Decentralized Energy Trading and Carbon Credit Management: Leveraging Solana Blockchain for Smart Contracts

M. S. Minu[1*], Kaviya Senthil Kumar[2], Vedha Varshini T[3], Mary Keerthana[4] and Muthaiah Vijay M[5]
{msminu1990@gmail.com[1*], kavs2602@gmail.com[2], vt7959@gmail.com[3], kk1493@srmist.edu.in[4], muthaiahvijaym@gmail.com[5]}

Assistant Professor, Department of Computer Science & Engineering, SRM Institute of Science & Technology, Ramapuram, Chennai, Tamil Nadu, India[1]
Department of Computer Science & Engineering, SRM Institute of Science & Technology, Ramapuram, Chennai, Tamil Nadu, India[2, 3, 4, 5]

Abstract. Increasing greenhouse gas emissions has raised the concern of climatic change and a global crisis. This study inspects the innovation in building smart contracts using blockchain technology in a decentralized nature. By trading energy digitally, focusing on the transaction prices within carbon credit markets incentivize the buyers. Introducing this significantly decreases energy consumption. Engages with the distributed ledger system in energy trading and carries out financial transactions in the carbon credit management system. The creation of carbon credits is to eliminate the emission of greenhouse gases and additionally allow tradeability. By using solana as a platform carbon credits are tokenized as NFTs or solana tokens. This proposal permits individuals, business organizations and industries to invest in a cleaner nature. While this solution holds immense potential, several fundamental challenges, including additionality, fraud, and inconsistent standards must be tackled.

Keywords: Blockchain, carbon credit, decentralized, distributed ledger system, solana, NFTs, incentivize.

1 Introduction

The steady rise in carbon and greenhouse gas emissions has been a major factor in global warming. To address this growing issue, carbon credits have become an important tool in the fight against climate change. These credits essentially give companies permission to release a specific amount of carbon dioxide, usually one ton per credit which they can purchase to balance out their emissions. As carbon trading has grown, the quality of some credits has declined. Still, many industries continue to rely on these credits to support climate action goals. Businesses can buy, sell or trade to meet regulatory or voluntary emission targets. The idea of "carbon trading" originated from the Kyoto Protocol, which introduced cap-and-trade systems to control emissions globally. This paper uses blockchain technology with a distributed ledger in which all the transactions are controlled in a decentralized way.

This system eliminates the need for middlemen and makes the market consistent, transparent, and reliable. The organizational and cultural views of several systems are managed by blockchain technology in carbon credit management. Blockchain, which started with Bitcoin (2008), helped in improving carbon trading with smart contracts and secure digital records that are immutable. Carbon credits are tracked in real time by the companies using blockchain. This

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system allows companies, individuals, and also governments worldwide to take part in reducing carbon dioxide emission.

In recent years, carbon credits trading has gained considerable momentum globally as an essential market-based tool for reducing greenhouse gas emissions (GHGs), and in the Indian context, it serves as a crucial strategy for aligning with international climate commitments, particularly following the ratification of the Paris Agreement in 2016, which underscored India's commitment to lowering its carbon footprint by pledging to reduce the emissions intensity of its GDP by 33- 35% by 2030 from 2005 levels, a target that is achievable through the strategic implementation of carbon credits trading mechanisms.

Essentially allow entities to earn credits through projects that reduce carbon emissions or carbon dioxide in the atmosphere and subsequently trade these credits in the market, thus enabling a flexible and economically viable approach to achieving emission reduction targets, with India's significant potential for carbon credits and energy trading.

2 Literature Review

By offering a decentralized and transparent infrastructure, blockchain technology makes carbon trading compliant with the Kyoto Protocol possible. It facilitates the development of virtual power plants (VPPs), which enable direct participation by people as energy producers, when paired with energy trading systems.

