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A SCALABLE AND INTEGRAL, NASH EQUILIBRIUM-ENFORCED BLOCKCHAIN ENABLED END-TO-END ENERGY TRADING FRAMEWORK

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A B S T R A C T

Peer-to-Peer energy trading is an effective way of utilizing the distributed energy resources efficiently. However existing energy markets utilize the traditional approaches which lack security, fairness and scalability. This paper focuses on Blockchain based energy trading model which encompasses permissioned participation of traders, cryptographic security and Nash equilibrium based strategy for pricing. This ensures transparent, secure and fair transactions of energy. A permissioned blockchain framework is used where RSA-based cryptographic signature ensures authenticity of participants. This is followed by submission of energy demands and offers which are signed digitally. For maximizing profits of producers and savings of consumers, Nash-based energy pricing is done and fairness for both is enforced by use of smart contracts. The outcomes of these trades are then recorded immutably on the blockchain ledger. Furthermore, experiments have also been performed for evaluation of scalability by finding the latency by considering the changes in network size while still maintaining the security, integrity and fairness. Comparative results show that the proposed system enforced fairness and security as compared to the conventional approaches of smart contract which lack incorporation of game theory. The results confirm that blockchain when combined with Nash equilibrium mechanisms give a robust, fair and scalable solution for energy trading.

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1. INTRODUCTION

Energy management strategies are essential for both residential and commercial systems to reduce energy expenses and raise revenue. According to recent assessments, there is an increasing need for power globally; by 2040, it is expected to expand by 40%. The most recent market research conducted by the European Union (EU) makes it clear that the costs associated with producing and distributing electricity are now a major concern. The creation of a grid architecture that can accommodate dispersed and renewable energy sources for power generation is the answer to this problem, and it should also be included into the antiquated, rigid, and overburdened centralized electrical systems (Mourtzis et al., 2023).

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This is a motivation to create energy exchange in the grid where information is constantly exchanged between energy suppliers and customers in modern grids as energy is distributed (Mourtzis et al., 2023). The clean, sustainable, and intelligent modern electrical power grid driven by technology is anticipated to be the most significant human achievement of the twenty-first century, ensuring a sustainable future. The term "smart grid" refers to this intelligent electrical power grid. This smart grid has to be equipped with robust structure for secure energy trading and also equipped with the capacity to forecast energy in view of stability of the grid. Becoming customer-centered rather than producer-centered is one of the basic ideas at the heart of the smart grid. This is the approach which aligns with the fundamental pillar of Industry 5.0 which is customer-centric approach (Khan et al., 2023).

This paper identifies the need of a smart energy trading system for secure energy transactions with minimum latency and ensuring that those transactions are fair towards the consumers.

2. RELATED WORK

Centralized approaches for energy trading rely on a central authority for transactions and their settlements. Their security models introduce limitations in trust and may have single point failures. The current centralized energy market does not support peer-to peer energy trading. The independent operators are unable to handle large number of prosumers. It also has risks associated with the security. Price settlement is late. The settlement prices may not be fair enough since the tariff is fixed. No dynamic pricing involved. The centralized energy market incorporates bid auctions with uniform price. There are decentralized approaches where coalition is formed yet they lack in security, scalability and flexibility in energy trading. A Blockchain method was suggested Thukral (2021). The existing approaches for energy market proposed by government include the Feed-in-Tariff (FiT), Net Energy Metering (NET) and the Power Purchase Agreements (PPA). Though these schemes have motivated consumers to be prosumers, yet these approaches are not financially sustainable due to lacunas like reduction in utility revenues, increase in fixed costs and the growing adoption of distributed energy resources. Though PPAs are better-off in the above approaches, yet it also suffers from inadequate flexibility and not much accessibility to small scale prosumers. Hence the work Aoun et al. (2024) suggested Blockchain.

The PKI and other distributed approaches for energy trading do improve security due to encryption and authoritative control yet show some dependency on centralized approach for their implementation. Public key Infrastructure (PKI) which ensures authentication and integrity due to authorization is combined with decentralized Web of Trust (WoT). This avoids reliability on central authority and promotes authorization. Work called RETINA was proposed here. The work Bolgouras et al. (2024) incentivized use of renewables and catered toward the sustainability of the grid. A flexible access system using renewables for energy trading in smart grids was proposed here. It is based on Key Policy Attribute based Encryption. It eliminated the use of centralized server to cater to trust issues. The work Guan et al. (2017) had less cost as compared to many other available options. The work Fragkos et al. (2022) introduced and compared two novel architectures in the work for access of distributed energy resources. The first is a centralized and is based on Lightweight Directory Access Protocol. The second one is based on a private Ethereum blockchain test network. They were compared in terms of security, speed and cost. Each one has its own advantages and disadvantages.

