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RESEARCH PAPER

Presenting a Multi-stage Automated Pricing Mechanism for Energy Exchange in the Distribution Network Electricity Market Based on Smart Contracts on the Blockchain Platform

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Abstract

The barriers to entry for small-scale renewable energy producers into decentralized electricity markets include the need for significant investment in infrastructure and management processes and the application of optimal and automatic pricing with consideration for multiple purchase and sale orders with low financial volume and consumption. Therefore, current market models for distribution networks face multiple challenges, including high transaction costs, lack of direct interaction between producers and consumers, and inefficiencies in supply and demand convergence. Additionally, energy transactions in centralized electricity markets are controlled by a central authority, leading to increased transaction costs. In other words, energy exchange researchers are seeking to develop a new distributed energy model to address the presumed challenges. The pricing strategy studied under the theory of double auction with factors and correction factors for adjusting updated prices in smart contracts is introduced to create a balance between supply and demand during different market execution cycles. This model is implemented on a blockchain platform using the developed environment Visual Studio Code (VSC) and simulated on an IEEE 33-bus network with 10 nodes, and the results obtained show the efficiency of the method in increasing acceptance and support for renewable energy participation with the ability to prioritize energy supply for sensitive and critical loads in the network. The novel contributions of this work include a dynamic multi-stage auction mechanism with correction factors, a decentralized settlement system reducing transaction costs by 25%, and a prioritization algorithm for critical loads, demonstrating a 92% efficiency in supply-demand balance.

Keywords Network electricity market · Automatic pricing · Smart contracts · Blockchain platform

1 Introduction

With the increasing penetration of Distributed Energy Resources (DER) and the development of Information and Communication Technology (ICT), electric energy customers will have the freedom to choose from a variety of energy services such as electricity power exchanges (Zhan et al. 2023; Das et al. 2023). However, the majority of consumers and producers with excess energy, without having an appropriate business model, can only exchange their energy directly with electricity distribution companies (Hou et al. 2023; Wang et al. 2023). Therefore, the key to solving the problem and developing energy markets in local networks lies in providing a suitable framework with the benefits of decentralized energy exchange mechanisms and encouraging customers to engage in direct energy transactions within communities or local groups (Tariq and Amin 2025). Nevertheless, in a decentralized energy market, scalability, trust, security and privacy, and transaction control by a central organization responsible for managing the exchanges remain primary concerns (Veerasamy et al. 2024; Oliveira et al. 2023). This central entity requires a transaction charge from both producers and consumers, which lowers producer revenue and raises consumer energy consumption expenses (Chen et al. 2017; Zhang et al. 2018). According to these explanations, the global energy market is working

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to create novel models that will enable decentralized energy exchange without middlemen, with low supply costs and ideal pricing.

Reasonable steps towards achieving specific goals encourage and motivate small-scale producers to generate more renewable energy so that they can produce more renewable energy worldwide (Huang et al. 2020; Wang et al. 2018). Therefore, changing the type and model of energy exchange and local electricity market to a decentralized, multi-stage system with targeted prices at each stage of market operation using information and communication technology offers a fundamental solution (Zhou et al., 2023) and a significant opportunity for energy trading, enabling active participation from all consumers (Saeed et al. 2024; Nadeem 2022). The emergence of new technologies such as the Internet Of Things (IoT) (Zhang et al. 2019), 5G networks (Hui et al. 2020), blockchain technology, and smart contracts (Christidis and Devetsikiotis 2016) has shifted the nature of local energy markets from centralized to decentralized, making energy exchange management at the end-user level more reliable and efficient. The integration of blockchain with smart contracts serves as a promising, user-friendly, and optimized technology for implementing a staged network energy market in a secure, reliable, and decentralized environment (Vieira and Zhang 2021; Ali et al. 2021). This technology ensures transparent data transfer among local market participants, allowing energy trading decisions to be made in a decentralized manner without the need for a central controlling authority. Blockchain provides a safe environment for producers and consumers to engage in energy exchanges while recording energy transaction data, regardless of energy quantity and price, based on predefined smart contracts (Zizzo et al. 2018; Zhang et al. 2021). In network electricity trading, blockchain and smart contracts play a crucial role in fostering trust, transparency, and efficiency in transactions. Due to its decentralized nature and immutability, this technology provides a secure platform for network trading without the need for intermediaries (Spiliopoulos et al. 2022; Zhou et al. 2023).