Additionally, a number of environmentally friendly cryptocurrencies are being used to streamline the generation and delivery of renewable energy and enable carbon credit trades. Mohammad Parhamfar et al. [1] Correlating this, Zhang et al. [2] offered that it's critical to use more economical and sustainable blockchain technologies, especially those that use ecologically friendly consensus techniques like Proof administration and supervision duties to be designated "super nodes"—can improve the general security, and credibility of carbon trading systems enabled by blockchain technology.

Saraji et al. [3] The goal is to develop an ecosystem for carbon credit provided by Point of Stake (PoS), to lower operating costs and energy usage. By reducing latency and speeding up transactions, Layer 2 scaling solutions like zkSync Era may improve the carbon trading market's efficiency. Furthermore, implementing novel governance frameworks—like delegating contracts -- are integrated with blockchain technology, aiming to enhance transparency, accessibility, liquidity, and standardization to carbon markets. This ecosystem includes a tokenization framework for securely digitizing carbon credits, governed by well-defined minting and burning protocols. It also includes a transparent token distribution system, a decentralized automated market maker (AMM) for seamless trading of carbon tokens, and engagement with mechanisms which are designed to involve all relevant stakeholders—such as the energy sectors, project verifiers, liquidity providers, NGOs, citizens, and governmental bodies.

In a similar vein, Kolli et al. [4] suggested that blockchain, as a decentralized ledger technology, has the potential to revitalize the struggling carbon credit system. They proposed a novel blockchain-based peer-to-peer(P2P) trading platform for carbon allowances, which enables producers to actively participate in pricing decisions and supports a fairer and balanced distribution of energy resources. The P2P platform leverages blockchain technology, a decentralized digital ledger, to provide transparency and security in carbon emission tracking and energy transactions developed by Ameni et al. [5].

Centobelli et al. [6] proposed a system to bridge the three circular supply chain reverse processes and three factors affecting the blockchain; he proposed integrated triple retry for designing circular blockchain. Tian et al. [7] analyzed carbon offset projects targeting household and transportation emissions are increasingly being integrated with renewable energy systems through blockchain-enabled energy trading. Of all potential sectors, renewable energy and forestry are identified as the most viable domains for blockchain application, meeting essential quality benchmarks for impactful carbon offset initiatives.

Richardson et al. [8] and Xu et al. [8] presented a model for a permissioned blockchain implementation based on the successful European Union (EU) ETS and discussed its potential advantages over existing technology. Singh et al. [9] built a model that integrates the electric utility companies within the P2P trading framework, thereby increasing members trading options. Chen et al. [10] aimed at security architecture for blockchain based services and also proposed a formal expression of security issues and solutions for defense mechanisms from the perspective of full stack architecture. This concern for security and traceability is echoed by

Yang et al. [11], who advocated for a trusted blockchain system for product traceability, and showcase blockchain's capacity to enhance transparency and trust. Zhou et al. [12] Value Trading and Concept Disseminating. Nori, a decentralized voluntary carbon offset project. Jaffer et al. [13] developed an efficient digital methodology that combines remote sensing data, modern econometric techniques, and on-chain certification and trading to create a new digital carbon asset (the PACT stablecoin). Manjunatha et al. [14] focused on formalizing carbon trading in India by establishing a structured and efficient carbon credit market.

Yun-Cheng et al. [15] highlighted how blockchain-based methods can effectively prevent fraud and ensure adherence to global carbon trading regulations. Adam et al. [16] examined carbon markets to determine carbon pricing and promote the development of a fluid, low-cost, and adaptable market that facilitates carbon avoidance, reduction, or removal. Yuting Pan et al. [17] emphasized the parallels between blockchain technology and the carbon trading framework, proposing Ethereum-based solutions.

Derek et al. [18] offered an overview of the current landscape of tokenied carbon credits and the broader blockchain ecosystem surrounding them. According to, Sun et al. [19] his research shows that the emission reduction level of manufacturers increases, it contributes with the increase in carbon emission trading price, and the output of manufacturers increases with the increase in emission reduction level of manufacturers.

Merchant et al. [20] defines the role of growing carbon credit markets and understands the shortcoming of the existing system and uses smart contracts to overcome the issues in the existing system. Sabine et al. [21] addresses the common barriers faced by the developers that could allow more blockchain solutions and benefits of the technology.