Blockchain based systems however, are immutable due to decentralized nature and hence provide security. Automatic execution of transactions and their settlement is possible due to smart contracts. Blockchain also eliminates single point failure. The research Yahaya et al. (2020) focuses on the energy trading without involvement of any middlemen. It presents a smart home system that assists people in controlling their energy expenses and usage. A unique demurrage system minimizes waste and promotes timely energy trading. According to the results, some setups can save up to 65% on their electricity bills. The study Hayes et al. (2020) examines the integration of peer-to-peer energy trading platforms built on the technology of blockchain with electrical distribution networks. It connects a blockchain-based double auction trading system with a simulation of a distribution system. Moderate peer-to-peer trading doesn't affect network performance, according to tests conducted on a suburban network in Europe. The approach aids in investigating how planning and operation of electricity distribution are impacted by local energy trading. A multi-component co-simulation framework is used in this study's methodology to examine how peer-to-peer (P2P) power exchange affects distribution networks. The article Ali et al. (2020) examines in detail how blockchain technology, by facilitating decentralized, peer-to-peer platforms, can transform energy trading within cyberphysical systems. It draws attention to how difficult it is to scale and secure centralized energy models. To get around obstacles, it presents three frameworks for energy trading based on blockchain technology. It considers prosumers who generate and use power as well as the growth of renewable energy.

The work Bhavana et al. (2025) focused on the latency change vs. node count for different types of consensus mechanisms like Proof of Stake, Proof of Work etc. Scalability measurements have been done in the work Westphall and Martina (2022). The work Pradhan et al. (2023) shows latency in a different messaging setting.

The work Wang et al. (2025) focuses on the trust of participants involved in energy trading using a credit-based decision tree. The work Yao et al. (2024) focuses on improving the consensus by use of improved consensus and improvement in authentication of users. The work Andoni et al. (2019) and Egunjobi et al. (2024) reviews the application of blockchain in energy with its pros and cons. It shows the necessity of proving the security of blockchain experimentally. Many researchers have used the game theory approach and Nash Equilibrium for energy trading. Researchers in the work Xie et al. (2023) incorporate Nash equilibrium under time-varying conditions for prosumers in peer-to-peer energy trading. The paper Wu et al. (2020) incorporates a generalized Nash game in energy trading for power and heat auctions. However all the approaches using Nash equilibrium for energy trading were either not implemented on blockchain or used a centralized approach. Research in papers like Han et al. (2020) focus on matching of trades and the automation of trades using smart contracts.

2.1. Key Novel Contributions

Although some works have studied the smart contract, blockchain-based energy trading and Nash equilibrium models separately, few studies have attempted to integrate these technologies to develop a unified framework for safe, fair, scalable and automated energy trading in smart microgrids. Current methods are mainly concerned with isolated economic optimization, decentralized trading or transaction security. In the proposed work, however, these elements are incorporated in a complete end-to-end energy trading framework.

Table 1. Limitation addressed by proposed work

Existing Approach	Main capability	Limitation addressed by proposed work
Blockchain-based trading	Transparency, Immutability	Does not necessarily guarantee economic fairness
Game-theoretic trading	Pricing and Fairness	Often lacks immutable on-chain enforcement
Smart contract based trading	Automated execution and settlement	Executes predefined rules but does not inherently determine fair equilibrium
Proposed Framework	Blockchain + Nash equilibrium + smart contracts	Fairness decision → automated enforcement → immutable recording

As suggested in Table 1, from a scientific standpoint, the novelty of the proposed study resides in the combination of blockchain security mechanisms, fairness modeling based on the Nash equilibrium, and automation based on smart contracts for intelligent energy trading between producers and consumers in smart microgrids. The proposed system guarantees the secure and immutable nature of transactions, automated execution of energy trade and fairness-aware decision making.

Our paper focuses on-

1. Development on blockchain-based energy trading platform ensuring security and transparency
2. Implementation of cryptographic hash mechanism for blockchain immutability.
3. Implementation of authorization mechanisms for allowing legitimate participants for trading.
4. Enrichment of transaction verification by use of RSA based digital signatures.
5. Analysis of system performance for scalability for various network sizes.
6. Implementation of Nash to maintain balance between fairness of producers and consumers.
7. Design and implementation of intelligent smart contracts for automated execution of transactions with storing the essentials.
8. Developing an end-to-end intelligent energy trading system to incorporate all the above mentioned features within a unified smart grid framework.

3. THEORETICAL BACKGROUND

3.1. Blockchain

Blockchain technology is an extremely secure method for transmitting digital assets, money, and contracts without the use of intermediaries as a result. A unique type of data structure called a blockchain executes and records transactions in blocks. Each block has a timestamp and a hash link that links it to the previous block. Blocks offer unchanged records of data and cannot be changed in the past. A chain of ledgers made up of many individual blocks is what is commonly referred to as a blockchain. (Zarour et al., 2020).

3.2. Nash Equilibrium in Energy trading (G. Li et al., 2021)

"Game Theory" a sub-branch of applied mathematics is the one where participants (players) involved in an activity (game) are take informed decisions because it helps them in examining the different scenarios where their decisions affect one another. The state of balance where every player has given his best decision, having known the decision of others is called as the state of equilibrium. In energy trading, a game-theoretic model is put out to explain the interaction between buyers and sellers as well as the pricing rivalry among the sellers in an effort to further analyze the decision-making processes in energy trading. Prosumers modify their strategic behaviour in accordance with the price in a price-based scheme, regardless of whether they use a non-cooperative theoretic approach or other alternative

techniques like a predetermined price, an auction-based method, or a shadow pricing framework. They also pay for the amount of electricity used. Without incentives, consumers and sellers—who are often motivated by profit—will not alter their energy tactics. Players in energy sharing are sufficiently incentivized via a non-pricing method known as the contribution-based energy trading mechanism. However, since participants receive the same rewards regardless of their efforts, fairness in the Nash Equilibrium-based techniques mentioned above is arbitrary. Therefore, creating a suitable incentive program to recognize participants' achievements remains a crucial issue. Our work takes care of the same.

