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A Hybrid Blockchain Solution for Electric Vehicle Energy Trading: Balancing Proof of Work and Proof of Stake

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Abstract: This research presents an innovative blockchain-based solution for the charging and energy trading of electric vehicles (EVs). By combining the strengths of two prominent consensus mechanisms, Proof of Work (PoW) and Proof of Stake (PoS), the proposed system balances security, decentralization, and energy efficiency. PoW secures the blockchain, while PoS enhances energy efficiency and scalability, key factors in meeting the growing demand for EV infrastructure. The system's decentralized nature allows for EV owners, charging stations, and stakeholders to interact and transact transparently, without relying on centralized entities. The research conducts a comprehensive simulation to assess the performance of the proposed hybrid blockchain model, demonstrating significant improvements in cost-effectiveness, scalability, and energy management. Additionally, dynamic pricing mechanisms within the blockchain enable real-time energy trading, optimizing charging times and balancing grid demand efficiently. Through the use of smart contracts, automated pricing adjustments, and incentive-driven user behaviors, the proposed system paves the way for more sustainable, cost-effective, and efficient energy solutions in the future.

Keywords: blockchain; Proof of Work; Proof of Stake; energy trading; electric vehicle charging; dynamic pricing; decentralized networks; smart grid; electric vehicle infrastructure

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1. Introduction

1.1. Background and Motivation

The rapid proliferation of electric vehicles (EVs) as a cornerstone of sustainable transportation has catalyzed transformative changes in energy systems, driven by the need for efficient, secure, and decentralized energy trading mechanisms [1,2]. In the past, several approaches to electric vehicle (EV) energy trading have explored distinct advantages and limitations. Traditional energy trading systems centralize models in which utility companies determine energy prices [3]. These systems typically involve purchasing energy from a central utility provider [4], leading to inefficiencies, high transaction costs, and a lack of transparency [5]. Smart grid systems centralize solutions that employ digital technology to optimize electricity distribution across the grid [6]. These systems aim to balance supply and demand while integrating renewable energy sources [7]. However, smart grids still rely on central authorities to manage energy distribution, introduce potential points of failure, reduce transparency, and prove inefficient in matching local demand with available supply in real-time.

With global EV adoption projected to reach 230 million units by 2030 [8], the integration of EVs into smart grids and peer-to-peer (P2P) energy markets [9] has emerged as a critical research area. This growth rests on the "3Ds", Decarbonization, Decentralization, and

Digitalization [10], which necessitate innovative frameworks to manage energy transactions between EVs, charging stations, and renewable energy sources [11]. Blockchain technology, with its decentralized ledger capabilities, emerges as a promising solution for ensuring transparency, security, and trust in transactions, particularly through the use of smart contracts, self-executing agreements encoded directly on the blockchain [12,13].

Therefore, blockchain serves as an ideal tool to achieve the key objectives of EV smart energy trading systems, including cost reduction through optimized energy processes, enhanced energy security, and improved sustainability and energy efficiency [14]. However, the choice of consensus mechanisms, such as Proof of Work (PoW) and Proof of Stake (PoS), significantly influences the scalability, energy efficiency, and security of blockchain-based energy trading systems [15]. This research proposes a hybrid blockchain framework that synergistically combines PoW and PoS with smart contracts to optimize EV energy trading, addressing the limitations of standalone consensus protocols while enhancing system performance.

1.2. Literature Review

The application of blockchain in energy trading, particularly for electric vehicles (EVs), has been extensively explored in the recent literature [15–17], reflecting its potential to revolutionize energy markets. Blockchain's decentralized nature eliminates reliance on centralized intermediaries, reducing transaction costs and enhancing trust among untrustworthy parties, such as EV owners and energy providers [18]. A systematic review by [19] highlighted over 390 blockchain initiatives in the energy sector, with a significant focus on peer-to-peer (P2P) energy trading and EV charging. More recently, [11] surveyed blockchain-enabled energy trading between EVs and smart grids in Internet of Things (IoT) environments, emphasizing the role of consensus protocols like PoW and PoS in ensuring ledger consistency. They noted that while PoW, pioneered by Bitcoin [20], offers robust security through computational effort, its energy-intensive nature, estimated at 127 TWh annually for Bitcoin alone, poses sustainability challenges incompatible with the decarbonization goals of EV ecosystems [21].

In contrast, PoS, adopted by Ethereum in its 2022 Merge [22], reduces energy consumption by replacing computational work with economic staking, where validators stake cryptocurrency to participate in block validation. Ref. [23] demonstrated that PoS-based blockchain systems could achieve up to 99% lower energy usage compared to PoW, making it an attractive option for energy-conscious applications like EV trading. However, PoS introduces vulnerabilities, such as the "nothing-at-stake" problem, where validators might support multiple blockchain forks without penalty, potentially compromising security [24]. These trade-offs have spurred interest in hybrid consensus models that combine the strengths of PoW and PoS to balance security, efficiency, and scalability [25], particularly in contexts requiring both high trust and operational efficiency, such as EV energy trading [26,27].

The concept of hybrid blockchain structures, integrating multiple consensus mechanisms, has gained traction as a solution to the limitations of standalone PoW and PoS systems [23]. Early explorations, such as [28], proposed combining PoW and PoS to enhance security in cryptocurrency networks, introducing the notion of "Proof of Activity" (PoA), which alternates between mining and staking phases, the same as ref [29], who proposed a PoA consensus model social networks application. This foundational work laid the groundwork for more sophisticated hybrid designs tailored to specific use cases. Ref. [30] advanced this paradigm with their PSC-BChain model, a hybrid of Proof of Credibility (PoC) and PoS, applied to secure e-voting systems. By integrating sharding with a hybrid consensus, we can achieve up to a throughput of 300 transactions per second (TPS), a 240%

improvement over traditional PoW systems [23], demonstrating the scalability potential of hybrid architectures.

In the energy domain, hybrid blockchain models have begun to address the unique demands of decentralized markets. Ref. [31] introduced a fork-free hybrid consensus combining PoS with PoA, targeting blockchain networks for IoT applications. Their system helps to reduce fork occurrences compared to pure PoS, offering insights into maintaining ledger consistency in dynamic environments like EV trading. More recently, Ref. [32] proposed a dual-blockchain system for EV charging coordination, integrating a public PoW-based chain for secure identity management with a private proof of node rank (PoNR)-based chain for selecting miners and creating blocks. Their hybrid approach achieved an 89.23% reduction in energy price compared to standalone PoW systems, highlighting the synergy of combining PoW's robustness with PoNR's efficiency. However, their reliance on complex interoperability protocols introduced latency overheads, a challenge this research seeks to mitigate.

In the specific context of EV energy trading, while much work has been conducted using either PoW or PoS blockchain models [33,34], PoW–PoS-based hybrid blockchain structures remain underexplored but show significant promise. Ref. [35] implemented a PoAh (Proof of Authority Hybrid) consensus mechanism that combines elements of Proof of Authority (PoA) and Proof of Work (PoW). It prioritizes performance and governance by enabling a select group of authorized nodes to validate transactions, ensuring faster processing while maintaining decentralization and security. While PoAh harnesses the strengths of both PoA and PoW, providing a practical solution for blockchain networks that demand high throughput and strong governance mechanisms, the proposed model lacks the integration of energy-efficient consensus mechanisms like PoS, which are crucial for EV energy trading applications. Ref. [36] proposed a new consensus protocol based on device online duration, called Proof of Online Duration (PoD). PoD can significantly enhance transaction verification efficiency and reduce resource consumption. The results show that PoD outperforms both PoW and PoS, with a memory consumption of only 0.43 MB, compared to 16.2 MB for PoW and 1.87 MB for PoS; however, this approach has security and scalability issues, as PoD might be more vulnerable to attacks that target the availability of devices, and, as the number of devices in the network grows, managing and verifying the online duration of each device can become more complex.

Smart contracts play a pivotal role in enhancing blockchain functionality, particularly in energy trading [37,38]. Ref. [39] investigates the integration of blockchain smart contracts technology into smart grids, focusing on optimizing both electrical billing and peer-to-peer energy trading between producers and consumers. While the integration of the proposed smart contract blockchain reduces the need for intermediaries, lowers transaction costs, and ensures the immutability and transparency of records, contributing to a more efficient and secure energy management framework, the design shows a key blockchain challenge such as scalability. Another recent work [40] proposed a blockchain-based smart contract system for decentralized Vehicle-to-Grid (V2G) load management. While the simulation results demonstrate that the system effectively manages varying grid demands while maintaining operational efficiency, the proposed model also highlights the scalability limitations of public blockchains.

Despite these advancements, hybrid blockchain structures for EV energy trading face several unresolved challenges. First, the energy efficiency of PoW conflicts with EV sustainability goals, while PoS's security limitations hinder its standalone adoption. And second, the integration of smart contracts with hybrid consensus remains still underexplored.

This work builds on these foundations, proposing a hybrid PoW–PoS blockchain with smart contracts tailored for EV energy trading. By leveraging PoW's security for critical

operations and PoS's efficiency for routine trades, augmented by optimized smart contract execution, the framework aims to overcome the scalability and energy efficiency challenges identified in the literature, offering a robust solution for decentralized EV energy markets.