3 Existing System

The traditional energy trading and carbon credit management systems operate on centralized authorities. These centralized platforms have limited transparency, inefficiency and limited access. In most cases they are burdened by high transaction fees, insufficiency of real-time data integration, they face risks of data manipulation, processing delays, and diminished trust. This happens especially in case of rural concerned entities and small-scale producers.

3.1 Challenges in Carbon Credit Systems

Carbon credits are there to lower the greenhouse gas emissions by allowing industries or organizations to trade. However, the entire process is not always straightforward. The major challenge lies in proving that a project helps to reduce real emission. The validation process can be slow, expensive and often needs expert involvement, which makes it hard for the smaller and local communities to initiate innovation. There is another issue of double counting where a single carbon is sold or claimed more than once. Due to this, it weakens the credibility of the system and reduces its world impact on the environment.

3.2 Transparency and Accessibility issues

There is a problem of accessibility too. There are platforms which cannot support instant trading, which leads to unpredictable credit prices. This volatility makes it difficult for the small players like individuals or small firms to compete with larger corporations having more resources. Transparency is a concern in the existing system. In systems controlled by central bodies, it is not always known how funds from carbon credit purchases are used or whether they genuinely support eco-friendly projects. Unfortunately, some companies appear environmentally responsible but do not make any meaningful changes in the technology. Without strict rules and clear tracking mechanisms, trust in the carbon market can quickly erode, undermining their role in tackling climate change. What's more, poor transparency and issues like double counting in current carbon credit systems reduce their quality of being accepted and weaken their environmental contributions.

3.3 Coordination and Data Fragmentation

Lack of coordination among key players in the energy sectors like producers, consumers, regulators and certification bodies often leads to fragmentation and poor data sharing across the system.

3.4 Blockchain-Based Solution

Addressing these challenges, blockchain offers a decentralized solution that builds trust without needing a central authority. With Solana's high-speed processing and low transaction fees, smart contracts can handle independent tasks such as energy trading, carbon credit issuance and rule enforcement. This reduces the need of third parties, lower risk of frauds and supports transparency, real time trading of energy and carbon assets.

3.5 Tokenization and Traceability

The system uses SPL tokens to represent renewable energy, making it traceable and enduring that once a token is used, it's permanently retired. It ensures there is no double counting during transactions

3.6 Integration with IoT and Real-Time Data

Internet of Things (IoT) devices - like smart meters and environmental sensors - can provide accurate, real-time data. This enables energy producers to sell surplus power directly to consumers, bypassing intermediaries. Similarly, blockchain - based issuance and monitoring of carbon credits ensures that every credit is unique and trackable. With the help of oracles, real - world data can be integrated into the blockchain, allowing automatic verification and updates. This model strengthens the role of local energy producers, encourages the use of clean energy, and builds a reliable and scalable system for carbon credit management. It promotes environmental responsibility while also improving access to energy markets, paving the way for a greener and more inclusive energy future.

4 Proposed System

The proposed system is aimed to encourage the use of a decentralized blockchain platform where energy producers can turn their surplus energy into digital tokens and sell them directly to consumers.

4.1 Carbon Credits as NFTs and Utility Tokens

Carbon credits are digitized– either as NFTs or utility tokens and their environmental contributions are verified automatically. Solana is chosen as the foundation for managing these transactions due its strong focus on speed and security. Using Solana's hybrid consensus model, the platform supports seamless trading of tokenized energy and carbon credits. Buyers and sellers can use stablecoins or Solana-based tokens to carry out the transactions.

4.2 Smart Contracts for Automated Market Matching

The smart contract is built in such a way that the producers and consumers connect automatically based on supply and demand. To participate, energy producers must first register and verify their identities. Once on board, buyers can place offers for tokenized energy, and smart contracts handle the exchange process securely.