3.3. Smart Contracts in Energy trading

Smart contracts, first described in 1994 by Nick Szabo referred to "a computerized transaction protocol", that puts a contract's terms into action (Vigliotti, 2021). Put simply, smart contracts are algorithms based on blockchains that run when specific conditions are satisfied. They are frequently used to automate the execution of an agreement so that there is no need for a middleman or further delay and all parties may be certain of the outcome immediately. A decentralized energy distribution system is proposed by researchers, in which consumers can easily sell their excess energy to the grid. Using smart contracts, consumers can either manually or automatically sell their extra energy through the grid. Whereas some might chose to opt out instead of selling. To solve this problem, some researchers suggest using smart contracts with a mechanism of scheduling for energy selling to the grid. It is suggested to have a distributed energy management system that makes use of smart contracts to track energy usage and carry out energy-related transactions in an attempt to fully automate grid management. To calculate energy use, they used sensors that communicated with a smart contract. (Kemmoe et al., 2020). Customizable user behaviours, dependable and transparent transaction records, and other characteristics with a multitude of applications to meet these objectives are made possible by smart contracts in energy trading (Y. Li et al., 2019).

4. PROPOSED METHODOLOGY

4.1. Blockchain Architecture

The proposed framework utilizes permissioned blockchain architecture. It is designed especially for decentralized smart grid environments. This architecture of energy trading consists of consumers, producers, prosumers, smart meters and the utilities and supervisory nodes. It consists of four main layers.

A. Energy layer: This layer consists of all consumers and loads consuming energy and all sources of energy like distributed sources, renewable sources and battery storage systems.
B. Communication layer: This layer takes care of secure communication of energy related information using communication channels. Information like energy consumption, source of energy consumption, consumer information, energy used and billing related information is exchanged bidirectionally.
C. Blockchain layer: This layer is responsible for transaction validation, validation of legitimate participants, and immutable storage of data in blocks and cryptographic security of the data.
D. Application layer: This layer is responsible for energy pricing logic, Nash-based fairness among participants and automated settlements of energy transactions using smart contracts.

4.2. Consensus Mechanism with Participant authorization and authentication

The proposed method adopts permissioned blockchain architecture. Hence only authorized and authenticated users are allowed to participate in the trading process. It uses a validation based consensus process. Proof of Work (PoW) is used as consensus. All participants who wish to participate in energy trading are authenticated and their integrity is checked. Initially, all the participants who wish to involve in the trade have to undergo one time registration process for authorization. The authorized users are then assigned with a unique signature using RSA for authenticity. Both authorization and identity verification is done if any participant wishes to get involved in the trading activity. Upon its success only, the participant is allowed to undergo bidding. Once the transaction is validated, it undergoes PoW mechanism as consensus for the block to get added in the blockchain. This maintains the security and immutability in the transaction records.

4.3. Offer and Demand submission

The producers and consumers submit their offers of sell and buy respectively. Each tries to maximize their profit/savings. The producer’s submission is a function of available energy for selling and the offer price. The consumer’s submission is a function of the demand of energy and the maximum price if any is applicable for buying.

4.4. Fairness estimation

The proposed fairness mechanism is based on the non-cooperative game theory, where the consumers and the energy suppliers are modeled as rational agents trying to maximize their own utility functions in the trading. In decentralized energy markets, conflicts are unavoidable because producers seek to maximize their profit while consumers aim to minimize their energy consumption. Therefore, for the sustainable energy trading, it is important to reach a stable operating point which meets the needs of the two parties.

The proposed paradigm employs Nash equilibrium because it offers a mathematically stable solution where, once equilibrium is achieved, no member can improve its payout by unilateral deviation. This property makes Nash equilibrium particularly suitable for decentralized smart microgrid scenarios with many independent participants and conflicting interests. Let P be the participating Producers and C be the participating Consumers. The strategic interaction between them is represented by $G = (N, S, U)$, where $N = P \cup C$ is the set of participating players, S is the strategy space and $U = \{ U_i \}$ represent the utility functions of the players.
The strategy for the producer can be given as follows-

$$S_p = \{p_{ij}, E_{ij} : p_{ij}^{min} \leq p_{ij} \leq p_{ij}^{max}, 0 \leq E_{ij} \leq E_i^{avail}\}$$

And for the consumer can be given as follows-

$$S_c = \{E_{ij} : 0 \leq E_{ij} \leq D_j\}$$

where p_{ij} is the trading price, E_{ij} is the traded energy, E_i^{avail} is available producer energy, and D_j is consumer demand.

The utility functions for consumers and producers can be given using following

$$U_p = (p_{ij} - C_p)\, E_{ij}$$
$$U_c = (P_{market} - p_{ij})\, E_{ij}$$

where:

- U_p is the producer utility,
- U_c is the consumer utility,
- p_{ij} is the negotiated trading price,
- C_p is the production cost,
- P_{market} is the current market price,
- E_{ij} is the amount of traded energy.

Higher the trading price, higher would be the utility of the seller and lower would be the utility of the consumer. Whereas, reduction in the trading price produces an opposite effect. This opposing utility structure creates the strategic conflict that motivates the application of Nash equilibrium. Thus the proposed framework utilizes the following Nash equilibrium to have a maximum utility for both producers and consumers.