1.3. Objectives and Structure

The primary objective of this research is to design and evaluate a hybrid blockchain system that optimizes EV energy trading by combining the complementary strengths of PoW and PoS, enhanced by smart contracts. This approach aims to improve key aspects of energy trading, including transaction throughput, scalability, energy consumption, and security. Specific goals of the study include enhancing transaction speed, minimizing energy costs, and safeguarding the system against common blockchain vulnerabilities such as 51% attacks. The proposed hybrid model seeks to balance security, scalability, and sustainability, providing an efficient and secure platform for EV energy trading applications.

The paper is organized as follows: Section 2 presents the proposed methodology, which covers the design of the hybrid consensus mechanism, and the implementation of smart contracts tailored for the energy trading system. In Section 3, we showcase the simulation results, followed by a comprehensive discussion of the findings. Section 4 explores the opportunities and challenges presented by the hybrid blockchain model, addressing potential limitations and areas for further development. Finally, Section 5 concludes with a summary of the research, its implications for the future of blockchain-based energy trading, and suggestions for future research directions.

2. Methodology

This research aims to design a hybrid PoW–PoS blockchain system to optimize decentralized energy trading in EV charging networks, addressing issues of high energy consumption, stake concentration, and scalability. This study evaluates the system's performance in terms of energy efficiency, security, and scalability compared to existing models in the literature. The methodology involves selecting and designing the blockchain technology, designing the smart contract and simulating the system using MATLAB R2024a. Performance metrics, including energy consumption, transaction costs, and scalability, will be evaluated through simulations. The results will offer insights into the potential of hybrid blockchain systems for EV energy trading. Figure 1 represents the overall process of defining, simulating, and analyzing the blockchain models to assess the hybrid PoW–PoS model's performance.

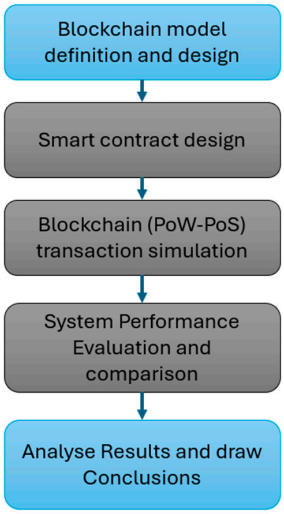


Figure 1. Flowchart representing the general research algorithm.

2.1. Selection of Blockchain Technology

Blockchain, while powerful and flexible, does not offer a one-size-fits-all solution to every problem. It is essential to select the most appropriate blockchain for the specific issue at hand, adapting it as needed [41]. Accordingly, the following factors must be carefully considered when determining a suitable blockchain implementation: consensus mechanism, speed, permission model, and resilience, as stated in [42]. In this work, we aim to design a blockchain-enabled energy exchange framework suitable for EV charging technology. Consequently, we introduce additional equilibrium criteria for selecting the ideal blockchain technology [41]:

- **Security**: This includes data integrity, ensuring transactions cannot be altered, and confidentiality through encryption to protect user privacy. It also involves resistance to attacks, such as Sybil and 51% attacks [43], and ensuring that consensus mechanisms are secure.
- **Scalability**: Scalability measures the blockchain's ability to accommodate an increasing number of participants (i.e., EVs) and transactions (i.e., charging process). Specifically, this includes the speed at which consensus is achieved among nodes, the rate at which new transactions are added to blocks, and the overall transactions per second the system can handle.
- **Sustainability** refers to the long-term viability of the blockchain system, ensuring it can maintain performance and security while minimizing environmental and resource impacts. This involves optimizing energy consumption, energy efficiency, supporting scalable growth, and using eco-friendly consensus mechanisms for carbon footprint reduction.

To design our blockchain model for EV energy trading application, we present a comparative analysis of the most popular consensus mechanism in blockchain, i.e., PoW and PoS. Table 1 reveals that PoW provides the highest security, owing to its resilience against attacks like the 51% attack, as it demands immense computational resources to breach the network. However, this strength comes at the cost of excessive energy consumption, making PoW the least favorable in terms of sustainability. Additionally, its design presents scalability issues, limiting the number of transactions it can process per second. In contrast, PoS offers robust security, although its strength is tied to the number of tokens held by validator nodes. PoS enhances scalability by supporting more transactions per block and significantly reduces energy consumption, making it a more sustainable option, as it does not rely heavily on hardware [23].

Table 1. Comparison of equilibrium criteria.

Consensus Algorithm	Security	Scalability	Sustainability
Proof of Work (PoW)	Very High	Low	Low
Proof of Stake (PoS)	High	Medium	High

Table 2 illustrates that PoW exhibits the highest energy consumption, reaching 707.6 kWh per transaction. In contrast, PoS demonstrates remarkable efficiency, with energy consumption not exceeding 0.002 kWh. This stark difference underscores PoW's high computational demands, as it requires substantial processing power to solve cryptographic puzzles for block validation [23].

As our work aims to achieve a balance between security, scalability, and sustainability, adopting a hybrid PoW–PoS algorithm appears to be the optimal solution for EV energy trading applications. This hybrid approach balances security by utilizing PoW for initial validation and PoS for final confirmation, offering a high level of security, albeit slightly

lower than PoW alone. It provides a balanced compromise, improving scalability over PoW, while also reducing energy consumption, thus offering a better balance between security and sustainability. In addition, hybrid algorithms (PoW–PoS) are more energy-efficient than PoW [23]. Focusing on high security, scalability, and energy efficiency for EV energy trading scenarios, we concluded that the hybrid PoW–PoS algorithm is the most appropriate choice.

Table 2. Energy consumption per transaction (kWh).

Algorithm	Energy per Transaction (KWh)
Proof of Work (PoW)	707.6
Proof of Stake (PoS)	0.002

2.2. Blockchain System Architecture:

This section describes the design and implementation of a blockchain-based energy trading system tailored for electric vehicles (EVs). The system architecture, stakeholder, the blockchain model integration using hybrid Proof of Work (PoW) and Proof of Stake (PoS) consensus mechanisms, and energy trading process have been breaking down. This methodology lays the foundation for understanding how the system operates and interacts with participants in the energy trading network. The proposed energy trading system leverages blockchain technology to facilitate peer-to-peer energy exchanges between electric vehicles (EVs) and charging stations. The system aims to create a decentralized, transparent, and efficient platform for trading energy. The architecture is designed to handle a range of functionalities, including energy transactions, monitoring, pricing, and validation, all while ensuring the security and privacy of all involved parties.

The system architecture includes the following:

1. Decentralized network: A blockchain-based network where EVs, charging stations, and other participants (e.g., validators) are distributed across different locations.
2. Smart contracts: These automate the energy trading process, including dynamic pricing, transactions, and incentives.
3. Consensus mechanisms: The blockchain employs either PoW or PoS to validate transactions and secure the integrity of the energy trading process.

The architecture of the system can be illustrated as follows (Figure 2):

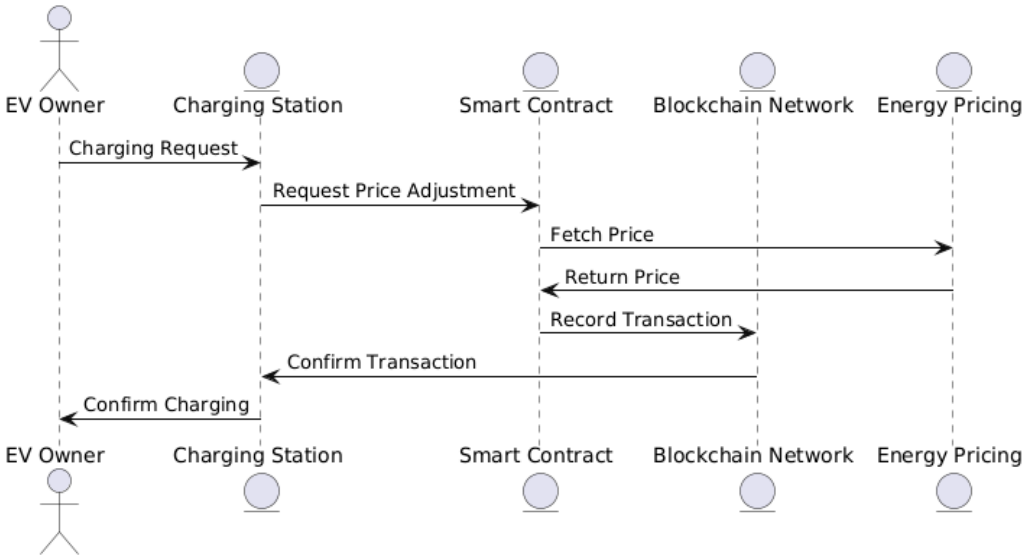


Figure 2. Architecture of blockchain-based EV charging network.

This diagram illustrates the integration of blockchain technology within electric vehicle (EV) charging networks. The process begins when the EV owner requests to charge their vehicle and takes responsibility for initiating the transaction. Upon receiving the request, the charging station verifies its validity, confirms the EV's eligibility for charging, and proceeds with providing the necessary energy. The transaction is subsequently validated, and the blockchain network records essential data, including transaction details, pricing, and incentives. Smart contracts autonomously adjust pricing based on factors such as demand and Time-of-Use, in alignment with dynamic energy pricing models that reflect real-time grid demand and predefined pricing rules (e.g., Time-of-Use and Real-Time Pricing). The final step involves logging the transaction onto the blockchain, allowing for the EV owner to charge their vehicle.

