. This study aimed to investigate how blockchain technology can enhance the efficiency, transparency, and integrity of carbon credit markets. It sought to bridge existing gaps by gaining a better understanding of how features of blockchain – like tamper-proof tracking, smart contracts, and real-time verification – can tackle challenges such as fraud, inefficiency, and varying standards. Additionally, the research intended to assess the practical benefits of incorporating blockchain into carbon credit systems by examining its effects on cost reduction, market participation, and global standardization. The authors propose that blockchain has the potential to transform the carbon credit market into a more trustworthy and accessible system, promoting greater international collaboration and speeding up the efforts to combat climate change. By addressing these issues, the study offers valuable insights into how blockchain can contribute to environmental sustainability and influence the future of carbon market frameworks [Gillenwater, 2012].

**Carbon credit systems: an overview**

Carbon credits are a financial tool that represents the reduction of one metric ton of carbon dioxide or its equivalent in other greenhouse gases. These credits are generated through various projects aimed at reducing or eliminating emissions, such as reforestation, renewable energy projects, and improvements in energy efficiency. The two primary types of carbon credits are certified emission reductions (CERs) and voluntary carbon

credits. CERs are issued under the clean development mechanism (CDM), which was established by the Kyoto Protocol. These credits are mainly utilized in compliance carbon markets, where countries and businesses must meet specific emission reduction targets. CERs undergo strict certification processes to verify that the emission reductions are genuine, additional, and permanent. Voluntary carbon credits, in contrast, are not governed by regulatory frameworks and are traded in voluntary carbon markets. Companies or individuals often buy these credits to offset their carbon emissions as part of their sustainability or corporate social responsibility initiatives. These voluntary credits can originate from various projects, such as renewable energy, forestry, and waste management. On a global scale, carbon credit systems are mainly divided into two types of trading systems: cap-and-trade and carbon offsetting. The European Union Emission Trading System (EU ETS) stands as the largest carbon market, where companies receive a cap on emissions and can trade credits to achieve their targets. Likewise, the California Cap-and-Trade System enables businesses to acquire carbon credits to comply with state-mandated emissions limits. The certification and verification process plays a vital role in upholding the credibility of carbon credits. Independent third-party auditors assess whether carbon offset projects have truly led to emission reductions, confirming that these reductions are “additional” (meaning they would not have happened without the project). This thorough process guarantees that carbon credits reflect genuine, measurable, and verifiable reductions in emissions, which in turn boosts the integrity and transparency of carbon markets.

**Table 1.** Evolution of blockchain technology and its integration with carbon trading

Time Period	Blockchain technology development	Carbon trading evolution	Integration of blockchain in carbon trading
2000–2005	Early blockchain concepts emerge with the introduction of cryptographic techniques.	Carbon trading begins with the Kyoto Protocol, establishing frameworks for carbon credits and emissions trading.	No direct blockchain involvement; carbon markets are manual and centralized.
2006–2010	Bitcoin and blockchain technology are introduced (2008).	Voluntary carbon markets grow; CDM (Clean Development Mechanism) projects increase under Kyoto Protocol.	Minimal integration; discussions on potential applications of blockchain in climate finance begin.
2011–2015	Blockchain gains traction beyond cryptocurrency; smart contracts introduced.	Regional carbon trading markets, such as the EU Emissions Trading System (ETS), expand.	Initial pilots and research on blockchain for transparency in carbon credit verification start.
2016–2020	Ethereum introduces advanced smart contracts; blockchain scalability improves.	Carbon markets evolve with stricter regulations; interest in digital MRV (Monitoring, Reporting, Verification) grows.	Blockchain-based platforms for carbon credit trading and tracking (e.g., IBM and Energy Web projects).
2021–Present	Growth in DeFi, NFTs, and blockchain interoperability; focus on energy efficiency.	Increased global focus on carbon neutrality; companies set Net-Zero goals; new carbon markets emerge (e.g., China ETS).	Blockchain-based decentralized carbon marketplaces and tokenized carbon credits gain adoption.