The Nash stability equation is given by Eqn. (1).

$$B_i(p^*) \geq B_i(p) \quad \forall i \tag{1}$$

Where $B_i(p^*)$ is the benefit obtained for a player i at the Nash equilibrium price p* and the $B_i(p)$ is the benefit obtained for a player i at the any other price p. $\forall i$ denotes that it is applicable for players of both sides. The equation implies that no player can gain more benefit by making a unilateral decision by changing the price p other that p*. The same concept is applied for the benefit of producers and consumers for trading of energy to ensure the fairness in the trade.

$$F_{ij\ producer} = \frac{P_{producer}}{A_{ij}} \geq \theta_p \tag{2}$$

$$F_{ij\ consumer} = \frac{P_{consumer}}{A_{ij}} \geq \theta_c \tag{3}$$

$$A_{ij} = E_{ij}\,.\,p_{ij}$$

With uncertainty considered,

$$E_{ij} = E_{ij} \pm \Omega$$
$$P_{producer} = A_{ij} - Cp$$
$$P_{consumer} = P_{market} - A_{ij}$$

where $F_{ij\ producer}$ is the fairness index for the producer between the buyer and seller (i and j), $F_{ij\ consumer}$ is the fairness index of the consumer, E_{ij} energy transacted, Ω is the uncertainty in the transaction due to intermittent nature of renewables and transmission losses, p_{ij} is the price of the energy per unit, A_{ij} is the total amount during energy transaction, Cp is the cost price of the producer and θ_p is the minimum fairness threshold for the producer and θ_c is the minimum fairness threshold for the consumer. $P_{producer}$ is the profit of the producer and $P_{consumer}$ and the profit/savings of the consumer. The value of θ_p is normally chosen to be 10% of the marginal contribution of the producer. By maintaining nash price more than θ_p ensures minimum profit to the producer. Whereas θ_c is chosen to be 10% of the existing market price of the energy. Having the nash price to be at least equal to θ_c ensures minimum savings to the consumers. And by following both equation (2) and equation (3) ensures bilateral fairness. The uncertainty parameter Ω improves the robustness of the system under practical operating conditions especially smart grids using renewables.

The proposed fairness indices normalize the profit obtained with respect to the transaction amount, which allows proportional fairness evaluation regardless of the scale of the transaction. The normalized fairness formulation makes sure that small scale and large scale participants are evaluated in a consistent manner whereas profit-based alternatives are absolute.

Compared with the current market price, the bilateral fairness limitations guarantee that consumers obtain quantifiable economic benefits and producers obtain minimum acceptable profit margins. This also discourages price manipulation and encourages participation of the long-term sustainable in the decentralized energy trading market.

Thus the fairness index is a function of the amount of energy traded (E_{ij}), price of energy per unit (p_{ij}) and the uncertainty in trading (Ω) .

$$\text{Fe} = \begin{cases} if\ A_{ij} \geq Cp & Fair: P, Fair/Unfair: C \\ if\ P_{market} \geq A_{ij} & Fair: C, Fair/Unfair: P \end{cases} \tag{4}$$

The fairness estimation process can be done using Eqn. (4). When the energy producer's selling price (A_{ij}) is more than or equal to the cost of producing the energy (Cp), it is fair for the producer but may be fair or unfair for the consumer. Moreover, when the price that consumers pay for energy (A_{ij}) is less than or equal to its true market value (p_{market}), it is fair for consumers but may be fair or unfair for producers. Thus the producers try to maximize the A_{ij} and consumers try to minimize A_{ij}. The nash price (p*) should satisfy the Eqn. (5).

$$p_{max} \geq p^* \geq p_{min} \quad (5)$$

where p_{min} is the Cp and p_{max} is the p_{market}.

Hence all trades which are unfair are converted to fair by adjusting the price per energy unit (p_{ij}) and the by reallocation of energy to be transacted (E_{ij}).

The iterative best-response mechanism converges if no participant can increase its utility with the current trading strategy. The proposed iterative optimization procedure converges to a stable Nash equilibrium point as the reward functions of the producer and the consumer are bounded in the feasible price interval [pmin, pmax].Consumers get energy at or near the market price. Producers get a minimum assured profitability. No one has any incentive to do anything different. The proposed mechanism thus treats the Nash equilibrium as decision mechanism and the fairness indices as acceptance constraints. A stable price-energy strategy profile is identified by Nash and the bilateral fairness constraints determine if the resulting equilibrium provides acceptable benefit to both producers and consumers. Either of the conditions is violated the trading price or energy allocation is revised to again find equilibrium. This ensures the stability, fairness and economic efficiency of the decentralized trading mechanism. Thus only the strategy which satisfies Nash stability and bilateral fairness is further passed on to the smart contracts.

Following algorithm helps in understanding the implementation of Nash equilibrium in brief.

