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Green Gauge-Decentralized Carbon Accounting: A Blockchain-Based Framework for Transparent and Scalable Emission Tracking

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ABSTRACT

Day after day, climate change intensifies, necessitating tracking solutions for carbon emissions that offer transparent operations and efficiency, alongside scalability and sustainable behavioural incentives. The proposition to track carbon emissions is not new, yet standard tracking systems present multiple deficiencies, including double reporting, fraud, high operational costs, and constrained access for small organisations. We have developed a blockchain system that follows a framework to track both carbon emissions and trading activities, using smart contracts and decentralised ledger technologies to establish security, trust, and automation. Our system requires IoT sensor integration and AI analytics to enable continuous monitoring and safe storage, along with direct carbon trading without third-party involvement. The proposed framework addresses blockchain energy consumption issues by examining Proof of Stake (PoS) and hybrid consensus models. The model presented facilitates a massive reduction in carbon emissions and enhances transparency and efficiency.

Keywords: *Blockchain, Carbon Emissions, Climate Change, Decentralization, Smart Contracts, Carbon Credit Markets*

1. Introduction

The rapid pace of industrial development and urbanization in present times leads to exponential energy consumption that actively generates two significant environmental problems: higher carbon emissions and climate impacts. Sustainable development, along with effective monitoring of energy usage and carbon emissions offset, requires immediate attention during this critical period, which affects the global community [1]. Early defect predictions and optimisation methods create the conditions for dependable software in sustainability applications, as in Green Gauge [2].

A transformation is currently reshaping the energy industry that produces major greenhouse gas emissions due to technological developments, regulatory requirements, and increased public environmental awareness. The combination of renewable energy policies worldwide, reduced renewable technology costs, and rising usage of environmental power in heating and transport systems will drive a projected 60% rise in renewable power consumption between 2024 and 2030.

The web application GreenGauge supports blockchain technology to let users check power usage instantly and discover abnormal usage patterns while helping them operate carbon reduction initiatives by maximizing efficiency. GreenGauge, along with other sustainable systems, can operate at superior speed and precision by adopting deep spectral-spatial learning and innovative combination techniques [3]. GreenGauge implements Polygon Chain technology to provide tamper-resistant, secure management of its energy consumption data. Users obtain real-time dashboard insights from the system that help them select sustainable energy options to operate more efficiently.

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2. Problem Statement

The deployment of renewable energy systems alongside carbon-reduction methods does not provide effective solutions to current energy management challenges and carbon balance issues. Ensuring robust security in sustainability-driven platforms like GreenGauge is challenging, as cloud-based systems are vulnerable and require intelligent intrusion detection mechanisms [4]. Traditional approaches to energy consumption management face difficulties because non-transparent systems lack real-time tracking and issue insufficient alarms. When operational data cannot be accessed in real time, potential business opportunities to boost energy efficiency and reduce emissions lose their value.

Many organizations face crucial difficulties with the demanding method needed to establish carbon footprints. Various non-standard approaches to environmental assessment lead to errors and irregularities due to a lack of unified standards. Climate reduction goals become challenging to prove for organizations since carbon offset programs struggle with confirmation methods and reliability testing [5], [6].

The existing framework for renewable energy subsidy distribution creates substantial operational difficulties due to system composition issues that result in poor performance, a lack of transparency for real-time monitoring, and deficient alert modules, making it difficult for individual users and commercial operators to manage their energy consumption effectively. Quick feedback responses to absence triggers prompt businesses to miss multiple opportunities to control energy usage and reduce emissions.

Annual CO_2 emissions, which are eventually used to calculate carbon footprints, pose a significant obstacle to the evaluation path. Multiple errors happen in environmental impact assessments since current evaluation methods are inconsistent. Organizations dealing with transportation face difficulties proving their carbon reduction initiatives because of issues Carbon offset programs experience when establishing credible and verified programs.