2.2.1. Stakeholder Setup

In an advanced EV charging network, various stakeholders collaborate to ensure efficient energy exchange and optimal system functioning. EV owners, acting as both consumers and potential producers of energy, are responsible for initiating transactions to either purchase or sell energy. They engage in dynamic pricing schemes and are incentivized to charge their vehicles during off-peak hours, while maintaining digital wallets to facilitate these transactions. Charging stations, which serve as physical locations for EVs to recharge, act as energy suppliers within the system. These stations provide electricity at dynamic prices, monitor energy dispensed, and process payments. Additionally, they may have surplus energy, enabling them to participate in peer-to-peer energy trading or sell excess energy back to the grid.

The validators play a critical role in maintaining the integrity of the blockchain. Through the selected consensus mechanism, such as Proof of Work or Proof of Stake, they verify the legitimacy of energy trading transactions and secure the system by resolving disputes. In return for their participation, validators are rewarded with transaction fees or energy credits. In more advanced setups, the energy grid can also function as a central authority. It regulates energy flow, provides backup energy during high demand, and facilitates energy transactions between EV owners, charging stations, and the grid. The grid helps balance supply and demand, ensuring energy availability during peak periods and enabling energy trading across various network participants (Figure 3).

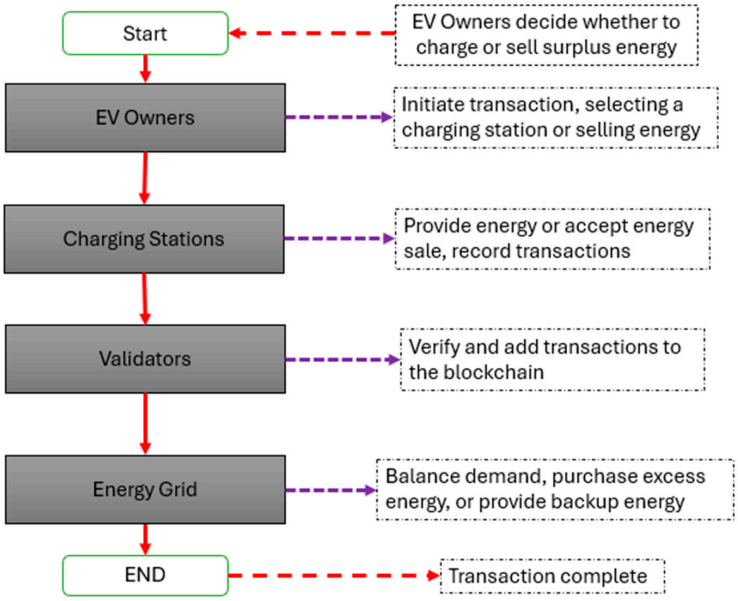


Figure 3. Stakeholder setup.

The relationship between these stakeholders is driven by smart contracts that automate transactions and ensure trust. The interaction between EV owners, charging stations, and validators is managed securely via the blockchain.

2.2.2. Blockchain Integration

The integration of blockchain technology in the energy trading system ensures that all transactions are transparent, secure, and irreversible. Blockchain serves as the underlying foundation for storing and recording transactions, while smart contracts automatically execute trading agreements between stakeholders. Two key consensus mechanisms are employed in this work: Proof of Work (PoW) and Proof of Stake (PoS) (Figure 4).

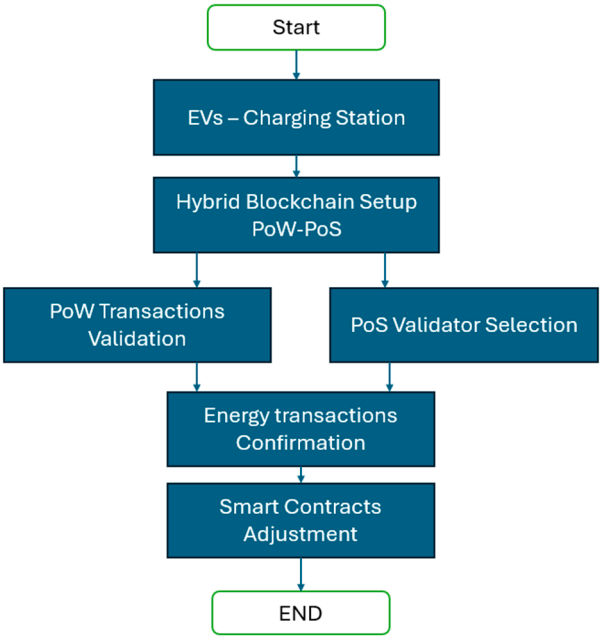


Figure 4. Hybrid blockchain integration.

2.2.3. Proof of Work Mining

In this energy trading system, PoW ensures the integrity and security of transactions between EVs and charging stations. By using PoW, the system can prevent fraudulent transactions and ensure that all energy exchanges are securely validated before being added to the blockchain. The process is resource-intensive, especially regarding energy consumption. The mining process can be broken down as follows (Figure 5).

Each energy transaction between an electric vehicle (EV) and a charging station generates a data block that must undergo validation. This block contains essential details such as the amount of energy transferred, the transaction cost, and the identities of the involved parties, the EV owner, and the charging station. To ensure the integrity of the blockchain, miners engage in a competitive process to solve a cryptographic puzzle tied to the transaction block. The complexity of this puzzle escalates as more transactions are added to the blockchain, fortifying the security of the network. The miner who successfully resolves the puzzle first broadcasts the solution to the network, thereby validating the transaction. Upon solving the puzzle, the transaction is confirmed, and the newly validated block is incorporated into the blockchain. In recognition of their efforts, the miner receives a reward in the form of a modest transaction fee, ensuring an alignment of incentives within the system. Additionally, the energy consumption associated with the mining process itself is a significant factor in this model. This energy expenditure, a hallmark of the Proof of Work (PoW) consensus mechanism, serves as a critical metric for assessing the environmental impact of the system.

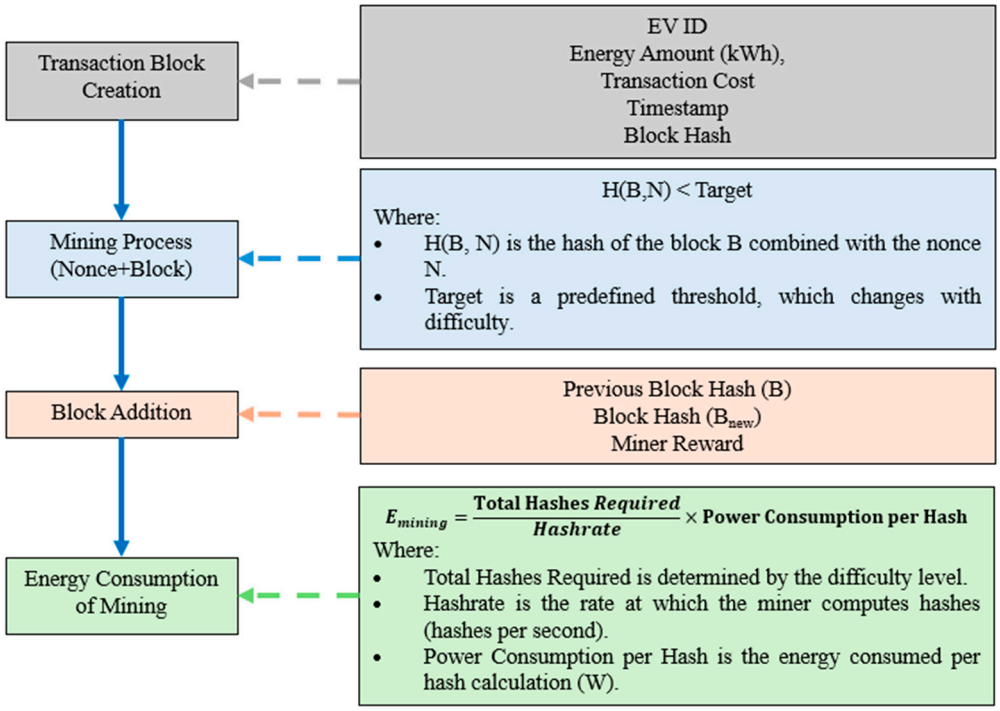


Figure 5. Proof of Work mining.

2.2.4. Proof of Stake Validator Selection

In the proposed model, Proof of Stake (PoS) selects validators based on their cryptocurrency stake, rewarding them with transaction fees. It is energy-efficient compared to Proof of Work (PoW), making it ideal for blockchain-based energy trading; it promotes decentralization, security, and sustainability, reducing carbon footprints while ensuring scalability. The selection process can be broken down as follows (Figure 6).