Algorithm for Nash equilibrium calculation

Start

Step 1: Strategy space initialization ()

For a producer k, price is : $p_k \in [p_k^{min}, p_k^{max}]$ and $E_k \leq E_k^{avail}$

For a consumer I, demand is: $E_i \leq D_i$

Step 2: Pay off formulation ()

For a strategy profile s = (p, E)

Producer pay-off is $P_{producer} = A_{ij} - Cp$

Consumer pay-off is $P_{consumer} = P_{market} - A_{ij}$

Step 3: Best response computation ()

Iteratively compute best responses

$$p_k^* = \boldsymbol{arg}\max_{p_k} \boldsymbol{P_{producer}}(\boldsymbol{p_k}, \boldsymbol{p_{-k}})$$

$$E_i^* = \boldsymbol{arg}\max_{Ei} \boldsymbol{P_{consumer}}(\boldsymbol{E_i}, \boldsymbol{p})$$

Step 4: Nash equilibrium check ()

A strategy profile (p^*,E^*) is a nash equilibrium if

$P_{producer(k)}$ (p^*) $\geq P_{producer(k)}$ (p), $\forall_k$

$P_{consumer(i)}$ (p^*) $\geq P_{consumer(i)}$ (p), $\forall_i$

If not satisfied, repeat Step 3. This gives the nash price p^*.

Stop

4.5. Smart contract

A smart contract is a safe and automated agreement that is confirmed on an authentication. It is used in the selling of smart energy inside interconnected microgrids. Utilizing cryptographic authentication guarantees that only authorized players (prosumers, utilities) can engage in purchasing and selling. To eliminate trust dependencies and streamline transactions, the contract stipulates terms such as price, quantity, and delivery. Additionally, it executes trades automatically upon fulfillment. Within the microgrid network, this promotes energy exchange that is efficient, transparent, and secure hence fostering efficiency.

$$SC = f(ID_C, E_{tot}, \Delta E, N_{tx}) \quad (6)$$

The smart contract function can be done using Eqn. (6). Here, ID_C indicates the customer's identity which is checked to ensure that it is accurate, E_{tot} indicates the total amount of energy that is connected to the consumer in the microgrid before the trade happens. This energy is later updated after the trade happens. Buying will increase the energy of consumer and selling will decrease the energy of seller. ΔE represents the amount of energy involved in the transaction (energy sold or bought), and N_{tx} represents the transaction count. Thus the smart contract execution is a function of parameters- trader identity, energy before trade, energy involved in trade (+ or -) and the transaction count which gets updated after every transaction. Thus the execution of smart contract ensures the identity of the trader in the market, maintains a log of the transaction like incrementing the transaction count and the updation of the energy balance each with buyer and seller. Thus the incorporation of smart contract ensures the automated and secure execution of all the stable, optimized and fair decisions of energy trading taken by the proposed system.

4.6. Algorithm

Following explains the overall flow of the system in which authorization and authentication is done, fairness metrics are computed using Nash equilibrium, they are validated and finally immutable recorded in the permissioned blockchain ledger.

Overall Algorithm of the system

Start
Step 1: Participant Authorization ()
Nodes are registered //Now they are authorized participants
Authorization check of nodes done
Identity verification done using RSA
If above is found ok, allowed to be bid, else rejected
Step 2: Offer and demand submission ()
Producer submits price offers
Consumer submits energy demands
Each submission is RSA digitally signed
Step 3: Nash Equilibrium calculation ()
Game Theory is implemented

Producers maximize profit, consumer maximize savings

Nash price is calculated //ensures no unilateral fairness/decision
Step 4: Fairness metric calculation ()

Producer Fairness Index (PFI)

$$PFI = \frac{p_{Nash} - C_{prod}}{p_{Nash}}$$

Consumer Fairness Index (CFI)

$$\boldsymbol{CFI = \frac{P_{market} - p_{Nash}}{P_{market}}}$$

Step 5: Trade Decision ()
Savings ≥ θ(c) //Ensures consumer fairness
Profit ≥ θ(p) //Ensures producer fairness

Above is met, trade is executed
Else rejected/re-negotiated (producer incentive or consumer rebate)

Step 6: Smart Contract Execution ()
Validation of- Authorization, Authenticity, Fairness
Energy transacted, payments settled
Required data stored immutably on blockchain
Stop

As per the methodology proposed above, the system was built and empirical results were found out. Following section shows step-wise results of the developed model.

5. RESULTS

5.1. Immutability and Authenticity in Blockchain

The implementation is done in Python 3.11. The simulated blockchain went through number of tests to check denial of transaction acceptance from unauthorized users/nodes, invalid blockchain due to data tampering, denial of transaction getting added in the block due to any missing field or invalid signatures by using RSA. The Postman tool along with Python was used for the same. Only, the registered nodes will be allowed to send the transaction. In this work 3 nodes are registered. This would control the participation. But an additional trust or authenticity is needed for which digital signatures are used. Before the data has to get added in the block, it is important to check the authenticity of the transaction in case of a registered node compromise. It adds a second layer of cryptographic security to the system and maintains its integrity. In this work, this is done by the method of digital signature using the RSA algorithm. The immutability of blockchain would be checked by 'hash'. And this can be detected after the block has been created after which data has been tampered. It was tested for around 10 transactions. The consolidated results are depicted in the Table 2.

Table 2. Authorization, Authenticity and Immutability results

Test	Description	Successful?	Error Message/ Output
Authenticity	Transaction tampered, so signature mismatch	Yes	Invalid Signature. Transaction Rejected
Missing fields	Transaction data incomplete	Yes	Missing field. Transaction Rejected
Authorization	Invalid/unregistered user trying to send data	Yes	Unauthorized node
Immutability	Data tampered, so Hash changes	Yes	Block is tampered. Chain invalid

5.2. Scalability

The latency and throughput being the fundamental metrics of blockchain, Scalability is also an important metric of blockchain. The rate at which the latency changes, indicates the computational scalability of the system. It is expected that the system should be scalable enough to maintain security. The latency for the proposed blockchain system was calculated under various conditions as discussed in the subsequent sections. The required code was written in Python-version 3.11. The results vary depending on the specifications of the machine used for deployment. The proposed method for the local blockchain was simulated on a single deploy machine with an Intel Core i3 processor (2.53 GHz), 4GB RAM, 417 GB of storage with Windows 10 (64-bit) of operating system.