Studies related to distributed energy exchanges based on smart contracts in blockchain can be divided into two main categories: the first category includes research conducted in the physical and practical layer, and the second category includes research conducted in the virtual and systemic layer. The first category consists of technical and economic elements such as scalability, transaction speed, minimum energy supply, multi-stage participation, and targeted energy prices, in which researchers seek to create optimal conditions for energy trade based on network topology loading. The second category consists of planning elements such as blockchain test networks, developed web environments, and types of smart contract applications that provide control, planning, and monitoring of exchanged energy accounting; for example, Si et al. (Si et al. 2018) have proposed a blockchain-based energy management and exchange model. The proposed storage system operates using neural networks as the reasoning engine, providing users access to the system through an internet-connected gateway and server. When a user wants to register an energy request in the system, transaction costs are incurred that ensure privacy and accelerate data exchange. These costs depend on the complexity of the search request, so more complex requests incur higher costs, improving system scalability and transaction acceleration but limiting optimal energy exchange and cost minimization. Ferreira and Martins proposed an artificial intelligence approach to enable two-way transactions while considering minimal product offerings (Ferreira and Martins 2018). This approach utilizes blockchain-based accounting for energy transactions, leading to the implementation of centralized control unit requirements and describing distributed energy exchanges and Peer-to-Peer (P2P) trading mechanisms with the aim of profitability. In this study, the presence of a central control unit enhances the proposed advantages for participants and encourages their participation. Furthermore, game theory is used to regulate user behavior in energy trading and achieve predetermined goals. However, this model somewhat reduces the speed and acceleration of transactions. Silvester et al. (Di Silvestre et al. 2018) proposed a blockchain-based model for managing ancillary services and technical issues in networks. Beyond the economic aspects of transactions, their proposed model supports technical decision-making regarding operations in decentralized energy exchange. The main goal of this research is to preserve data related to transactions between different types of entities. However, collecting such information significantly affects the speed of data and the pricing tariffs for energy storage services, leading to inconsistencies and complexity in managing ancillary services. Umar et al. (Umar et al. 2024) and Yang et al. (Yang et al. 2019) introduced a blockchain-based P2P energy trading model that incentivized consumer participation through Demand Response (DR), aiming to obtain positive feedback by encouraging energy transactions through incentives. Participants in this system received rewards by providing energy to existing demands, playing a significant role in P2P energy transactions by changing the pricing structure. However, this model was only effective for a very small number of network nodes. Lin (Lin 2019) and Nguyen et al. (Nguyen et al. 2018) proposed an analytical approach to decentralized energy exchange of photovoltaic (PV) and electricity storage in electric vehicles (EVs) based on blockchain technology. According to the findings of these studies, this approach plays a significant role in reducing operational costs and increasing network stability. One of the main objectives of these studies is to

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reduce the potential power fluctuations resulting from high penetration of distributed generation sources. The formulation section addresses issues such as potential power fluctuations, production uncertainty, and production capacity to facilitate participation in the energy market. Production and energy trading planning is done using various algorithms such as the hill climbing algorithm, and simulation results establish the effectiveness of proposed models for multiple smart homes. However, these studies have paid little attention to the possibility of P2P exchange and the benefits of operational optimization techniques for these types of energy sources for participants. Hou et al. (Hou et al. 2019) and Tushar et al. (Tushar et al. 2019) P2P energy storage in the industrial IoT sector and P2P smart contract transactions have been implemented using the Ethereum platform and Solidity programming language with the Proof Of Work (POW) consensus algorithm, executed on the Remix test network. These studies utilized blockchain's virtual layer to track and securely execute all transactions between consumers and producers, adhering to smart contract regulations to reduce vulnerability to malicious attacks. The mentioned studies used the POW consensus algorithm for node agreement, which is computationally expensive and consumes significant energy. Despite the simplicity and high efficiency of the proposed method, this approach faces challenges such as reduced transaction speed due to data congestion, which can lead to delays and high costs for users to confirm transactions and secure energy. Hasan et al. (Hasan et al. 2022) and Alam et al. (Alam et al. 2024) implemented P2P smart contract exchanges and DER2G using the Tendermint platform, which is programmed in the Solidity language with the POW consensus algorithm and deployed on the MainNet. These proposed methods demonstrate high scalability in terms of the number of participants and are capable of processing a large number of transactions per second, making them an ideal platform for developing and running programs. The achievements of these studies in the virtual layer include high-speed and automatic transactions without the need for human supervision or intervention. However, the proposed studies also face specific constraints such as how to efficiently exchange excess energy and at what cost to reduce transaction operational costs. Bruel and Godina (Bruel and Godina 2023), as well as, Boumaiza and Sanfilippo (Boumaiza and Sanfilippo 2024) Previous studies have addressed the challenges in the Hyperledger Fabric blockchain system. By utilizing advanced development environments and the Polygon blockchain network, and adopting the Proof Of Stake (POS) consensus algorithm, they reduced the issues of previous studies. In these studies, the POS-based validation is carried out based on the stake credibility in producing new blocks, and unlike POW, this method allows any user with a valid transaction to become a transaction validator and minimize energy consumption and consensus time, but faces the concentration of a large number of tokens in a few digital wallets.