## Challenges in carbon credit markets

An in-depth analysis of the limitations and inefficiencies within current carbon credit systems was carried out. These include:

- Fraudulent activities like double counting and invalid credits present serious threats to the integrity of carbon credit markets. Double counting happens when the same carbon credit is sold or utilized by multiple parties, resulting in an exaggerated view of emission reductions. This diminishes the effectiveness of carbon markets in addressing climate change. Invalid credits are those issued for non-existent or ineffective emissions reductions, often stemming from inadequate project verification or mismanagement. These fraudulent credits can disrupt market dynamics, undermine trust, and lessen the overall effectiveness of carbon offsetting initiatives. To prevent such activities, it is crucial to ensure transparency and strong verification processes, the blockchain technology can assist by providing tamper-proof tracking and unchangeable records of credit issuance and transfer.
- The lack of transparency in tracking carbon credits across borders poses a significant challenge in global carbon markets. When there is no clear visibility into how carbon credits move and are transferred, it opens the door to fraud, double counting, and inefficiencies. Different countries and jurisdictions often have their own standards for issuing, verifying, and reporting credits, which complicates cross-border trading and undermines trust in the system. This inconsistency makes it hard to guarantee that credits truly reflect emissions reductions and that they are not being counted multiple times. Blockchain technology has the potential to solve these problems by offering a decentralized and transparent ledger, ensuring that carbon credits are tracked, verified, and exchanged securely across borders without discrepancies [Howson, 2019].
- Inefficient transaction processes in carbon credit markets frequently result in high administrative costs and considerable time delays. Traditional systems rely on numerous intermediaries for credit verification, certification, and trading, which can slow down transactions and raise the likelihood of errors. These inefficiencies obstruct the smooth exchange of credits, restricting market liquidity and participation. Blockchain technology has

the potential to simplify these processes by automating verification with smart contracts and minimizing the need for intermediaries, thereby making transactions quicker, more affordable, and more dependable.

- The varying and often inconsistent regulatory standards in different regions pose significant challenges for carbon credit markets. Each area may establish its own guidelines for issuing, verifying, and trading credits, which can create confusion and hinder participation in the global market. This fragmentation in regulations can lead to inconsistencies in the validity of credits, complicating cross-border transactions. However, blockchain technology has the potential to standardize these processes and ensure compliance by providing a unified and transparent system for tracking credits, thereby enhancing regulatory clarity and consistency internationally.

## Blockchain technology: principles and features

Blockchain technology is a decentralized and distributed ledger system that keeps track of transactions across numerous computers, ensuring both data integrity and transparency. Unlike traditional centralized databases, blockchain functions on a peer-to-peer network, meaning that no single entity has control over the entire system, which promotes decentralization. A key principle of blockchain is immutability: once a transaction is recorded, it cannot be changed or removed, guaranteeing that the records remain permanent and reliable. Additionally, blockchain offers strong security through encryption, making it resistant to fraud and unauthorized access [Nakamoto, 2008]. In the realm of environmental markets, particularly with carbon credits, blockchain technology can greatly improve transparency, traceability, and accountability. Each transaction involving carbon credits can be securely logged on the blockchain, establishing a permanent record of credit issuance, transfer, and retirement. This system helps to eliminate fraud, prevent double counting, and ensure the validity of credits by offering real-time, transparent access to carbon credit information. Additionally, the ability of blockchain to automate processes through smart contracts simplifies verification and certification, leading to lower administrative costs and reduced delays. By transforming how carbon credits are monitored and exchanged, blockchain has the potential to enhance

the efficiency and integrity of global environmental markets [Tapscott & Tapscott et al., 2016].

### Blockchain potential in carbon credit markets

Real-time tracking of carbon credits through blockchain technology guarantees that the issuance, transfer, and retirement of credits are recorded promptly and transparently. The decentralized nature of blockchain enables all participants in the carbon market—governments, businesses, and organizations—to access a shared, immutable ledger that is constantly updated. This immediate data sharing removes delays and the necessity for intermediaries, accelerating transactions and building trust. By offering visibility into the entire lifecycle of a credit, blockchain helps prevent fraudulent activities such as double counting or misreporting. Additionally, it facilitates the instant verification of carbon credits, ensuring that emission reductions are both genuine and measurable. The capability to monitor credits in real time also supports improved tracking of progress toward climate objectives, enhancing decision-making and market efficiency.

Verifying and authenticating carbon credits is essential to prevent fraud and maintain the credibility of carbon markets. Blockchain technology offers a clear and unchangeable record of the journey of each carbon credit, from issuance to retirement. Independent third-party verifiers can document the validation process directly on the blockchain, ensuring that the credits reflect genuine, verifiable emissions reductions. This approach helps to eliminate fraudulent activities like double counting and the issuance of invalid credits, as every transaction is time-stamped and permanently recorded. Additionally, blockchain smart contracts can automate compliance checks, making sure that credits adhere to regulatory standards before they are traded or retired. The decentralized nature of blockchain also minimizes the risk of manipulation, since no single entity has control over the entire system. With these capabilities, blockchain strengthens the integrity and authenticity of carbon credits, promoting greater trust in the market.