Table 3 shows the values of latency for 10 transactions each in 3 such sets. The same experiment is carried out for varying number of nodes. Here 3, 5, 10 and 20 nodes are taken into consideration.

Table 3. Latency for change in network size

Timestamp	Number of Nodes	Set number	Number of transactions	Average latency in seconds
2026-01-08	3	1	10	10.32
2026-01-08	3	2	10	15.61
2026-01-08	3	3	10	11.16
2026-01-08	5	1	10	22.26
2026-01-08	5	2	10	20.02
2026-01-08	5	3	10	19.65
2026-01-08	10	1	10	33.84
2026-01-08	10	2	10	42.52
2026-01-08	10	3	10	49.33
2026-01-08	20	1	10	81.32
2026-01-08	20	2	10	82.59
2026-01-08	20	3	10	86.46

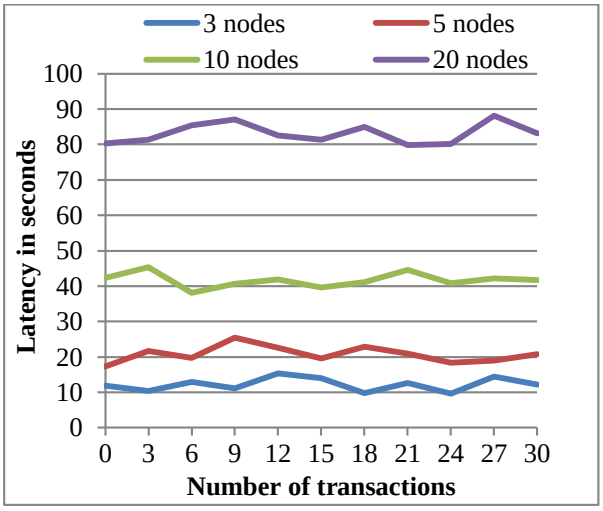


Figure 1. Number of transactions vs Latency for varying nodes

Figure 1 shows the graph of Latency in seconds for multiple transactions and with varying network size, i.e. with varying number of nodes. As expected the latency increases with increase in the network size. This is due to the increase time of propagation and the consensus time taken. The latency increase which accounts for the RSA digital signature signing and verification at each validating node increases the security in the network. However the proposed framework maintains stability in the execution of transactions for moderately sized decentralized energy trading environments.

Table 4 consolidates the average latency of 30 transactions for number of nodes as 3,5,10 and 20.

Table 4. Summary of Latency for different network size

Number of Nodes	**Number of sets**	**Number of transactions**	**Average latency in seconds**
3	3	30	12.36
5	3	30	20.64
10	3	30	41.89
20	3	30	83.45

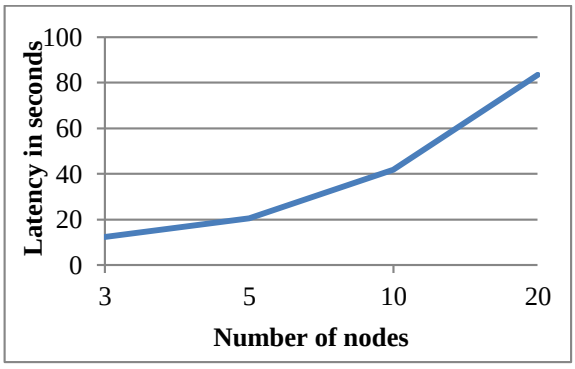


Figure 2. Number of nodes vs Latency

The Figure 2. Number of nodes vs Latency shows the graph of latency with respect to the changes in the number of nodes. The latency growth shows approximately a linear trend, showing that the even with increase in the network sixe, the latency increase is within the acceptable limits. The rate at which latency changes, demonstrates the computational scalability of the blockchain. Hence this figure demonstrates that the blockchain system effectively scales up while ensuring the required security and integrity. Though the proposed work is in controlled local simulation environment, it is feasible to integrate the immutable blockchain, fairness based Nash equilibrium and smart contracts for automation in energy trading. The future work will focus on extending the experimental analysis with larger network size in larger and distributed environments and real-time test-beds for further scalability analysis.

Nash Equilibrium

Now, a local energy trading market is considered where there are multiple producers and consumers. Each one of them is considered to be an authorized node. Each one of them submits requirement of their energy demand and the price at which it can be sold. Accordingly the Nash equilibrium is applied on the trades in which each participant looks for its own benefit. The producer would think of increasing the trading price to maximize the profit. However, the consumer would think of minimizing the trading price to ensure maximum savings. All this is done while ensuring equilibrium in the grid with respect to the demand and supply.

Table 5 shows the fairness for producers in the trade with respect to producers for 6 such trades. The marginal contribution, total cost, and gain of every option are listed for different trades in the fairness table. The marginal contribution (in monetary units) is the transaction amount during the trade. Hence it is the product of the Nash accepted trading price and the energy transacted. Higher the marginal contribution more is the benefit to the society since it reduces the stress on the grid. Final cost (in monetary units) is the cost incurred by the producer.