4.3 Solana–Blockchain Technology

By integrating with established platforms like Solana, the system can also offer better liquidity, making it easier for users to convert their digital tokens into traditional currency. The payments are settled immediately via Solana Blockchain. The transactions are recorded on a tamper-proof decentralized ledger. Carbon credits are issued to corporations or organizations based on verified greenhouse gas or carbon emissions reduction. Firms reducing carbon emissions earn tokenized carbon credits. The smart contracts prevent double spending and false claims. Fraudulent transactions are reduced by using tokenized credits. Solana's high throughput (65000 TPS) ensures higher speed and lower transaction fees compared to Ethereum based-solutions. The aim is to have global acceptance and carbon neutrality.

4.4 Market Adoption, Education and Incentives

The proposed methodology is an encouragement for green energy adoption by means of direct trading marketplace eliminating proxies and manual intervention. A decentralized system can still be a new concept to many energy consumers and producers. They are not given proper knowledge about the system so they have interactive training sessions and trading. At the same time offering rewards or bonuses for early users can encourage more people to use and trust the system.

4.5 Regulatory Flexibility and Policy Alignment

To have varying regulations regarding decentralised energy trading and carbon credits in the absence of legal frameworks can create resistance from regulatory bodies, smart contracts are used for the flexibility in environmental policies, energy regulations, and carbon emission limits. There must be enough buyers and sellers to maintain market liquidity. If there are many participants for energy trading, they might suffer from price instability and low adoption.

4.6 Securing Market Liquidity and Viability

For futuristic thinking, taking accordance with key challenges for no hindrance and spreading knowledge about the Solana smart contracts to test and deploy it to run through live stats. The characteristics of leveraging Solana is for high transparency and high throughput. Acknowledging the resources for carbon credits and energy produced for trading and good cause. Therefore, the proposed system aims for the growth in the field of study of blockchain and smart contracts. Fig 1 shows the architecture diagram of the proposed system.

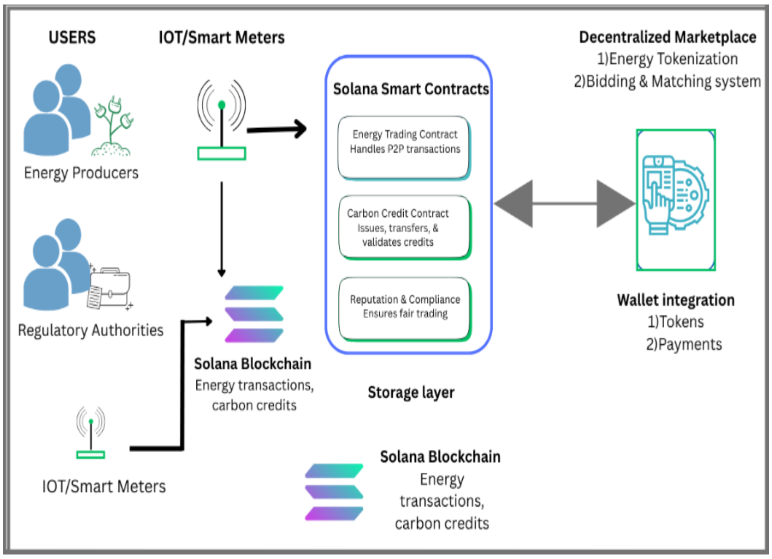

Fig.1. Architecture Diagram of the Proposed System.

5 Implementation

By describing the hardware, software, and architectural configuration required to enable a decentralized energy exchange and automated carbon credit management system utilizing the Solana blockchain and smart contracts, this section describes the algorithmic framework and evaluates the advantages and disadvantages of the suggested system.

To build a decentralized energy and carbon credit management system, both hardware and software must work together efficiently. No less than the hardware should include an Intel i5 or i7 processor. Developers prefer macOS because it enables quicker software builds. At least 8 GB of RAM is required, but 16 or 32 GB is ideal for blockchain simulation performance. For stable network performance, a minimum of 100 GB SSD storage and a stable, high speed internet connection—either via Ethernet or WIFI. To compile and deploy blockchain programs, the system makes use of Solana Command Line Interface (CLI). Smart contracts on Solana blockchain are developed using the Anchor framework and leveraging the Rust programming language. Package manager of Rust and Cargo are the core tools for development while Solana playground is used for testing and development. For data analysis and visualization, tools like Power BI are used.