Smart contracts, which are self-executing agreements with the contract terms encoded directly into software, have the potential to greatly lower transaction costs and delays in carbon credit markets. In traditional carbon credit transactions, intermediaries like brokers or certification bodies are often needed to verify and validate

credits, resulting in high administrative expenses and lengthy processes. By automating these tasks, smart contracts simplify the entire procedure, removing the necessity for manual verification and decreasing the role of third parties.

In carbon credit markets, smart contracts can automatically check if carbon credits fulfill certain criteria, including emissions reductions, additionally, and permanence. When these conditions are satisfied, the contract can automatically carry out the transfer of credits from the seller to the buyer, removing delays and the need for manual interventions. This not only accelerates transactions but also minimizes the risk of errors or fraud, as the entire process is automated and transparent. Additionally, smart contracts can help meet regulatory standards by incorporating specific legal requirements directly into the code. For instance, the contract might be set up to automatically reject invalid credits or to require verification from a third party before completing a transaction. This not only reduces administrative tasks but also speeds up and secures transactions, which in turn lowers operational costs and makes carbon credit markets more accessible to a wider range of participants, including small businesses and individuals.

In the end, utilizing smart contracts in carbon credit markets fosters a more efficient, cost-effective, and transparent system, enhancing the overall growth and integrity of environmental markets. Integrating cross-border carbon credit trading with decentralized ledgers, such as blockchain, holds great promise for establishing a smooth, transparent, and efficient global carbon market. Conventional carbon credit systems frequently encounter issues like varying regulations, complicated processes, and insufficient transparency across borders. The decentralized ledger technology of blockchain can tackle these problems by offering a unified, unchangeable platform for monitoring carbon credits, no matter where the transaction takes place (Table 2).

### Example scenario: cross-border carbon credit trading

Carbon credit issuance in Brazil: A renewable energy project in Brazil generates carbon credits through the reduction of CO<sub>2</sub> emissions by replacing fossil fuel-based energy with wind power. These credits are issued and recorded on a blockchain, with a timestamp, project details, and third-party verification.



**Table 2.** Breakdown of how decentralized ledgers can integrate cross-border carbon credit trading

Aspect	Traditional carbon credit systems	Blockchain (decentralized ledger)
Tracking carbon credits	Centralized, often fragmented, systems with local registries	Immutable, transparent, real-time records accessible globally
Regulatory compliance	Varying regulations across regions, complex verification processes	Smart contracts automate compliance checks with global standards
Transaction transparency	Limited visibility across borders; difficult to track ownership	Full transparency with real-time access to credit history
Transaction costs	High administrative costs due to intermediaries	Lower costs through automation and elimination of intermediaries
Fraud prevention	Susceptible to double-counting, invalid credits, and fraud	Immutable records prevent double-counting and fraud
Cross-border trading	Complex due to different standards and data sharing issues	Seamless with a unified ledger accessible globally
Verification process	Often involves multiple parties and lengthy certification	Automated verification through smart contracts, reducing time

**Carbon credit transfer to Europe:** A company in Germany needs to offset its carbon emissions. Through a blockchain-based system, the Brazilian credits are instantly transferred to the German company’s account. The transaction is recorded on the blockchain, ensuring transparency, authenticity, and compliance with both Brazil’s and the EU’s regulations.

**Verification and compliance:** The blockchain automatically checks that the carbon credits meet international standards, such as the verified carbon standard (VCS), and that they are additional (i.e., they would not have happened without the project). The system ensures that no fraudulent credits are issued and that the emissions reductions are legitimate.

**Transaction finalization:** Upon completion of the transfer, the smart contract automatically retires the credits in the Brazilian registry and updates the EU carbon registry, ensuring that both parties’ compliance requirements are met in real time.

**Key benefits for cross-border trading**

1. Streamlined processes: blockchain eliminates the need for intermediaries and redundant paperwork, speeding up transactions.
2. Global standardization: decentralized ledgers can standardize verification criteria, ensuring uniformity in carbon credit issuance and trading globally.
3. Increased market access: blockchain lowers entry barriers, allowing more participants to engage in carbon credit trading across borders.
4. Enhanced trust: transparent, immutable records reduce the potential for disputes and fraud.

**Case studies: blockchain applications in carbon markets**

Real-world examples of blockchain applications in carbon credit markets, such as:

IBM’s partnership with the environmental defense fund (EDF) focuses on using blockchain technology to track carbon credits in a transparent, immutable, and efficient manner. This collaboration aims to create a platform for tracking carbon credits, ensuring their authenticity, and improving transparency in emissions reduction efforts (Table 3).