The annual CO_2 emissions from fossil fuels and industry worldwide are shown in Figure 1, spanning 2000 to 2023. Public records show a continuous rise in emissions, exceeding 35 billion metric tons in recent years, despite minor interruptions. The development shows that reducing global carbon emissions remains difficult despite increased awareness of sustainability and related efforts.

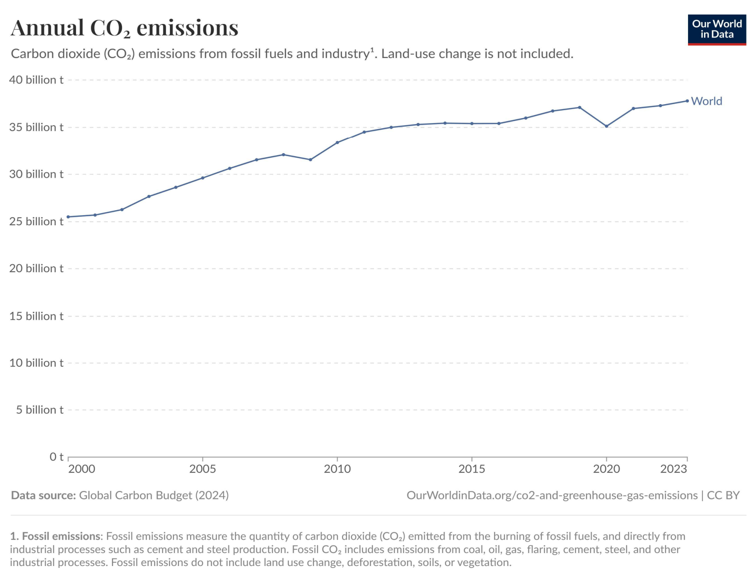

Figure 1: Annual Carbon Emission from 2000 to 2023 showing a continuous rise in global emissions.

3. Literature Review

Maria-Victoria Vladucu and a group of researchers authored a 2022 review article on blockchain-based environmental sustainability monitoring. The research paper outlined the main aspects of blockchain technology implementation, including incentives, essential features, and supporting systems. The authors indicate that future research should address the persistent issues of scalability, data protection, and privacy concerns [7].

The paper by Felix Thalhammer et al. (2021) examined the research paper, outlining the main aspects of blockchain technology implementation, including incentives, essential features, and supporting systems. The authors indicate that future research should address the persistent issues of scalability, data protection, and privacy concerns [8].

The authors Lanxin Jiang, together with colleagues (2023), developed the GETS system that integrates blockchain with IoT and LCA to produce transparent climate disclosure solutions while maintaining accuracy. The GETS model succeeded in improving both the accuracy and speed of climate reports so multiple stakeholders benefited from its implementation. Active involvement from participating companies represents a main challenge for the system to meet its success objectives [9], [10].

The research paper "A New Platform Based on Various Sensors Offers Smart Contracts to Reduce Carbon Emissions" by Ibrahim Abaker et al. (2020) examined blockchain technology as a tool for enhancing carbon trading. Based on its transparent, decentralised model, the authors proposed blockchain as a solution to remove intermediaries, thereby accelerating operations. Although smart contracts enabled automated carbon trading, the research did not identify effective solutions to regulatory obstacles [11].

Akiladevi R. (2022) presented tokenisation strategies for renewable energy assets through his paper "Tokenisation of Energy Assets: A Multichain Blockchain Approach", which utilised a multichain blockchain system. By using tokenization the study showed that transparency levels rose and energy sector investments increased [12]. In the discussion, the author addressed complex technical requirements and regulatory uncertainties, both of which present substantial obstacles.

"The Carboncoin: Blockchain Tokenisation of Carbon Emissions with ESG-Based Reputation" system was developed by Oscar Golding with his team in 2023. An approach was recommended to collect ESG data to derive market participant reputation scores while creating a decentralised carbon trading system without a centralised permission system. This system offers greater transparency, yet incorporating on-chain assets and ESG data negatively impacts overall system performance [13].