The platform's fundamental component is an algorithmic based smart contract framework that automates key operations like carbon credit distribution and peer-to-peer energy exchanges. Credits are assigned under these agreements according to quantifiable environmental results, including carbon offset achievements or the amount of renewable energy generated. Prior to being published on the blockchain, every transaction is authenticated by means of embedded preconditions. Before transactions are recorded on the blockchain, they are validated according to defined rules.

The system is clear and open because it uses public records. It checks everything automatically with smart contracts. Blockchain makes it secured, and the information is immutable. Sending and receiving data is faster and cost efficient. The system includes features that prevent cheating or scams. It does the things automatically so people don’t have to sit and do them by hand. This saves money and time. This is seen by anyone around the world, so it automatically builds trust. Its design attracts more public users and meets government standards more easily.

The system has many benefits, but there are also challenges. Learning Rust and Solana tools can be hard and can feel overwhelming. Things like Anchor macros and account setups can be confusing. Testing smart contracts on blockchain is also a tricky one. Managing multiple addresses and seed-derived accounts adds complexity. Solana has strict rules for changes, so it is difficult to update the system. It has to manage the versions and redeploy the system. Using many addresses and label-based accounts makes things harder to manage. To get more people to use the system, we need to help them understand blockchain. This is especially true for energy producers who may not be familiar with blockchain technology. It can also be difficult to organize data from different energy sources. On top of that, linking this new system with current energy setups might not be easy. Furthermore, by offering concrete incentives (carbon credits) for the use of clean energy, the system promotes environmental sustainability and is readily expandable to areas with high penetration rates of renewable energy.

6 Methodology

The project leverages real-time energy inputs and Solana-based smart contracts to support decentralized energy exchange and automated carbon credit issuance. It offers a secure, transparent, and scalable solution that drives clean energy adoption and environmental integrity.

6.1 Data Collection and Acquisition

After energy and carbon credit data is collected, it goes through a process to make it clean, organized, and ready to be used on the blockchain. Firstly, we have to remove any incorrect values or missing information and arrange it in a logical format. For example, energy-related data is grouped based on production and consumption levels, whereas carbon credits are sorted by their owner and issuer. To help tracking every entry, timestamps are attached to each data point. Details about each user whether they are a consumer or producer are included. Once the data is checked for accuracy and completeness, it is sent to the Solana Blockchain. From there, smart contracts take over to handle the transactions in a secure and automated way.

6.2 Data Structuring and Utilization

After gathering the information or inputs from energy producers and carbon credit platforms, the system double checks everything to make sure all the data is clean and usable. This includes spotting any errors, reformatting any inconsistent errors and sorting details like how much energy was produced or used, who the users are, and who owns which credits. Each entry is timestamped to record when it was collected. The system verifies the integrity of the data before it interacts with the blockchain. By following these methods, we ensure the smart contracts on Solana receive clean and reliable inputs, which helps the whole platform to work efficiently without any confusion.

6.3 Transaction Management using Solana Smart Contracts

Smart contracts are designed to trigger the creation of carbon credits once certain environmental targets are met like a verified drop in emissions. This helps to ensure that only legitimate, meaning actions result in new credits, strengthening the credibility of the platform. The contracts allow for smooth trading of both energy tokens and carbon credits between users in a secure, decentralized way. It's quicker, more affordable and the process doesn't need a middleman. All transactions are stored permanently, therefore no tampering.

6.4 Reporting and Analytics

This module helps everyone to be involved—users, developers and regulators to see what's happening in real time. It keeps track of how energy is being used, how credits are issued and traded, and the overall progress in reducing carbon emission. To make sense of the data, tools like Chart.js, Power BI, or D3.js are used to turn it into simple visualization like graphs or charts. Here, we have used Power BI for visualization to help users understand trends.