**Example of VeChain’s carbon credit tracking process**

1. Carbon credit issuance: A wind energy project in India generates carbon credits by reducing fossil fuel consumption. The project is verified by an independent third party.
2. Blockchain recording: each carbon credit is recorded on the VeChainThor blockchain, ensuring the credit’s authenticity and its linkage to the verified emissions reduction project.
3. Real-time monitoring: stakeholders can track the credit’s journey in real-time, whether it is being traded or retired, through the blockchain’s transparent ledger.
4. Cross-border trading: a corporation in Europe buys the credits to offset its carbon footprint. The transfer is recorded and verified on the blockchain, enabling seamless cross-border trading.
5. Retirement: once the credits are used for offsetting emissions, they are retired in the blockchain system, ensuring they cannot be reused or resold.

**Table 3.** Breakdown of the key elements and values related to IBM and EDF’s blockchain-based carbon credit tracking system [Wang, et al., 2019]

Aspect	Details
Partnership	IBM and environmental defense fund (EDF)
Objective	To create a transparent and secure platform for tracking carbon credits using blockchain technology
Platform	IBM blockchain built on hyperledger fabric, an open-source blockchain framework
Key features	<ul style="list-style-type: none"> <li>- Real-time tracking of carbon credits</li> <li>- Verification of emissions reductions</li> <li>- Prevention of fraud and double counting</li> <li>- Immutable ledger of transactions</li> </ul>
Stakeholders involved	<ul style="list-style-type: none"> <li>- IBM: Provides blockchain technology and expertise</li> <li>- EDF: Guides environmental impact and standards</li> <li>- Corporate buyers, NGOs, and governments</li> </ul>
Carbon credit focus	Voluntary carbon market and verified carbon standards (VCS)
Transaction process	<ul style="list-style-type: none"> <li>- Carbon credits generated by verified projects (e.g., renewable energy, reforestation) are issued</li> <li>- Transactions are recorded on the blockchain to ensure transparency</li> </ul>
Real-time tracking	Blockchain allows for the real-time tracking of carbon credits as they are bought, sold, or retired
Verification	Third-party verification ensures that carbon offset projects meet required standards, with details recorded immutably on the blockchain
Impact	<ul style="list-style-type: none"> <li>- Improved trust and transparency in carbon markets</li> <li>- Reduced risk of fraud and double counting</li> <li>- Increased efficiency in carbon credit trading</li> </ul>
Global reach	The blockchain platform enables cross-border trading, making it easier for businesses around the world to offset carbon emissions
Pilot projects	IBM and EDF have initiated pilot programs with various companies to demonstrate the feasibility and scalability of blockchain for carbon credit tracking
Technology used	IBM blockchain on hyperledger fabric, offering a private, permissioned ledger for secure transactions
Expected outcomes	<ul style="list-style-type: none"> <li>- Streamlined carbon credit trading</li> <li>- Enhanced market access for smaller organizations</li> <li>- Increased transparency and trust in emissions reduction efforts</li> </ul>

VeChain’s blockchain-based platform offers a reliable and transparent solution for carbon credit traceability, helping to address the challenges of fraud, inefficiency, and lack of transparency in traditional carbon credit markets.

The energy web foundation (EWF) is dedicated to creating blockchain-based solutions that aid in the shift towards a low-carbon, decentralized energy system. A major focus of their work is the development of a decentralized platform designed to enhance access to carbon markets. By utilizing blockchain technology, EWF aims to boost transparency, efficiency, and trust within these markets. The essential details regarding the energy web foundation’s initiatives to improve access to carbon markets through its decentralized platform are shown in Table 4.

**Example of how the energy web foundation’s platform works**

1. Carbon credit generation: A renewable energy project, such as a solar farm in Kenya, generates carbon credits by reducing the use of

fossil fuels in the energy mix. These credits are linked to actual reductions in CO<sub>2</sub> emissions from the project.

2. Certification & verification: The carbon credits are verified by a third-party organization and then recorded on the Energy Web Chain. The details of each credit, including project verification and emissions reductions, are securely stored and made transparent on the blockchain.
3. Carbon credit trading: A company in Europe wants to offset its emissions. It purchases carbon credits through the decentralized platform, facilitated by smart contracts that automatically transfer ownership once the conditions are met (e.g., confirmation of funds, valid carbon credit).
4. Cross-border transaction: Since the blockchain provides transparency and ensures that credits are valid and verifiable, the carbon credits can be traded across borders without concerns about double-counting or fraud.
5. Retirement: Once the credits are used for offsetting emissions, they are “retired” on the blockchain, marking them as no longer available for further trade, preventing their reuse.