A blockchain-powered platform for carbon credit exchange was proposed in "A Blockchain-based Carbon Credit Ecosystem" by Soheil Saraji et al. (2021) to address problems in carbon credit markets. Blockchains enable improvements in liquidity and transparency while ensuring standardisation within carbon markets, according to research findings. The current carbon credit system faces two main limitations involving over-crediting and expensive transactions that require additional development work [14].

Eduard Romulus Goean, along with his colleagues, presented "Using the Blockchain to Reduce Carbon Emissions in the Visitor Economy" in their paper introducing the Carbon Tokenomics Model (CTM) in 2024. Tourism decarbonization strategies find support through blockchain-enabled decentralised carbon credit systems provided by the model. A delegated Proof of Commitment consensus mechanism was introduced in the paper to improve the credibility of investments within climate finance. The research recognized widespread adoption as the main barrier [15].

4. Technical Definitions

4.1 Blockchain Technology Overview

Blockchain: a decentralised ledger system that maintains records of transactions across different nodes through a secure, transparent mechanism [16], [17]. Decentralised ledgers operate independently of centralised control, so no single entity maintains control over them.

How Blockchain Ensures Transparency and Security: The open examination of transactions is possible through blockchain because it keeps an immutable record accessible to all participants. The system's security bases on cryptographic methods together with distributed architecture and consensus protocols that stop unauthorized data manipulation. Blockchain technology functions best as a tool for monitoring ESG (Environmental, Social, and Governance) information, as it provides reliable sustainability reporting [13].

Smart Contracts and Their Role in Automating Transactions: Self-executing business agreements operate as code-based implementations that execute predefined terms automatically. The removal of intermediaries results in lower overall costs and accelerated performance of carbon trading operations and emissions monitoring.

Consensus Mechanisms: Consensus mechanisms validate and secure blockchain transactions. The most common types include:

- **Proof of Work (PoW)** – Requires computational effort to validate transactions (e.g., Bitcoin).
- **Proof of Stake (PoS)** – In order to save energy, validators are chosen according to the quantity of cryptocurrency they stake [21].
- **Delegated Proof of Stake (DPoS)** – Uses elected validators to approve transactions, improving scalability and efficiency [21].

4.2 Carbon Emissions and Climate Change

Definition of Carbon Emissions: People produce carbon emissions when they discharge carbon dioxide alongside greenhouse gases (GHGs) due to human-caused activities. A carbon footprint is the total of greenhouse gases emitted by any individual, entity, or product [17].

Sources of Greenhouse Gas Emissions: Major sources of GHG emissions include:

- **Energy Production** – Burning coal, oil, and natural gas for electricity and heat.
- **Transportation** – Emissions from vehicles, airplanes, and ships.
- **Industrial Processes** – Manufacturing cement, steel, and chemicals.
- **Agriculture and Land Use** – Livestock farming, deforestation, and soil degradation.

5. Research Methodology

A blockchain-based system increases carbon-tracing transparency by implementing dynamic data capture technology alongside automatic carbon credit allocation and secure transaction validation.

5.1 System Architecture

The system consists of:

- **Web Interface** – A dashboard for real-time carbon footprint visualization.
- **Backend & Database** – The system backend together with its database component processes IoT sensors' data as well as user transaction details.
- **Blockchain Layer** – The Polygon (Layer 2 Blockchain) runs smart contracts for conducting both carbon credit distribution and transaction verification operations.

5.2 Implementation Approach

Initialisation & Authentication: The system configures and sets blockchain parameters during user registration.

Real-Time Data Collection & Alerts: IoT sensors monitor energy consumption by saving data securely on the blockchain in an immutable method. Through the implementation of smart contracts the system automatically sends notifications when energy consumption exceeds specified thresholds.