Table 5. Fairness for Producers

Transaction	Marginal contribution (monetary unit)	Final cost (monetary unit)	Gain/unit energy (monetary unit)	Adjustment done for fairness?
Trade 1	203.62	-26.14	11.31	Yes, Incentive/subsidy
Trade 2	363.66	218.83	15.16	No
Trade 3	371.03	-47.65	20.60	Yes, Incentive/subsidy
Trade 4	363.63	276.94	15.14	No
Trade 5	516.27	-66.32	28.67	Yes, Incentive/subsidy
Trade 6	1818.23	355.65	90.92	No

This final cost takes into account the cost price of the energy by the producer with the uncertainty compensation (due to renewable intermittency, market price volatility etc.) and the Nash adjustment (i.e. either the subsidy or the incentive given to the producer). The final costs which have negative values are a result of this.

The gain in the third column is the profit that the producer gets after transaction. This gain is the difference between the per unit energy price of transaction (marginal contribution) and the per unit energy cost price (final cost). High marginal cost in the table ensures high social benefit. The negative final cost represents the incentive or subsidy given to the producer. With larger profits, smaller costs, and favorable marginal contributions signifying fairer options, it aids in assessing various decisions based on their fairness. With a bigger gain, lower cost, and favorable marginal contribution, judgments are thought to be fairer when compared to one another according to the table. The Nash equilibrium can give subsidy sometimes to make the transaction fair.

Table 6. Fairness for Consumers

Transaction	Market Price (monetary unit/kWh)	Nash Price (p) (monetary unit/kWh)	Traded Energy (E) (kWh)	Savings /kWh (monetary units)	Total Savings (monetary units)	Consumer Fairness Index (CFI)	Savings ≥ θ(c)?
Trade 1	7.00	6.10	2.8	0.90	2.52	0.1286	Yes
Trade 2	6.80	5.90	1.5	0.90	1.35	0.1324	Yes
Trade 3	7.30	6.35	3.1	0.95	2.945	0.1301	Yes
Trade 4	6.20	5.60	2.0	0.60	1.20	0.0968	**No**
Trade 5	8.00	6.75	4.2	1.25	5.25	0.1563	Yes
Trade 6	5.80	5.40	1.2	0.40	0.48	0.0690	**No**

Table 6 shows the fairness obtained for consumers. The table lists the market price, Nash price, savings of the consumer, traded energy, total savings and the consumer fairness index. The savings are compared with the fairness threshold for consumer i.e. $\theta(c)$ to decide whether any correction is needed in the price to meet the fairness criteria. The threshold is normally considered as 10% of the market value. Thus the fairness in the prosumers is taken into account. In some cases as can be seen above, some trades may be unfair for consumers, though they are fair for producers.

The tables of fairness for producers and consumers are generated by implementing the Nash equilibrium process of game theory. By ensuring the bilateral fairness results, further, smart contracts execute the trades automatically. The trading data is then immutably stored on blockchain.

6. DISCUSSION

The tests conducted for 30 transactions in our proposed work to check all the following aspects have been consolidated in the following table.

Table 7. Summary of work done in proposed model

Test	Description	Successful?	Error Message/Output
Authenticity	Transaction tampered, so signature mismatch	Yes	Invalid Signature. Transaction Rejected
Missing fields	Transaction data incomplete	Yes	Missing field. Transaction Rejected
Authorization	Invalid/unregistered user trying to send data	Yes	Unauthorized node
Immutability	Data tampered, so Hash changes	Yes	Block is tampered. Chain is invalid
Scalability	Latency vs. number of nodes (empirical results)	Yes	Linear change in graph ensuring scalability
Producer Fairness	Nash price found (empirical results)	Yes	Profit ensured by adjustment in Nash price or giving incentives
Consumer Fairness	Nash price and CFI found (empirical results)	Yes	Acceptable savings shows “fair” trade else shows “unfair”
Automated execution	Use of smart contracts	Yes	Relevant traded data stored immutably

Table 7 show the immutable and secure nature of blockchain while enforcing fairness of producers and consumers by use of smart contracts. While having checked the above, the scalability of the system is also evaluated. The scalability graph shows approximately a linear trend which demonstrates that latency increases with increase in network size and is yet within acceptable limits. The RSA signing and the process of verification due to increase in the number of nodes is a reason for this rise in latency. Though the current evaluation is limited to 3-20 nodes, the approximate linear trend of latency gives a baseline proof of concept for the scalability of the proposed blockchain system. This baseline establishes a reference for broader scalability testing which would involve larger network sizes and distributed deployment environments. Thus the observed increase in latency shows a security-performance trade-off due to additional authentication and verification overhead.

The fairness of producers and consumers is also taken into account by use of Nash equilibrium in non-cooperative game theory. Smart contracts execute the trades automatically and store the relevant data on blockchain securely. Thus all aspects in energy trading have been taken care of and the results for the same have been demonstrated.