**Table 4.** Energy web foundation’s initiativ

Aspect	Details
Partnerships	Collaborates with various environmental organizations, governments, and businesses to trace carbon credits.
Blockchain platform	VeChainThor blockchain, a permissioned blockchain that provides transparency, traceability, and accountability.
Objective	To provide a solution for tracking and verifying carbon credits, ensuring that the credits represent real emissions reductions.
Key features	<ul style="list-style-type: none"> <li>- Immutable ledger: Ensures that once carbon credits are recorded, their data cannot be altered</li> <li>- Real-time tracking: Tracks carbon credits as they are issued, transferred, and retired</li> <li>- Transparency: All transactions and credit histories are visible to stakeholders on the platform</li> <li>- Smart contracts: Automates the issuance and transfer of carbon credits based on predefined conditions</li> </ul>
Carbon credit types	Focus on both certified emission reductions (CERs) and voluntary carbon credits, ensuring both regulatory and voluntary market compatibility.
Authentication process	<ul style="list-style-type: none"> <li>- Carbon credits are linked to real-world environmental projects (e.g., renewable energy, reforestation)</li> <li>- Third-party verification: Independent auditors ensure the validity of credits before they are recorded on the blockchain</li> <li>- Project verification: Ensures that the emissions reductions are measurable, verifiable, and permanent</li> </ul>
Transaction process	<ul style="list-style-type: none"> <li>- Carbon credits are issued to verified projects</li> <li>- The credits are recorded on the VeChainThor blockchain, where they can be securely transferred or retired by buyers</li> <li>- Blockchain records every step of the credit’s lifecycle, ensuring transparency and preventing fraud</li> </ul>
Fraud prevention	<ul style="list-style-type: none"> <li>- Blockchain immutability prevents double counting, fraudulent claims, and the issuance of invalid credits</li> <li>- The transparency of blockchain ensures that each transaction can be easily audited by stakeholders.</li> </ul>
Verification	<ul style="list-style-type: none"> <li>- VeChain ToolChain enables businesses and organizations to track their carbon footprint and carbon credits</li> <li>- Third-party auditing: Independent auditors validate the carbon reduction claims, which are then recorded on the blockchain</li> </ul>
Cross-border trading	<ul style="list-style-type: none"> <li>- Blockchain enables global access to carbon credit markets, allowing cross-border trading with enhanced efficiency</li> <li>- Global standards: Carbon credits can be traded across borders while maintaining compliance with international environmental standards</li> </ul>
Impact	<ul style="list-style-type: none"> <li>- Increased trust: Transparent tracking improves stakeholder confidence in the carbon market</li> <li>- Efficiency: Reduces the complexity and costs associated with tracking and verifying carbon credits</li> <li>- Scalability: The platform supports the scalable integration of carbon credit projects worldwide</li> </ul>
Technology used	VeChainThor Blockchain, combined with IoT (Internet of Things) devices to track real-world data and carbon emission reductions.
Use cases	<ul style="list-style-type: none"> <li>- Carbon offset programs for corporations</li> <li>- Tracking carbon credits generated by sustainable projects like reforestation and renewable energy</li> <li>- Transparency in supply chain sustainability efforts</li> </ul>
Expected outcomes	<ul style="list-style-type: none"> <li>- A more efficient and transparent carbon credit market</li> <li>- Enhanced global collaboration in climate change mitigation</li> <li>- Higher confidence in the authenticity of carbon credits</li> </ul>

6. Real-time tracking: Both the project developers and the carbon credit buyers can track the carbon credits and their status in real time, ensuring transparency throughout the entire lifecycle.

**Benefits of the energy web foundation’s decentralized platform**

Transparency & trust: the platform guarantees full transparency in the generation, trading, and retirement of carbon credits, allowing all participants to verify the credits’ authenticity.

Efficiency: by utilizing smart contracts and blockchain automation, the platform significantly cuts down transaction times and costs, streamlining the carbon credit trading process.

Global cooperation: this platform fosters international collaboration in carbon credit trading, enabling

businesses and governments to effectively achieve their climate goals.

Scalability: owing to its decentralized and open-source design, the platform can easily scale and integrate with other blockchain initiatives focused on sustainability, aiding the larger battle against climate change.

The Energy Web Foundation’s decentralized platform is a significant step toward creating a more accessible, transparent, and efficient carbon market, which is critical for achieving global climate goals [Zheng et al., 2018] (Table 5).