6.5 Testing, Deployment, and Optimization

Before going live, everything is first tested on Solana's developer environment like Solana playground. It is a safe zone where developers can try things out without risking real assets. During this phase, each smart contract is thoroughly checked, both on its own and the rest of the system. This helps identify any delays or performance issues. In addition, security tests are run to look for possible bugs or weak points that could be exploited. The smart contracts are improved to make them faster and cheaper to run. All of this testing helps ensure the system is safe, fast, and ready to be used in the real world.

7 Results and Discussion

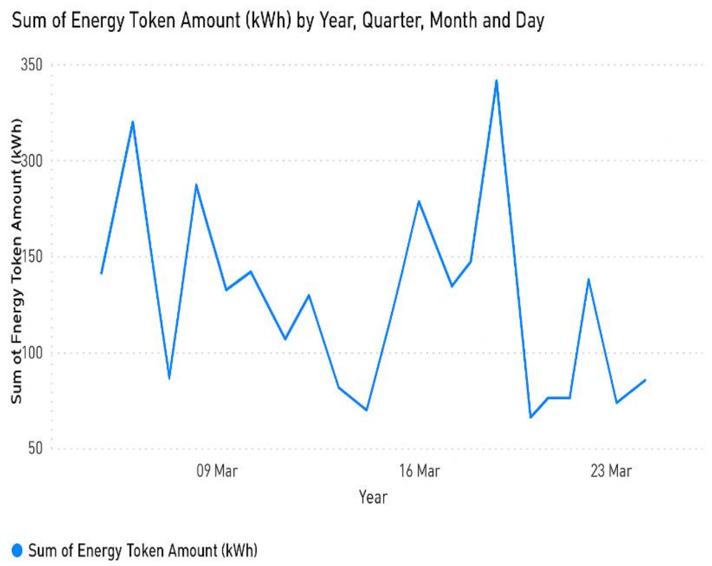

Fig. 2. Energy Trading Insights Total Energy Traded (KWh).

Fig.2 depicts the energy trading dashboard illustrates the total energy traded in kilowatt-hours (KWh), reflecting active participation in the decentralized market. The line chart reveals an upward trend in transitions, with peaks aligning with periods of high renewable generation. These insights highlight the system’s efficiency in enabling transparent, real-time energy trading on the Solana blockchain.

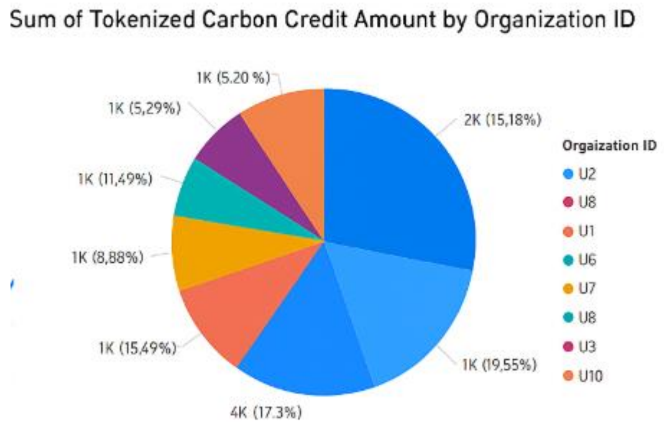

Fig. 3. Carbon Credit Management Total Carbon Emission Reduced (pie chart).

Fig.3 depicts the total carbon emissions reduced, quantified in metric tons, indicating the environmental impact achieved through the platform. The pie chart displays the distribution of carbon credit issuance across different organizations, revealing the varying levels of participation and contribution to emission reduction efforts.