Through a review of research in the physical and applied energy trading sector, the need for a reliable and specific strategy to ensure optimal participation of all small and large members in a power distribution network becomes apparent. This strategy should be based on targeted pricing and adjusted with a quantitative correction factor in each market cycle compared to the previous cycle to create a balance between energy supply and demand. Additionally, providing cash incentives as rewards for small-scale participants seems necessary to increase efficiency, motivation, and competitiveness in their energy exchange. Furthermore, a review of studies in the virtual and systemic trade categories of energy shows that there is a research gap in the design and implementation of a multi-stage collaborative mechanism among peers in the energy trading market. This mechanism should be based on smart contracts in a blockchain-based environment that enables integration with various executive programs. Such a system should facilitate an increase in the number of energy trade transactions while maintaining transaction speed and supporting the development of agreement algorithms with lower transaction costs (consumable gas) in each time interval in a multi-stage market within the scope of an electric energy distribution network.

Table 1 summarizes the comparison and features of the reviewed articles in this section, as well as the capabilities of each proposed method. A quick overview of this table reveals that the studies conducted so far in the field of multi-stage participation and automatic pricing in a network under smart contracts have gaps that can be appropriately addressed using the proposed method in this article.

A novel concept for a multi-stage energy exchange mechanism in a distribution network market in a local network in a P2P way is presented in this article in light of the discussion above. To solve the issues raised in the review articles, this mechanism combines preference-based and cost-effective options for target prices and regulations with a blockchain framework and a web-based environment that has been designed with smart contract-based programmability. To overcome these obstacles, this paper presents a decentralized multi-stage energy market structure for the first time using three groundbreaking innovations:

1) Creating a multi-stage auction with automated and targeted prices in a dynamic and repetitive auction market, where market participants present their bids in successive stages using correction factors (CFs). This provides flexibility in pricing based on the sensitivity of the type of load, the variability of renewable production, and the

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Table 1 Comparison and characteristics of the conducted studies

REF.	Physical layer					Virtual layer		
	Scalability in exchanges	Accelerate transactions	Minimum energy available	Multi-stage participation	Automatic pricing	Blockchain testing structure	Integrated development environment	Energy Career Field
(Si et al. 2018)	√	√	×	×	×	Test-Net	Remix IDE	Energy management
(Ferreira and Martins 2018)	√	×	√	×	×	Test-Net	Remix IDE	P2P
(Di Silvestre et al. 2018)	√	√	×	×	×	Test-Net	Remix IDE	Ancillary services
(Yang et al. 2019; Umar et al. 2024)	√	√	√	×	×	Test-Net	Remix IDE	P2P on DR
(Lin 2019; Nguyen et al. 2018)	√	√	√	×	×	Test-Net	Remix IDE	P2P on PV, EVs
(Hou et al. 2019; Tushar et al. 2019)	√	√	×	×	×	Test-Net	Remix IDE	IOT & P2P
(Hasan et al. 2022; Alam et al. 2024)	√	√	×	×	×	Main-Net	Coda IDE	P2P & DER2G
(Bruel and Godina 2023; Boumaiza and Sanfilippo 2024)	√	√	√	×	×	Main-Net	Coda IDE	P2P & DER2G
Proposed exchange	√	√	√	√	√	Ganache	Visual Studio Code IDE	Multi-stage energy market in network electricity

behavior of market participants, resulting in achieving a 92% efficiency in balancing supply and demand.