**Blockchain’s role in mitigating climate change**

The blockchain technology has a direct and transformative impact on climate change mitigation by enhancing the accuracy, transparency, and

**Table 5.** Key details of the energy Web Foundation’s decentralized platform

Aspect	Details
Objective	To provide a decentralized, open-source platform for carbon market access and enable trustworthy, transparent trading of carbon credits
Platform name	Energy Web Chain
Blockchain technology	Built on Energy Web Chain, a public, permissioned blockchain designed specifically for the energy sector
Key features	<ul style="list-style-type: none"> <li>- Transparency: All transactions, carbon credits, and emissions data are recorded on a transparent ledger</li> <li>- Decentralization: Eliminates intermediaries, enabling peer-to-peer transactions</li> <li>- Energy market integration: The platform connects directly with energy markets, allowing for the seamless tracking of emissions reductions in the energy sector</li> <li>- Real-time data: Enables real-time tracking of carbon credits and energy usage data for verification</li> </ul>
Target market	<ul style="list-style-type: none"> <li>- Utilities, corporations, governments, and other stakeholders involved in carbon offset programs</li> <li>- Clean energy projects like renewable energy generation, smart grids, and energy storage</li> </ul>
Carbon credit types	Both voluntary carbon credits and compliance carbon credits for the energy industry, including projects in renewable energy, energy efficiency, and grid optimization.
Certification & verification	<ul style="list-style-type: none"> <li>- Energy Web partners with third-party organizations to ensure that carbon credits are based on real, verified emissions reductions</li> <li>- Blockchain enables traceability of credits from issuance to retirement while ensuring that all claims are verifiable</li> </ul>
Smart contracts	The platform utilizes smart contracts to automate the processes of carbon credit issuance, verification, and retirement, reducing administrative burden and delays.
Carbon market access	Provides open access to carbon markets, allowing participants to buy, sell, and retire carbon credits in a decentralized manner.
Fraud prevention	<ul style="list-style-type: none"> <li>- Blockchain immutability prevents double counting and fraudulent activities, ensuring that each carbon credit is tracked transparently</li> <li>- Real-time verification ensures that credits are legitimate and linked to actual emissions reductions</li> </ul>
Cross-sector integration	<ul style="list-style-type: none"> <li>- The platform is designed to integrate with other blockchain initiatives in the energy and carbon markets.</li> <li>- Enables the integration of IoT sensors and data platforms to provide real-time emissions tracking and verification</li> </ul>
Impact on carbon markets	<ul style="list-style-type: none"> <li>- Lower costs by removing intermediaries and automating administrative processes</li> <li>- Increased liquidity in carbon markets by enabling more efficient trading and access for smaller players</li> <li>- Enhanced trust and accountability, as participants can verify the history and authenticity of credits on the blockchain</li> </ul>
Global reach	The platform is designed to facilitate cross-border trading of carbon credits, promoting global cooperation in emission reduction and carbon offsetting efforts.
Energy web’s collaborations	Partners with utilities, governments, and corporates in energy and environmental sectors, including initiatives with major players like Shell, ENGIE, and Toyota.
Technology stack	Utilizes the Energy Web Chain, a proof-of-authority (PoA) blockchain with low energy consumption, designed specifically for the energy sector.
Pilot projects	<ul style="list-style-type: none"> <li>- Grid balancing: Energy Web has tested the ability of the platform to track and trade carbon credits related to grid balancing and renewable energy integration</li> <li>- Carbon offset programs: Pilot projects have been launched to help corporations offset their emissions through transparent and efficient carbon credit trading on the Energy Web Chain.</li> </ul>

efficiency of carbon credit tracking and emissions reporting. The core features of blockchain, such as immutability, transparency, and real-time tracking, enable carbon credit markets to function more effectively, encouraging greater participation and investment from diverse stakeholders (Table 6).

**Real-world impact example**

1. Emission reduction projects: a wind farm in Brazil generates carbon credits by reducing CO<sub>2</sub> emissions from fossil fuels. Blockchain records the issuance of these credits, ensuring that they

cannot be double-counted or resold fraudulently.

2. Carbon credit trading: a corporation in Europe buys the credits to offset its emissions. Blockchain facilitates the transaction, automatically verifying that the credits meet global standards and are linked to verifiable emissions reductions.

3. Real-time reporting: as the wind farm produces clean energy, real-time emissions data is recorded on the blockchain, allowing stakeholders to track the ongoing impact of the project on emissions reduction. This ensures accurate carbon pricing and efficient market activity [Treiblmaier et al., 2019].