Table 8. Comparison of proposed system with existing systems

Feature / Aspect	**Centralized Energy Trading**	**Smart Contract–Based Energy Trading**	**Game-Theoretic Energy Trading**	**Proposed Blockchain–Nash Framework**
Trading Architecture	Centralized server / utility (Fragkos et al., 2022)	Public or consortium blockchain (Han et al., 2020; Li et al., 2019; Yahaya et al., 2020)	Centralized / off-chain (Li et al., 2021; Wu et al., 2020)	Permissioned blockchain
Blockchain Usage	✗ No blockchain (Fragkos et al., 2022)	✓ Yes (Han et al., 2020; Li et al., 2019; Thukral, 2021)	✗ No blockchain (Li et al., 2021; Wu et al., 2020)	✓ Yes
Blockchain Type	—	Public / Consortium (Han et al., 2020; Yahaya et al., 2020)	—	Permissioned
Pricing Mechanism	Fixed / market-clearing (Fragkos et al., 2022)	Auction / dynamic pricing (Han et al., 2020; Yahaya et al., 2020)	Nash equilibrium (Li et al., 2021; Wu et al., 2020; Xie et al., 2023)	Nash equilibrium
Fairness Guarantee	✗ Not explicitly guaranteed (Fragkos et al., 2022; Hayes et al., 2020)	Partial / implicit (Li et al., 2019; Yahaya et al., 2020)	Theoretical / modeled (Li et al., 2021; Wu et al., 2020; Xie et al., 2023)	Explicit (CFI & PFI)
Consumer Fairness	✗ Not explicitly addressed (Fragkos et al., 2022)	Limited (Han et al., 2020; Yahaya et al., 2020)	✓ Modeled (Li et al., 2021; Xie et al., 2023)	✓ Enforced
Producer Fairness	✗ Not explicitly addressed (Fragkos et al., 2022)	Limited (Li et al., 2019; Yahaya et al., 2020)	✓ Modeled (Li et al., 2021; Wu et al., 2020)	✓ Enforced
Fairness Enforcement	Central authority (Fragkos et al., 2022)	Smart contract / pricing mechanism (Han et al., 2020; Li et al., 2019)	Off-chain/game-theoretic computation (Li et al., 2021; Wu et al., 2020)	Smart contract + fairness thresholds
Participant Authorization	Trusted third party / centralized control (Fragkos et al., 2022; Guan et al., 2017)	Wallet-based / blockchain-based (Han et al., 2020; Yahaya et al., 2020)	Assumed / participant-based (Li et al., 2021; Xie et al., 2023)	Permissioned authorization
Identity Verification	Central registry (Guan et al., 2017; Fragkos et al., 2022)	Wallet-based (Han et al., 2020; Westphall & Martina, 2022)	Assumed (Li et al., 2021; Xie et al., 2023)	RSA-based identity verification
Digital Signatures	✗ No (Fragkos et al., 2022; Guan et al., 2017)	✓ Yes (Han et al., 2020; Westphall & Martina, 2022)	✗ Not a primary mechanism (Li et al., 2021; Wu et al., 2020)	✓ RSA signatures
Immutability	✗ No (Fragkos et al., 2022; Guan et al., 2017)	✓ Yes (Han et al., 2020; Li et al., 2019; Yahaya et al., 2020)	✗ Not inherently provided (Li et al., 2021; Wu et al., 2020)	✓ Yes
Scalability Analysis	Rare / limited (Fragkos et al., 2022; Hayes et al., 2020)	Gas cost / blockchain overhead (Westphall & Martina, 2022)	Not a primary focus (Li et al., 2021; Xie et al., 2023)	Latency vs. node analysis
Non-repudiation	✗ No (Fragkos et al., 2022; Guan et al., 2017)	✓ Yes (Han et al., 2020; Westphall & Martina, 2022)	✗ Not a primary feature (Li et al., 2021; Wu et al., 2020)	✓ Yes

Table 8 compares the features offered by the proposed system and the existing systems for energy trading. While centralized and smart contract system do support automation in trades to some extent but they lack support in robust authorization and fairness enforcement of participants. Game-theory models do support fairness but are typically implemented off-chain hence lacking immutability in storage. Whereas the proposed system stores energy transactions immutably on a permissioned blockchain while maintaining strict authorization and identity verification using RSA signatures with scalability analysis and also enforcing the fairness of participants involved in the trade thereby addressing the limitations of the existing work. It simultaneously ensures immutability, security, fairness, transparency and automation in energy trading. From a practical perspective the proposed framework in future can support energy management in smart grids which consists of distributed energy resources, renewable resources, prosumers and electric vehicles. The ability to securely automate the trade while ensuring bilateral fairness makes the proposed system suitable for next generation intelligent energy management systems in smart grids.

7. CONCLUSION

The proposed system ensures an end-to end energy trading approach starting with node registration, nodes authorization, and assignment of digital signature using RSA, checking for authenticity, submissions of demand and offer of available energy, trading by ensuring fairness for producers as well as consumers and then the automatic execution of trade. The results show usage of blockchain for authorization and authentication. The empirical results for scalability of blockchain and its immutability with security make it suitable for energy trading markets. The Nash results show fairness for producers with or without corrective action taken. The fairness for consumers for maximum savings is also ensured. Then the smart contracts ensure automatic trade by upon meeting the required conditions and store the required data securely on the blockchain ledger thus completing the trading loop. Future directions may include the matching of trades between producer and consumer for the conditions like demand more than supply and supply more than demand of energy. It may incorporate advanced consensus mechanisms. In the future large scale deployment can be done by integrating the system with real-time data from the microgrid.

Data availability statement: All empirical evidence that substantiates the conclusions of this investigation is encompassed within the article

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