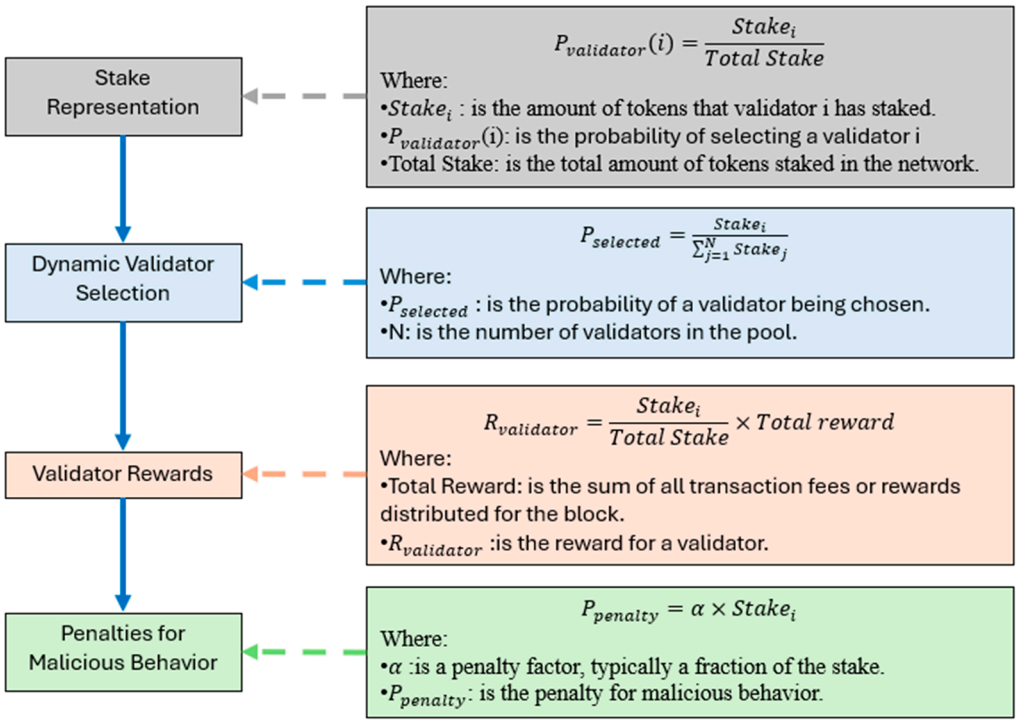


Figure 6. Proof of Stake validator selection.

The Proof of Stake (PoS) mechanism, within the context of this energy trading system, operates as follows:

Validators in the network are selected based on the amount of cryptocurrency or tokens they "stake" within the system, which serves as a representation of their investment in the network and their incentive to act with integrity. The selection of validators is dynamic, with those holding a larger stake having a higher probability of being chosen to validate a block of transactions. This stake ensures that validators possess a financial incentive to act honestly, thereby securing the network.

Validators who are selected to confirm transactions are rewarded with transaction fees or tokens, with the reward being proportional to their stake in the system. This structure motivates validators to uphold the integrity of the network. Conversely, validators who engage in malicious behaviors, such as approving fraudulent transactions, face penalties. These penalties involve the forfeiture of part or all of their stake, ensuring that their interests are aligned with the integrity of the blockchain and maintaining trust within the validator system.

2.3. Smart Contract

In a blockchain-based energy trading system, energy trading between users (i.e., EV owners and charging stations) is decentralized. Smart contracts allow for energy to be traded based on real-time pricing and grid demand, without needing a centralized intermediary.

2.3.1. EVs Requesting Energy

EV owners initiate energy requests (E_{EV}) when their vehicle's battery level drops below a certain threshold. This energy request is broadcast to the nearest charging stations (Equation (1)).

$$E_{EV} = E_{Bat} - E_{Actual} \tag{1}$$

where

- E_{Bat} is the maximum capacity of the EV's battery (kWh);
- E_{EV} is the energy requested by the EV (kWh);
- E_{Actual} is the actual charge the EV battery (kWh).

The energy traded ($£_{trade}$) between EV owners and the grid can be described mathematically as (Equation (2)):

$$£_{trade} = £_{energy} \times E_{EV} \tag{2}$$

where

- $£_{trade}$ is the total cost of energy traded between the EV owner and the grid (GBP);
- $£_{energy}$ is the energy price (GBP/kWh).

2.3.2. Energy Pricing

Charging stations set dynamic pricing based on factors such as energy demand, grid conditions, and current energy prices. This is often calculated using real-time market data, which may fluctuate in response to grid loads or renewable energy availability. Mathematical models for pricing, i.e., Time-of-Use (ToU) and Real-Time Pricing (RTP), have been designed.

Time-of-Use Pricing (ToU)

Time-of-Use (ToU) pricing is a model in which electricity rates vary depending on the time of day. The pricing structure is designed to encourage users to charge their electric

vehicles (EVs) during off-peak hours when electricity demand is lower. Mathematically, the pricing model can be expressed as follows (Equation (3)):

$$£(t) = \begin{cases} £_{peak}(t) & \textit{if } t \in \textit{day time hours} \\ £_{off\ peak}(t) & \textit{if } t \in \textit{night time hours} \end{cases} \quad (3)$$

where

- $£(t)$ represents the energy price at time t (GBP/kWh);
- $£_{peak}(t)$ is the energy price during peak (daytime) period (GBP/kWh);
- $£_{off\ peak}(t)$ is the energy price during off-peak (nighttime) period (GBP/kWh).

In the real word, the **price data** for these time slots is fetched via an API, which adjusts the pricing model based on actual demand and time-of-day, ensuring optimal cost for both users and charging stations.

Real-Time Pricing (RTP)

Real-Time Pricing (RTP) is another dynamic pricing model that fluctuates based on the real-time supply and demand of electricity. Unlike ToU pricing, RTP adjusts the price continuously according to grid load and market conditions (Figure 7).

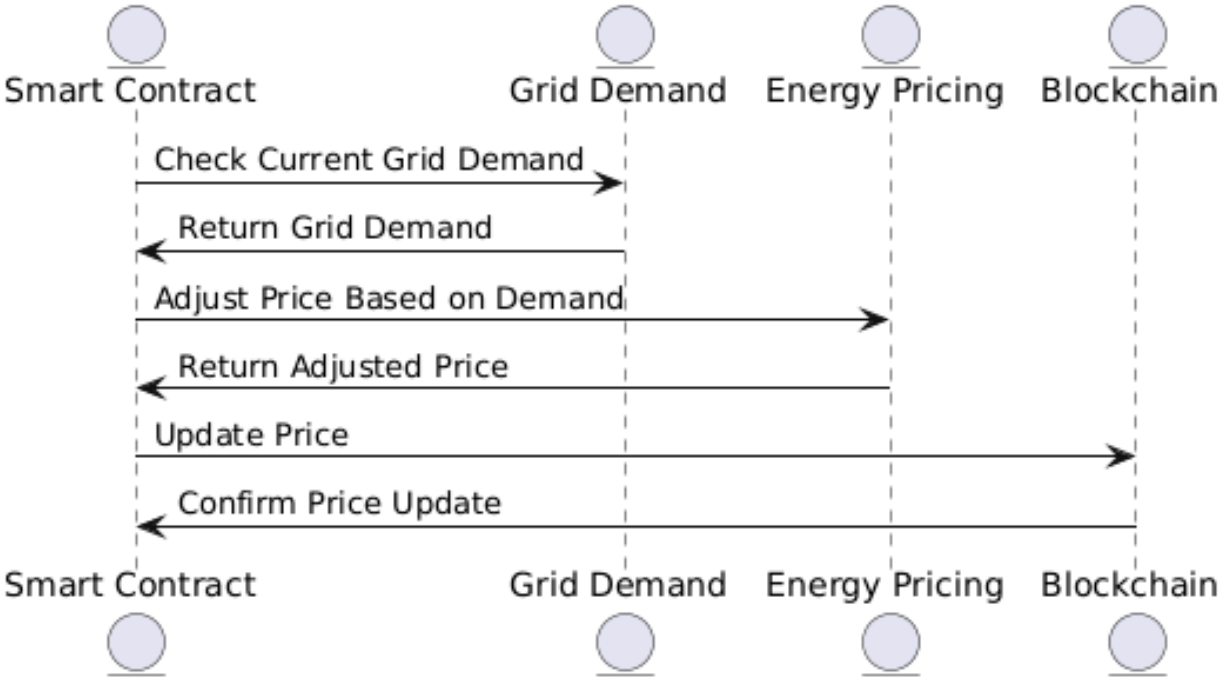


Figure 7. Grid demand-based dynamic pricing model.

The smart contract monitors the current time, energy price £(t), and grid load demand $G_L(t)$. During peak times or high demand, the price increases by a positive factor ($\alpha > 0$), while during off-peak or low demand, it decreases by a negative factor ($\alpha < 0$). The updated price is then recorded on the Blockchain, and the EV owner is notified of the price adjustment. The mathematical equation for RTP is as follows (Equation (4)):

$$£_{RTP}(t) = £(t) + \alpha \times G_L(t) \quad (4)$$

where

- $£(t)$ represents the actual energy price at time t (GBP/kWh), (Equation (3));
- $£_{RTP}(t)$ is the real-time price at time t for the EV (GBP/kWh);

- α is a coefficient that scales the price based on demand;
- $G_L(t)$ is the power grid load at time t (kWh).