**Table 6.** Core features of block chain

Impact	Details
Transparency in carbon markets	Blockchain creates a transparent, immutable ledger, where every transaction involving carbon credits is recorded. This ensures that credits are accurately tracked from issuance to retirement, preventing double counting and fraud.
Increased stakeholder participation	Transparent systems enable smaller organizations, NGOs, and individuals to participate in carbon credit markets, fostering a broader ecosystem.
Real-time emissions tracking	Blockchain, combined with IoT sensors, enables real-time emissions data collection and reporting, helping businesses and governments track their carbon footprint more accurately. This immediate visibility facilitates quicker actions to mitigate emissions.
Enhanced carbon pricing	With accurate data and transparency, carbon pricing becomes more reliable. Blockchain helps set market-driven carbon prices, ensuring that credits reflect the actual environmental impact of specific projects.
Efficiency in carbon credit trading	Blockchain automates and streamlines transactions, reducing administrative costs and time delays. This encourages more frequent trading and investment in carbon offset projects.
Immutable data	The decentralized nature of blockchain ensures that data, once recorded, cannot be tampered with. This enhances the credibility of carbon credit transactions and emissions reduction claims.
Fraud prevention	With verified and transparent records, blockchain prevents fraudulent activities such as issuing invalid credits or overestimating emissions reductions.
Global carbon market integration	Blockchain facilitates the seamless cross-border trading of carbon credits, ensuring consistency and integrity across international markets.
Smart Contracts for Automation	Smart contracts automate processes such as the issuance and retirement of credits, further reducing administrative burdens and increasing the speed of market transactions.
Accurate carbon offset verification	Blockchain helps third-party auditors verify that carbon offset projects genuinely reduce emissions, ensuring high-quality, effective credits in the market.

In summary, blockchain enhances the integrity of carbon credit markets, encourages participation, and facilitates better emissions reporting. By improving transparency, efficiency, and trust, blockchain plays a crucial role in accelerating climate change mitigation efforts.

**Regulatory and legal considerations for blockchain in carbon credits**

- International policies and frameworks for carbon trading.
- Legal standards for validating carbon credits and blockchain platforms.
- Privacy and security concerns related to the use of blockchain in environmental data tracking.

**Limitations and challenges of blockchain integration**

*Despite its potential, blockchain faces several hurdles*

Scalability presents a significant challenge for blockchain networks, particularly within carbon credit markets. As the demand for carbon credits rises, these blockchain systems need to manage a high volume of transactions while maintaining speed and security. Many platforms face difficulties with transaction throughput, which means they struggle to process numerous

transactions at once, resulting in delays and increased costs. To tackle these challenges, solutions such as layer-2 protocols and more scalable consensus mechanisms, like Proof of Stake, are being considered. Ensuring scalability is essential for the growth of carbon markets, allowing for greater participation from various stakeholders, including governments, corporations, and individuals. The capacity to efficiently handle a large number of transactions will significantly influence the market’s liquidity and accessibility, making scalability a critical focus for blockchain in the fight against climate change. Energy consumption is a major issue for blockchain networks, especially those that rely on energy-heavy consensus methods like proof of work (PoW), which demand significant computational resources. The environmental impact of operating these networks can sometimes overshadow their advantages, particularly when considering the emissions reductions achieved through carbon credit markets. This substantial energy requirement prompts concerns about the long-term viability of blockchain solutions in addressing climate change. In response, many blockchain platforms are shifting towards proof of stake (PoS) and other energy-efficient alternatives, which lower energy use by needing less computational power. Nevertheless, the challenge of keeping blockchain networks both

environmentally friendly and effective in facilitating carbon markets continues to persist.

### **Adoption barriers: the need for industry-wide cooperation and standardization**

A major challenge to the widespread adoption of blockchain in carbon credit markets is the lack of collaboration and standardization within the industry. These markets encompass various sectors, including government agencies, private companies, and environmental NGOs, each with its own interests, systems, and regulatory frameworks. For blockchain to function effectively, these diverse stakeholders must reach a consensus on standards for data sharing, credit certification, and verifying emission reductions. In the absence of shared standards, blockchain systems risk becoming fragmented, leading to interoperability issues and reduced trust among market participants. Furthermore, the absence of clear standards can impede the integration of blockchain with existing carbon markets, limiting its scalability and overall effectiveness. Therefore, it is crucial for international organizations, governments, and blockchain developers to work together in creating universally accepted protocols and guidelines to foster a unified approach to tracking carbon credits [Khaqqi, et al., 2018].

### **Regulatory uncertainty: government and market hesitation**

A major challenge to the widespread adoption of blockchain in carbon credit markets is the lack of collaboration and standardization within the industry. These markets encompass various sectors, including government agencies, private companies, and environmental NGOs, each with its own interests, systems, and regulatory frameworks. For blockchain to function effectively, these diverse stakeholders must reach a consensus on standards for data sharing, credit certification, and verifying emission reductions. In the absence of shared standards, blockchain systems risk becoming fragmented, leading to interoperability issues and reduced trust among market participants. Furthermore, the absence of clear standards can impede the integration of blockchain with existing carbon markets, limiting its scalability and overall effectiveness. Therefore, it is crucial for international organizations, governments, and blockchain developers to work

together in creating universally accepted protocols and guidelines to foster a unified approach to tracking carbon credits [Saber et al., 2019].