2) The execution and enhancement of decentralized settlement through smart contracts with an immutable mechanism that automatically runs on the Ethereum-based Ganache blockchain by real-time encryption consensus, eliminating intermediaries and reducing transaction costs by up to 25%.
3) Introducing a new algorithm for allocating energy to sensitive and vital loads with prioritization, such as healthcare and emergency service centers, even during peak network consumption times.

1.1 Novel Contributions and Paper Structure

This paper addresses the aforementioned challenges by introducing a decentralized multi-stage energy market framework with three groundbreaking innovations:

- A novel multi-stage auction mechanism: We propose an automated, targeted pricing strategy using dynamic correction factors (CFs) that adjust in each market cycle. This provides flexibility based on load sensitivity, renewable generation variability, and participant behavior, achieving a 92% efficiency in balancing supply and demand.
- Decentralized settlement via smart contracts: We implement an immutable settlement mechanism on an Ethereum-based Ganache blockchain. This system eliminates intermediaries and reduces transaction costs by up to 25% compared to conventional testnet environments, which is crucial for small-scale prosumers.
- A prioritization algorithm for critical loads: We introduce a new energy allocation algorithm that ensures reliable energy supply for sensitive and vital loads (e.g., hospitals, emergency services) even during peak demand periods, enhancing network resilience.

This article begins with introducing the structure of pricing and settlement equations in energy markets, and then these equations are further developed through smart energy exchange contracts in the advanced environment of the VSC using the Solidity programming language interacting with the JavaScript programming language code and utilizing Ethereum cryptocurrency in the Metamask wallet on the public blockchain platform of Ganache, and finally, the results and achievements of the proposed model simulation are examined on a test network to demonstrate the benefits and practical applications of a multi-stage local market.

2 Preliminaries

By establishing automated and multi-stage target prices of market execution amongst participating members in the form of smart contracts, within the context of energy trading, this article focuses on creating a market model for electricity distribution networks. In order to optimize operational

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decisions among numerous participating nodes in the electricity trading market, this study suggests a mixed-integer linear programming model. This model is effective enough to explicitly provide a pricing mechanism for each stage of market execution in the network's nodes. The technical and financial exchanges associated with different operational aspects, such as purchase and sale tariffs, network node investments for the production of renewable energy, and cost reductions in marginal expenses, may also be comprehended thanks to this model. Building the required foundations to accomplish a certain objective is crucial to achieving a general framework for energy exchange in the electrical market of a multi-stage distribution network based on smart contracts in blockchain technology. In order to reflect the real conditions of the suggested mechanism, which is explained through a flow chart, this article first presents the pricing and settlement structure in the energy market before looking at the platforms required for encrypting equations.

2.1 Multi-Stage Market Architecture

The overall process of the new mechanism presented in this paper can be depicted as a flowchart, as shown in Fig. 1. In this flowchart, the energy exchange between members is of the day-ahead market type, and the workflow of the market mechanism coded in the smart contract is outlined as follows:

The multi-stage energy exchange method among network distribution players, which is implemented through blockchain-based smart contracts, works as a decentralized, iterative process to optimize local energy market transactions. Within this framework, multiple producers and consumers buy and sell energy at the same time in a competitive market. Each participating node, validated and registered on the blockchain via a smart contract, initially submits it's offered or requested energy quantities to the local distribution market, based on the current network buy and sell reference prices. Subsequently, the Distribution System Operator (DSO) performs an automated assessment and dynamic regulation of network loads (nodes) according to their operational priority, sensitivity, and power imbalance levels (i.e., requested or surplus energy). This adjustment is achieved by applying a correction factor formulation to the initially proposed prices, enabling the system to progressively converge toward a supply–demand equilibrium. Through this mechanism, the DSO seeks to optimize individual node profitability and overall network cost-efficiency over several iterative market stages (cycles), leveraging the preceding day's market-clearing prices as reference inputs. During each cycle, both buying and selling price proposals are automatically updated in accordance with the newly derived correction factors and market equations, thereby enhancing price adaptability and competitiveness within the trading environment. Buyers in each cycle procure energy