Incentives for Optimal Charging Behavior

To further encourage optimal charging behaviors, the developed system can reward EV owners with incentives for charging during off-peak hours or when the grid load is low. Figure 8 illustrates how user incentives are determined by optimal charging behavior, specifically charging during off-peak times, and how these incentives influence energy consumption. The smart contract calculates and applies incentives based on this behavior, granting discounts if the charging occurs during optimal times. Both the transaction and the applied incentives are then recorded on the blockchain.

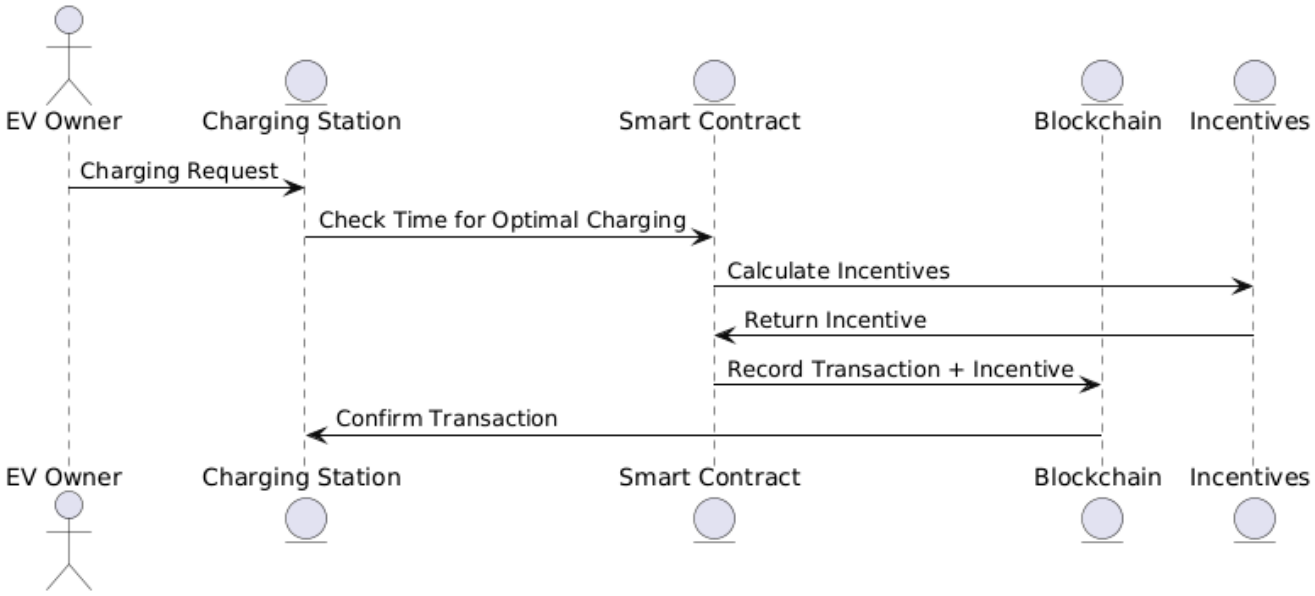


Figure 8. Energy consumption and incentives flowchart.

This incentivization can be expressed mathematically as follows (Equation (5)):

$$£_I = \beta \times (£_{peak} - £_{off-peak}) \times T_{Charging} \quad (5)$$

where

- $£_I$ is the incentive provided to the EV owner for off-peak charging period (GBP);
- β is the incentive factor;
- $T_{Charging}$ is the charging time (s).

The energy trading process begins when the charging station offers a price per unit of energy in response to an EV owner's request. The EV owner can then accept or reject the offer. If accepted, a smart contract on the blockchain locks the agreed-upon energy amount and corresponding cost, ensuring transparency, verifiability, and immutable recording of the transaction. Once validated, the energy is delivered to the EV, and payment is processed via the blockchain. Both the EV owner and the charging station receive confirmation, ensuring secure and efficient trading. The entire process is modeled using parameters such as energy demand, price fluctuations, transaction time, and user behavior.

3. Results and Discussion

The system's performance is assessed using a simulation implemented in MATLAB, modeling a network of six nodes (three EVs and three charging stations) using real world

energy prices from the Elexon database [44]. This section presents the results obtained from the simulation of the blockchain-based energy trading for electric vehicles (EVs) and compares them with existing strategies, focusing on key performance metrics, including energy consumption, cost, transaction speed, and blockchain efficiency (Algorithm 1).

Algorithm 1: The proposed system simulation algorithm

1. Initialization:

- **Define Stakeholders:** Create a list of stakeholders with initial stakes and names (e.g., Node1, Node2, Node3).
- **Define EVs:** Create a list of EVs with unique IDs, energy needs, and battery capacities.
- **Define Charging Station:** Set the maximum energy capacity of the charging station (e.g., 100 kWh).
- **Set PoW Difficulty Target:** Define the target hash string (e.g., '0000') for the Proof of Work process.
- **Fetch Real-Time Pricing:** Fetch the real-time energy price for the current time from: bmrs.elexon.co.uk.

2. PoW Mining Simulation (Proof of Work):

1. **Block Initialization:**
   - Prepare the block data including:
     - EV_owner: The ID of the EV.
     - charging_station: The ID of the charging station.
     - energy_traded: The energy consumed by the EV.
     - total_cost: The cost for trading the energy.
2. **Hashing and Mining Process:**
   - Initialize the nonce (nonce = 0).
   - Compute the SHA-256 hash of the block data concatenated with the current nonce.
   - Check if the hash meets the PoW target (starts with "0000").
     - If yes, the block is mined.
     - If no, increment the nonce and try again.
3. **Track Mining Time:**
   - Measure and record the time taken for mining the block.

3. PoS Validator Selection (Proof of Stake):

1. **Dynamic Stake Update:**
   - Randomly adjust the stake of each stakeholder (e.g., stake = stake + random_value).
2. **Validator Selection:**
   - Compute the total stake of all stakeholders.
   - Generate a random value between 0 and the total stake.
   - Iterate through the stakeholders, summing their stakes until the random value is reached, and select the corresponding stakeholder as the validator.
3. **Record Selected Validator:**
   - Store the selected validator for this round of PoS.

Algorithm 1 *Cont.*

4. EV Charging and Energy Trading:

1. **EV Charging Process:**
   - For each EV:
     - Check if the EV's energy needs can be fulfilled by the charging station's current energy capacity.
     - If the energy need can be met:
       - Charge the EV by consuming the required energy.
       - Calculate the cost of energy based on real-time pricing.
       - Update the charging station's available capacity.
       - Record the transaction in the blockchain ledger.
     - If the energy need cannot be met:
       - Notify that the EV cannot charge due to insufficient energy.
2. **Update Blockchain Ledger:**
   - Each transaction will include:
     - EV ID.
     - Energy traded (in kWh).
     - Total cost for the transaction.

5. Display Results:

1. **Display Blockchain Ledger:**
   - Print the blockchain ledger with details about each transaction, including EV ID, energy traded, and total cost.
2. **Show PoW Mining Time:**
   - Display the time taken for PoW mining.
3. **Show PoS Validators:**
   - List the selected PoS validators for each round.

6. Performance Evaluation:

1. **Measure Overall Time:**
   - Calculate the total simulation time from start to finish, including PoW, PoS, EV charging, and blockchain ledger updates.
2. **Comparison with Other Strategies:**
   - Compare the blockchain-based strategy with other energy trading strategies.
3. **Store and Display Comparison Metrics**

7. Output the Final Results:

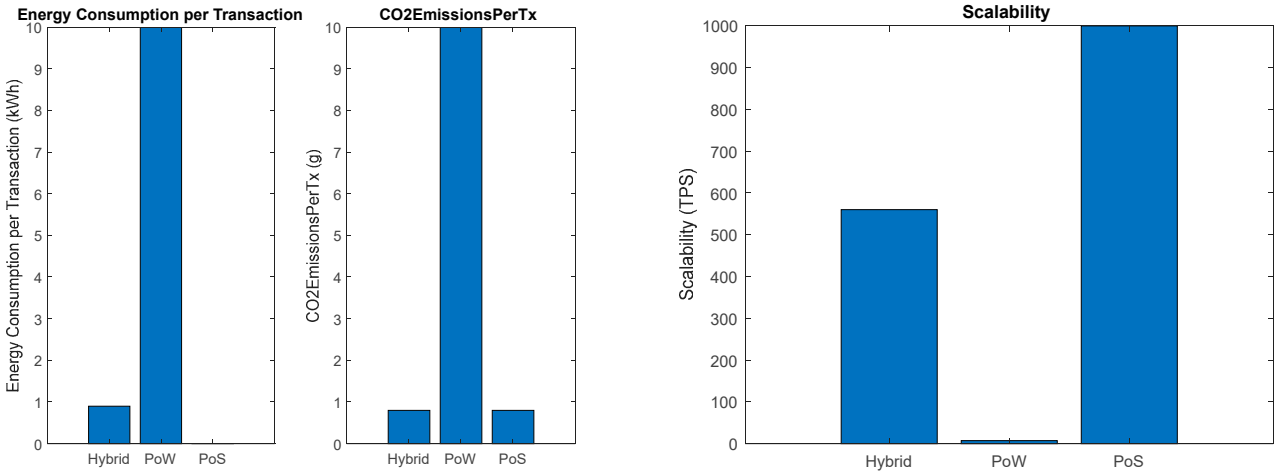
1. **Return Final Blockchain Ledger:**
   - Output the blockchain ledger containing all the EV charging transactions.
2. **Display Strategy Comparison:**
   - Present a comparison of different energy trading strategies.