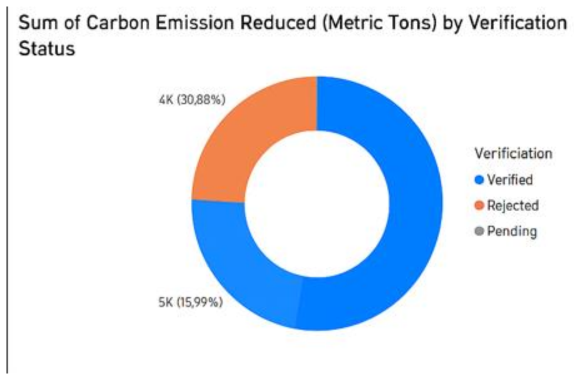

Fig. 4. Carbon Credit Management Total Carbon Emission Reduced (donut chart).

Fig. 4 provides a breakdown of verification statuses, showing the proportion of verified, pending, and rejected credits. Together, these visualizations demonstrate the system's ability to tokenize, allocate, and transparently track carbon credits, while ensuring accountability through verifier-led validation on the Solana blockchain.

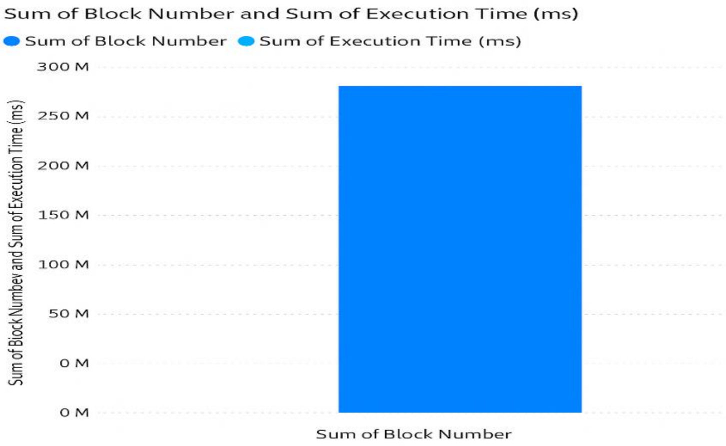

Fig. 5. Blockchain Performance Transaction.

Fig.5 depicts the column chart illustrates transaction execution times across block numbers, with most blocks showing low latency, demonstrating Solana's high-speed processing capabilities ideal for real-time carbon and energy transactions.

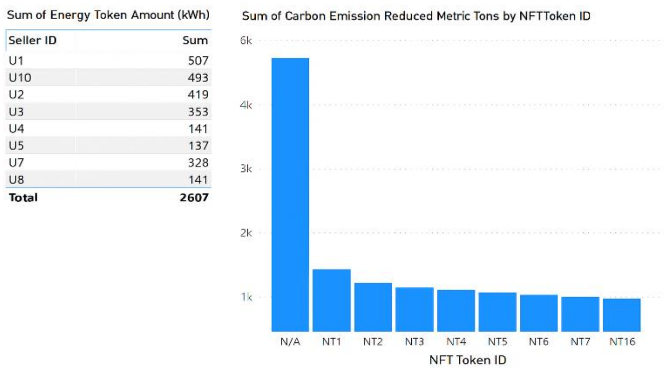

Fig. 6. Carbon emission reduced by NFT Token.

Fig.6 depicts the column chart illustrating the sum of carbon emission reduced metric tons by NFT Token ID.

8 Conclusion

This project effectively illustrates the viability and benefits of utilizing the blockchain, more especially the Solana ecosystem, to create a decentralized platform that enables transparent carbon credit management and peer-to-peer energy trading. This system creates a secure, scalable and transparent energy marketplace by bringing together real-time data from IoT sensors, automated validation through smart contracts, and rewards in the form of digital tokens for those who engage in eco-friendly practices. With smart contracts running on Solana, energy data can be recorded quickly and securely, ensuring accuracy without the risk of tampering. Users who contribute to renewable energy generation are automatically awarded carbon credits based on their impact, making the process both fair and efficient. Looking ahead, the model has the potential to grow by including sustainability initiatives, connecting with national energy grids, supporting NFTs as proof of carbon offsets, and allowing for cross-blockchain compatibility. As the climate crisis continues to be a global concern, decentralized solutions like this one pave the way for a cleaner, more inclusive, and community - driven energy landscape.

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