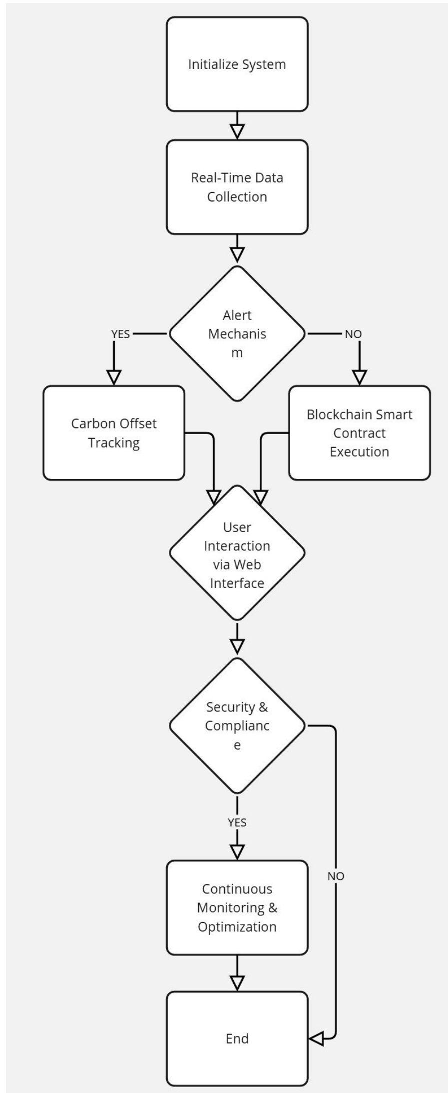

Figure 2: Flowchart of the proposed blockchain-based carbon accounting system showing data flow and process steps.

Carbon Offset Tracking: The system determines carbon footprint by measuring renewable energy consumption to assign carbon credits. Blockchain ensures secure, transparent transactions.

6. Results and Discussion

Blockchain systems serve as an inclusive framework to monitor and cut down carbon emissions through their implementation of decentralized structures alongside transparent interfaces and strong security measures and automatic functionalities and motivational schemes.

Figure 3 depicts the Green Gauge web application which serves as an interface to monitor and han- dle energy usage along with carbon emissions. The homepage displays platform introduction alongside a promotional message followed by an energy consumption and carbon offset trends depiction through dynamic graphical representations. Through its profile section the application presents crucial sustain- ability information that includes both most effective consumption times and major warning signs which help users correct their usage.

Figure 3: Green Gauge Web Application Interface showing dashboard, energy consumption trends, and carbon offset tracking features.

The proposed blockchain system will generate transparent trustworthy carbon tracking through its unalterable verified records. The approach will establish distributed control and data protection which stops digital alterations. Smart contracts enable automatic process handling through the system which enhances operational effectiveness and decreases human involvement. The ability to scale will enable more stakeholders to join carbon markets through wider market accessibility.

7. Conclusions

The proposed blockchain-based carbon accounting framework addresses critical challenges in emission tracking through decentralization, transparency, and automation. By integrating IoT sensors and smart contracts, the system enables real-time monitoring, secure data storage, and direct carbon trading with- out intermediaries. The use of energy-efficient consensus mechanisms like Proof of Stake mitigates blockchain's environmental impact while maintaining security and scalability. Future development will concentrate on enhancing blockchain speed through optimization and AI data analysis features as well as standard compliance to increase global market adoption. Through this system the public gains an efficient approach and reliable access to combat climate change together with business and individual opportunities to perform meaningful climate action. The platform aims to democratize carbon markets and incentivize sustainable behavior at scale. The main strength of this work lies in its practical in- tegration of blockchain technology with IoT sensors for real-time emission tracking, while limitations include the need for broader stakeholder adoption and regulatory framework alignment. Future research should focus on cross-border carbon credit interoperability and integration with existing international climate reporting standards to maximize global impact.

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Conflict of Interest

The authors declare no conflict of interest.

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