3.1. Result Verification Compared to Previous Studies

Figure 9a presents the comparison results of energy consumption per transaction and CO_2 emissions per transaction, while Figure 9b depicts the scalability; the obtained

results were carefully compared with those from the referenced work by [23]. From the obtained results:

- Scalability: The hybrid model achieves 560 TPS, which is a significant improvement over PoW's 7 TPS. It provides much better throughput than PoW, making it suitable for real-world applications that require higher transaction volumes.
- Energy efficiency: While the hybrid model's energy consumption (0.8987 kWh/Tx) is higher than PoS (0.002 kWh/Tx), it is dramatically lower than PoW (707.6 kWh/Tx). This represents a substantial reduction in energy use compared to PoW while retaining the benefits of the PoW consensus mechanism, such as increased security.
- Reduced environmental impact: CO_2 emissions for the hybrid model are 0.7974 g per transaction, much lower than the 3.8×10^5 g per transaction from PoW. While PoS is still more eco-friendly, the hybrid solution significantly reduces environmental harm compared to PoW, making it a more sustainable choice.



(**a**) (**b**)

Figure 9. Result verification compared to previous study. (**a**) Energy consumption comparison, (**b**) Scalability comparison.

The hybrid model effectively combines the best of both worlds, leveraging the security and trust mechanisms of PoW with the efficiency and sustainability of PoS. This model provides:

- Significantly better scalability than pure PoW.
- Reduced energy consumption compared to PoW, while still maintaining a strong security protocol.
- Lower CO_2 emissions, contributing to a more eco-friendly solution.

This makes the hybrid model an ideal compromise between performance, sustainability, and security. It outperforms traditional PoW models in terms of energy efficiency and environmental impact, while still being more secure than PoS alone.

Figure 10 below shows that the hybrid model provides an 89.68% energy savings compared to pure PoW, which is a significant benefit, especially in terms of sustainability. It allows for blockchain networks to retain PoW's security while reducing the environmental impact.

The following results (Figure 11) highlight the contrast in energy consumption between PoW and PoS, with the hybrid model offering a substantial reduction in energy usage compared to PoW while still maintaining a balance of security and efficiency. This is especially relevant for sustainable blockchain solutions, where energy efficiency is a growing concern.

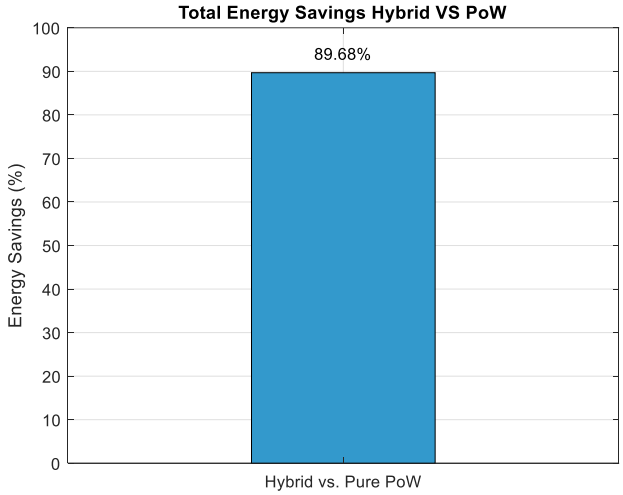


Figure 10. Total energy savings (hybrid vs. PoW).

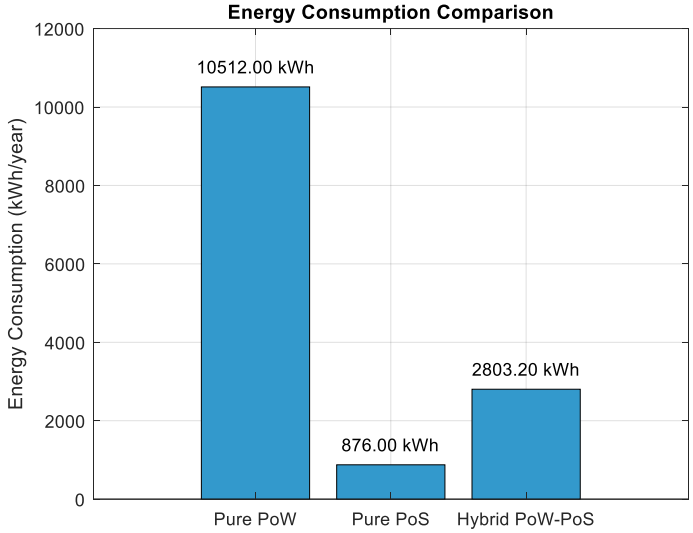


Figure 11. Total energy consumption (hybrid vs. PoW vs. PoS).

3.2. PoW Mining Time

Figure 12 demonstrates the time required for blockchain transactions under the Proof of Work (PoW) consensus mechanism. The average mining time for this scenario was around 86 s, indicating a reasonable balance between security and processing time.

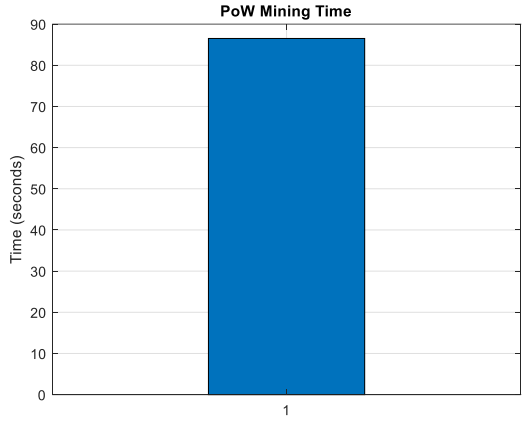


Figure 12. PoW mining time.

A higher load of transactions increases mining time due to the computational complexity involved in PoW, which can affect real-time pricing and incentives.

3.3. Transaction Costs per EV

Figure 13 presents the cost of energy traded by each EV during the charging process, calculated using real-time pricing data. The cost for each EV varies according to the energy consumed, with EV002 having the highest transaction cost due to its higher energy consumption.



Figure 13. Transaction costs per EV.

3.4. Energy Consumption per EV

Figure 14 illustrates the energy consumption of three EVs: EV001 (30 kWh), EV002 (50 kWh), and EV003 (20 kWh). The energy consumption is directly tied to the individual needs of the EVs, based on their respective battery capacities and energy required for a full charge. The results confirm that the total energy consumed across the three EVs totals 100 kWh, which corresponds to the initial charging station capacity.

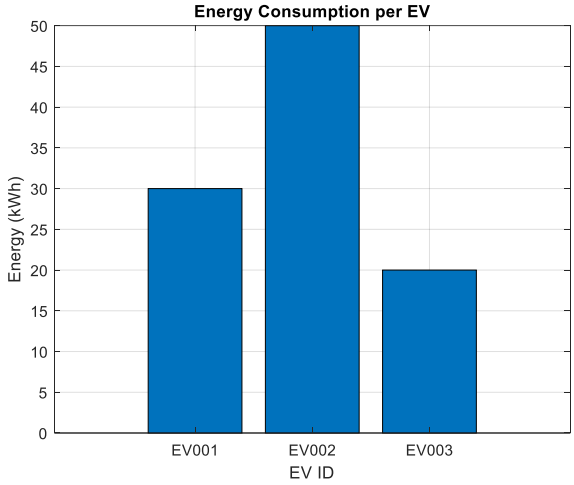


Figure 14. Energy consumption per EV.

3.5. Proof of Stake (PoS) Validator Participation

Figure 15 shows the distribution of stakes among the stakeholders, highlighting the **PoS validator selection** process. In the developed model, stakeholders randomly increase or decrease their stakes, which influences the probability of being selected as a validator.

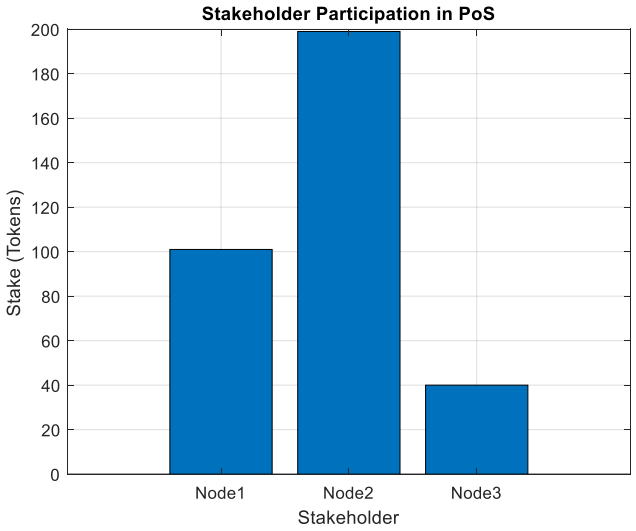


Figure 15. PoS stakeholder participation.