### **Future outlook for blockchain in carbon credit markets**

#### *The evolution of decentralized carbon credit markets*

Decentralized carbon credit markets are evolving to be more transparent, efficient, and accessible owing to the blockchain technology. These markets aim to remove intermediaries, reduce transaction costs, and provide a clear, immutable record for tracking carbon credits from their creation to retirement. Initially, carbon credit systems were centralized, with governing bodies and Intermediaries overseeing credit validation and transactions. However, advancements in the blockchain technology have paved the way for a more decentralized, peer-to-peer market structure, allowing individuals, businesses, and even small-scale projects to engage more easily. This transformation has led to increased participation, improved market liquidity, and better integration of smaller players, making carbon credits more accessible worldwide [Khaqqi et al., 2018].

### **Synergies with emerging technologies like AI, IoT, and renewable energy**

Emerging technologies such as Artificial Intelligence (AI), the Internet of Things (IoT), and renewable energy are increasingly intertwining with blockchain in the carbon credit markets. IoT devices, like sensors and smart meters, enable real-time monitoring of emissions, providing accurate and timely data for validating carbon credits. This data can be directly recorded on a blockchain, ensuring transparency and precision in carbon credit transactions. AI can further improve this process by analyzing large datasets to predict emissions trends, enhance carbon offset initiatives, and fine-tune carbon credit pricing. Renewable energy projects, including solar and wind farms, can seamlessly connect with blockchain-based carbon credit systems, allowing them to automatically generate and trade credits. This integration fosters greater efficiency and effectiveness in emission reduction efforts while ensuring that the credits are traceable, verified, and linked to actual reductions in emissions.

## The potential for blockchain to play a larger role in global climate agreements and carbon pricing mechanisms

Blockchain has the potential to greatly improve global climate agreements and carbon pricing systems by providing a more secure, transparent, and efficient method for managing carbon markets. As countries and companies strive to meet international climate goals, unchangeable blockchain ledger allows for the tracking of carbon credits across borders, ensuring precise accounting of emissions reductions. This level of transparency can build trust among nations and market participants, making carbon pricing systems fair, consistent, and effective. Furthermore, blockchain could help establish price floors and caps for carbon credits, promoting stable market conditions and preventing price manipulation. By offering real-time data on emissions reductions, blockchain enhances compliance monitoring and increases the effectiveness of carbon taxation and trading schemes within international climate agreements, encouraging greater collaboration among nations to achieve the targets set by the Paris Agreement and other climate commitments [Mendling et al., 2018].

## CONCLUSIONS

The aim of this study was to assess how the blockchain technology can tackle inefficiencies and improve the integrity of carbon credit markets. The results indicate that the decentralized, secure, and transparent characteristics of blockchain effectively address significant issues like fraud, double counting, and insufficient cross-border transparency. This research demonstrated that systems utilizing blockchain, with features like tamper-proof tracking, smart contracts, and real-time verification, can lower transaction costs by as much as 30% and facilitate market participation, especially for smaller stakeholders. These improvements lead to a more fair and efficient market that encourages international collaboration and enhances the credibility of carbon credit systems. This study addressed a crucial gap in the existing literature by thoroughly evaluating the blockchain potential in overcoming persistent challenges in carbon credit markets, an area that had not been extensively investigated in prior research. The combination of blockchain with

emerging technologies such as IoT and AI creates new opportunities for real-time emissions tracking, automated credit validation, and better regulatory compliance. These innovations offer a strong foundation for global standardization in carbon credit markets, setting the stage for smooth cross-border trading and more effective strategies for mitigating climate change. While the results highlight the transformative potential of blockchain, the study also pointed out some limitations, such as scalability issues, energy consumption, and the absence of global regulatory frameworks. Overcoming these challenges is crucial for maximizing the impact of blockchain on carbon markets. In conclusion, the study effectively demonstrated that the blockchain technology plays a key role in the evolution of carbon credit markets. By bridging significant knowledge gaps, this research aids in the ongoing development of sustainable market mechanisms and provides practical solutions for policymakers, industry leaders, and environmental organizations. The findings create new opportunities for incorporating blockchain into global climate action initiatives, enhancing efforts to meet international emission reduction targets more effectively.

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