The chart demonstrates the dynamic nature of stakeholder participation, with some stakeholders experiencing increases or decreases in their stakes. The validator is selected randomly, but the probability is proportional to the amount of stake each stakeholder holds. In this case, the selected validator was Node2, with the highest stake at the time.

3.6. Time-of-Use Pricing Model

The simulation results for price adjustment over time (Figure 16) demonstrate the effectiveness of ToU pricing; where the price fluctuates based on the time of day, during the off-peak period, the EV owner is rewarded. The smart contract automates these price adjustments, ensuring that users are charged the appropriate price according to the time they initiate the charging session.

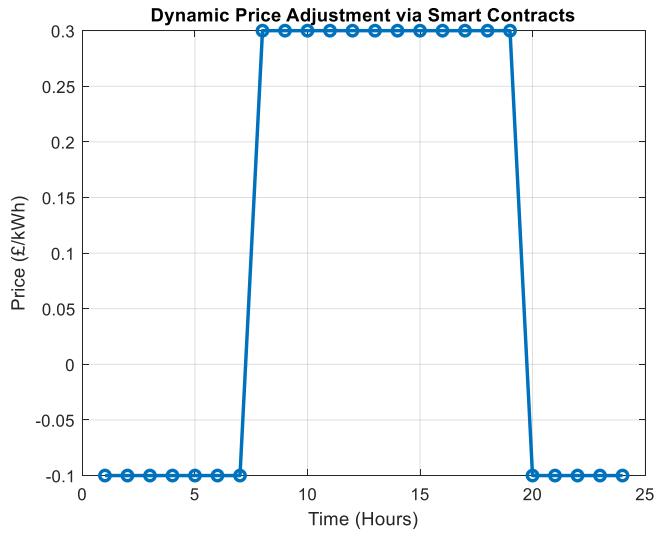


Figure 16. Dynamic price adjustment via smart contracts.

3.7. Incentive-Based Pricing

As depicted in Figure 17, users who charge during off-peak hours are rewarded with an additional incentive (circa GBP 0.5), thereby motivating them to shift their charging behavior, which leads to better load distribution on the grid.

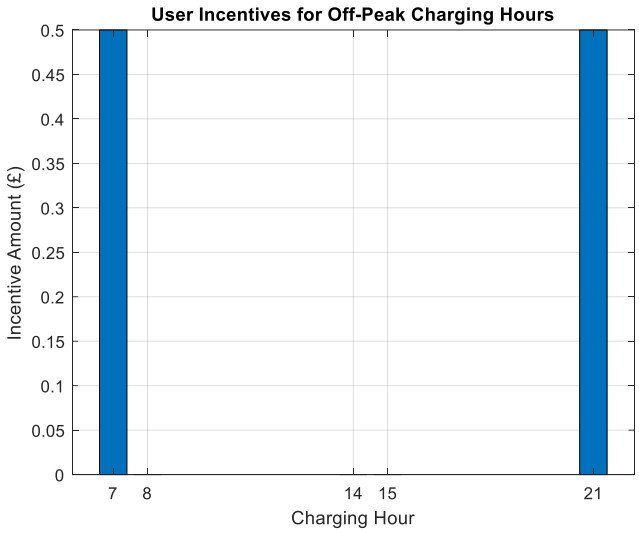


Figure 17. User incentives for charging during off-peak hours.

3.8. Energy Distribution Among EVs

Energy distribution among electric vehicles (EVs) is significantly influenced by the smart-contract-based dynamic pricing model. The incentives provided during off-peak hours encourage more users to charge their EVs during these periods, reducing peak demand and optimizing grid usage (Figure 18).

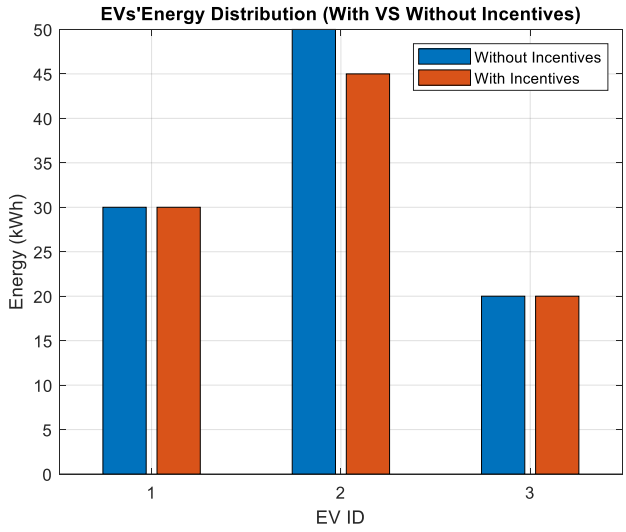


Figure 18. Energy distribution among EVs (with and without incentives).

The comparison shown in Figure 15 clearly demonstrates how the incentive-based pricing shifts charging behavior, leading to a more balanced energy distribution and a reduction in overall grid stress during peak times.

3.9. Grid Load Before and After Smart Contract Implementation

A crucial benefit of the proposed blockchain-based dynamic pricing strategy is its impact on grid load management. The implementation of ToU pricing through smart contracts helps flatten the grid load curve by shifting charging demand away from peak hours. This is particularly beneficial for optimizing grid efficiency and reducing the need for costly infrastructure upgrades. Figure 19 shows a test case for a car park of 1000 EVs.

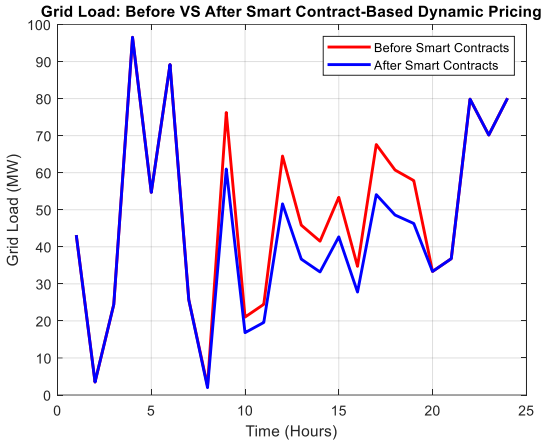


Figure 19. Grid load before and after smart contract-based dynamic pricing.

As seen in Figure 19, the load on the grid is reduced during peak hours, demonstrating how smart contracts facilitate grid optimization by promoting off-peak charging.

Table 3 effectively illustrates the changes and improvements in user behavior, energy consumption, and grid load, as a result of implementing smart contract-based dynamic pricing. It highlights how the system encourages optimal energy usage while benefiting both the users and the grid.

Table 3. Smart contract effectiveness.

	Period	Incentive (GBP)	Charging Load (kWh)	Peak Grid Load (MW)
Before Smart Contract	Peak	0	10	77
	Off Peak	0	8	97
After Smart Contract	Peak	0	9	60
	Off Peak	0.5	7	97

The developed solution offers several improvements over traditional and Ethereum-based energy trading systems. It reduces costs through dynamic pricing and decentralization, ensuring lower per kWh prices. The hybrid PoW–PoS approach balances security with energy efficiency, addressing scalability and consumption concerns. The system also improves energy efficiency by enabling real-time energy trading, better aligning with grid demand. The use of smart contracts for dynamic pricing in EV charging networks offers additional advantages. It optimizes grid load by shifting charging to off-peak times, resulting in cost savings for users. The incentive structure encourages behavior that benefits both users and the grid, while ensuring transaction transparency and automation.

4. Opportunities, Challenges, and Future Directions

4.1. Opportunities

The adoption of blockchain technology in energy trading, particularly within electric vehicles (EVs), presents numerous advantages that can significantly transform the energy landscape. By decentralizing energy distribution and ensuring transparency, blockchain can help overcome many existing inefficiencies in energy trading systems.

1. **Decentralized Energy Systems**
   The decentralization of energy production and consumption is one of the most transformative aspects of blockchain for energy systems. As smart grids and decentralized energy solutions gain traction globally, blockchain can provide a secure, transparent,

and immutable framework for managing these systems. Energy transactions can occur directly between users (peer-to-peer), reducing reliance on central utilities and traditional intermediaries. This decentralized approach not only improves security, but also helps to foster community-based energy networks, where local communities or regions can efficiently produce, consume, and trade energy without needing a central authority to manage the flow.

2. **Dynamic Pricing and Efficiency**
   Real-time pricing is a game changer for energy management. The blockchain-based solution facilitates dynamic pricing, ensuring that energy prices fluctuate according to demand, grid conditions, and renewable energy availability. With the widespread adoption of EVs, dynamic pricing can incentivize owners to charge their vehicles during off-peak times, or when renewable energy generation (such as solar or wind) is abundant, reducing the strain on the grid and lowering overall costs. This real-time optimization leads to more efficient energy consumption patterns, which ultimately contribute to a more sustainable and cost-effective energy ecosystem.
3. **Incentivizing Stakeholder Participation**
   By integrating the hybrid PoW–PoS model, blockchain introduces an incentive structure that rewards stakeholders for their participation in energy trading. The PoS model ensures that those who stake energy (whether EV owners, charging stations, or other energy producers) can benefit from both transactional rewards and long-term gains. This incentive framework encourages more active engagement in decentralized energy systems, particularly in areas where energy markets are fragmented or where traditional utility companies have limited access. Stakeholders are motivated to participate, not just to meet energy needs, but also to reap the benefits of a decentralized energy market.
4. **Integration with Smart Cities**
   As cities become "smarter", the integration of blockchain-based EV charging systems can complement existing smart city initiatives. In smart cities, vehicles, homes, and infrastructure are interconnected through the Internet of Things (IoT), allowing for them to dynamically exchange energy and information. Blockchain technology ensures that these exchanges are secure, transparent, and immutable. The integration of EV charging stations with this ecosystem allows for the seamless management of energy flows within the city, enabling real-time coordination between vehicles, charging stations, energy grids, and other stakeholders. This would not only improve the efficiency of energy use, but also contribute to the development of more sustainable urban transportation systems, ultimately helping cities reduce their carbon footprint.
5. **Support for Renewable Energy**
   One of the most promising aspects of blockchain technology in the energy sector is its ability to support the adoption and integration of renewable energy sources. With blockchain, the transparency and immutability of energy transactions make it easier for clean energy producers to sell their surplus energy directly to consumers, including EV owners. This facilitates the creation of a decentralized green energy marketplace, where renewable energy producers (such as solar or wind farms) can directly engage with consumers. Moreover, blockchain can provide consumers with assurances that the energy they are consuming is indeed green, as each transaction can be verified on the blockchain. As the world transitions toward renewable energy, blockchain could play a critical role in supporting these transitions by creating more efficient, transparent, and sustainable energy trading systems.

4.2. Challenges

Despite its promising potential, there are still several significant challenges that must be addressed before blockchain-based energy trading systems can be widely implemented. These challenges range from technical issues related to scalability and energy consumption to more practical concerns surrounding regulatory compliance and market acceptance.

1. **Scalability Issues**
   As the number of EVs and energy transactions grows, blockchain systems may face scalability issues, particularly when using PoW mechanisms. PoW requires significant computational power to validate transactions and add them to the blockchain, which can result in slower processing times and higher costs as the network expands. As EVs become more widespread and energy trading grows, the blockchain network may struggle to keep up with the increased demand. Exploring lighter, more scalable consensus mechanisms, such as PoS or hybrid PoW–PoS models, will be critical for ensuring that the blockchain system can handle the volume of transactions while maintaining decentralization and security.
2. **Energy Consumption of Blockchain**
   The PoW consensus algorithm, which is heavily reliant on mining, consumes a significant amount of energy. This is particularly concerning in the context of an energy trading system for EVs, as the benefits of adopting electric vehicles to reduce carbon emissions could be undermined by the environmental impact of blockchain mining. To mitigate this, there is a need to explore more energy-efficient consensus algorithms, such as PoS or Proof-of-Authority (PoA), that require far less energy to maintain the integrity of the blockchain. Transitioning to these mechanisms will not only make blockchain more sustainable, but also align with the goals of reducing global energy consumption and greenhouse gas emissions.
3. **Integration with Existing Infrastructure**
   The integration of blockchain-based solutions into existing energy grids and charging stations presents a major challenge. Traditional charging stations and grid management systems were not designed to support decentralized energy trading. Upgrading existing infrastructure to support blockchain-based solutions requires significant investment and collaboration between blockchain developers, energy providers, and regulatory authorities. Furthermore, interoperability between different charging stations, energy grids, and blockchain platforms needs to be established to ensure seamless communication and transaction processing.
4. **Regulatory and Legal Challenges**
   Energy trading is a highly regulated sector, and blockchain-based solutions must adhere to existing legal and regulatory frameworks. Decentralized energy trading challenges traditional market structures, and governments may be hesitant to embrace blockchain technology due to concerns about market stability, consumer protection, and regulatory compliance. Developing appropriate regulations that allow for decentralized energy trading while ensuring the protection of consumers and the stability of the energy grid will be crucial for widespread adoption. Furthermore, legal uncertainties surrounding the ownership and transfer of energy assets could hinder the development of a global blockchain-based energy market.
5. **Market Acceptance and Trust**
   Despite the potential benefits, there remains a level of skepticism and mistrust surrounding blockchain technology. Consumers, energy providers, and regulators may be wary of adopting blockchain-based energy trading solutions due to concerns about security, reliability, and long-term sustainability. Public education campaigns that demonstrate the technology's capabilities, security features, and potential economic

advantages will be essential in building trust and encouraging the large-scale adoption of blockchain systems for energy trading.

6. **Data Privacy and Security**
   While blockchain provides enhanced transparency and security, it also raises concerns about data privacy. The detailed records of energy usage and transaction data stored on the blockchain could reveal sensitive information about consumer behavior, energy consumption patterns, and private transactions. This information could be vulnerable to misuse if not properly managed. To address these concerns, privacy-enhancing technologies such as zero-knowledge proofs (ZKPs) or advanced cryptographic techniques will be crucial. These technologies allow for the secure verification of transactions without revealing sensitive details, thus maintaining user privacy while still benefiting from the blockchain's transparency.

4.3. Future Directions

While blockchain technology holds significant promise, it must overcome several challenges to reach its full potential. To make blockchain-based energy trading systems a reality, a number of future research areas and technological developments must be explored.

1. **Enhanced Consensus Algorithms**
   Future research should focus on developing consensus algorithms that are specifically designed for the energy sector. These algorithms must be scalable, energy-efficient, and able to support high volumes of transactions without compromising security or decentralization. Hybrid consensus models, combining PoW and PoS or PoA, may be particularly well-suited to address the scalability and energy consumption issues of PoW alone.
2. **Blockchain Interoperability**
   The ability of different blockchain networks to communicate and collaborate is essential for large-scale adoption. Researchers should focus on developing standards and protocols that allow for interoperability between different blockchain platforms, facilitating cross-border and cross-platform energy transactions. This will allow for energy trading to become more fluid and efficient, creating a global decentralized energy market.
3. **Decentralized Energy Markets**
   Future advancements could lead to the creation of fully decentralized energy markets where energy can be traded in real-time among EV owners, charging stations, renewable energy producers, and even consumers. Smart contracts could automatically execute energy transactions based on real-time market conditions, eliminating the need for intermediaries and reducing transaction costs. Decentralized markets would empower individuals and communities to become more self-sufficient, fostering a more resilient energy ecosystem.
4. **AI and Blockchain Integration**
   The combination of AI and blockchain could provide powerful synergies in optimizing energy trading decisions. AI can forecast energy demand, supply, and market fluctuations, enabling more informed decision-making for EV charging and energy trading. Machine learning algorithms can also optimize energy pricing in real-time, considering factors such as renewable energy availability, grid congestion, and consumer behavior. Integrating AI with blockchain ensures that energy trading remains adaptive and responsive to changing conditions.
5. **Cross-Sector Collaboration**
   To overcome the technological, regulatory, and infrastructural challenges, there must be close collaboration between multiple sectors, including blockchain developers,

energy providers, policymakers, and EV manufacturers. By aligning the goals of these various stakeholders, we can build a more cohesive framework for decentralized energy trading. Public–private partnerships will play a crucial role in ensuring that the infrastructure, regulatory landscape, and business models are compatible with blockchain adoption.

6. **Blockchain for Microgrids and Peer-to-Peer Energy Trading**
   Microgrids represent a promising area for blockchain-based energy trading. Blockchain can facilitate peer-to-peer (P2P) energy trading at the microgrid level, allowing for local communities to directly trade energy and reduce reliance on centralized utilities. This is particularly beneficial for rural and remote areas, where traditional grid infrastructure may be expensive or unreliable. The ability for local communities to trade energy directly could lead to more resilient, self-sufficient, and sustainable energy systems.
7. **Blockchain-Enabled Green Certificates and Carbon Credits**
   Blockchain can be used to track and verify renewable energy production through green certificates and carbon credits. EV owners could earn incentives for using clean energy for charging, and these incentives could be transparently recorded on the blockchain. This would create a more efficient and trustworthy system for verifying and trading carbon credits, promoting the wider adoption of renewable energy sources.

5. Conclusions

The proposed hybrid blockchain-based solution for electric vehicle (EV) energy trading presents several transformative benefits for the energy sector. Key advantages include enhanced security, greater scalability, and improved transparency compared to traditional energy systems. In addition, the integration of blockchain-based smart contracts with dynamic pricing models offers significant promise for optimizing EV charging networks. Through the automation of price adjustments, real-time incentive structures, and enhanced transaction transparency, the system can lead to better grid management, reduced costs for users, and more efficient charging behaviors. This ability to automatically adjust prices based on demand and time-of-use not only maximizes the efficiency of energy consumption, but also reduces grid congestion during peak times, contributing to the overall stability of the energy grid.

By surpassing traditional methods of energy trading, the proposed blockchain-based solution leverages the decentralization, security, and automation capabilities inherent in blockchain technology. It sets the stage for the future development of smart grids and sustainable energy systems, where decentralized, transparent, and automated solutions can drive innovation in energy distribution and consumption. In conclusion, this research highlights the transformative potential of blockchain for enabling more efficient, secure, and cost-effective energy trading systems, particularly in the context of electric vehicle charging and energy management.

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Data Availability Statement: The real world energy prices used in this study are available at [44].

Conflicts of Interest: The author declare no conflict of interest.

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