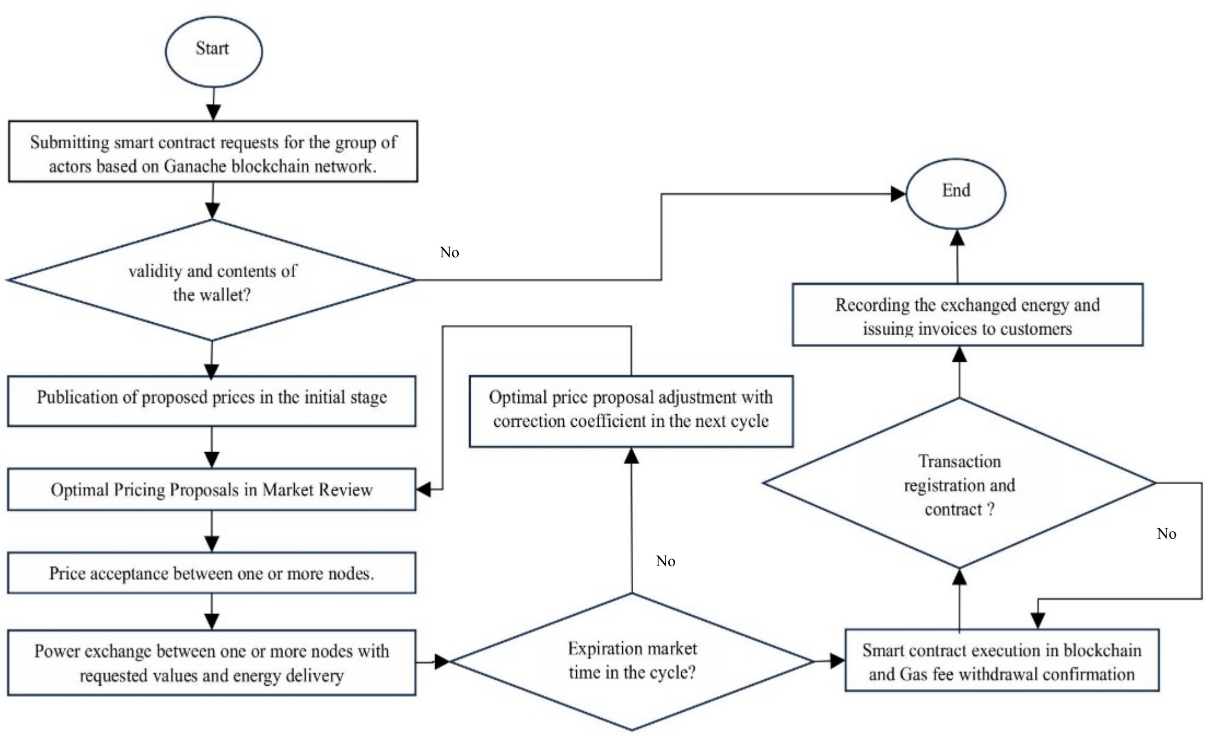

Fig. 1 The process carried out in this article

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from the pool of active sellers, while sellers whose offers have been fully matched exit the market as part of the natural turnover process. This multi-agent, multi-cycle exchange mechanism continues iteratively, with periodic price adjustments and participant realignments, until all trading groups have completed their transactions and the market reaches a cleared state. Market clearing is achieved when cumulative supply and demand convergence is established, and all financial settlements among participants are finalized. Importantly, in each trading iteration, the proposed selling prices from the supplier group are benchmarked against the lowest target sale price, with the minimum bid price adopted as the prevailing energy purchase price for that cycle. All market interactions occur within a virtualized blockchain environment, where the multi-stage auction protocol and node participation mechanism are governed and executed through smart contract automation. The overall process encompasses analytical processing of consumer and prosumer information, optimization of localized energy pricing relationships, and iterative bid–offer matching across successive market cycles. This approach ensures transparent, trustless, and economically optimal energy exchanges, promoting efficiency, resilience, and revenue maximization across the distributed energy network.

The process of interactions and exchanges between market members and smart contracts is performed according to the relevant algorithm. Smart contracts are used to control all energy exchange operations in the local energy market, and market participants directly interact with them. Initially, the users' credentials are verified, and registered users are granted permission to participate in local exchanges. When a market member sends a request for energy surplus or shortage, the status of the multi-stage network smart contract is reviewed, and the user's credentials and registration status in the market are determined.

Each stage of market operation is assumed to act as a closed-loop three-part process to allow energy transactions to occur sequentially and critical supply-demand balance to be achieved:

1) Bid submission: Participants (producers/consumers) submit their encrypted bids through smart contracts and adjust energy quantities and target prices with CFs.
2) Price matching: Price proposals are matched to critical loads in priority using CFs by a double auction mechanism, and prices are updated based on network conditions.
3) Settlement referral: Unfulfilled supply and demand is readjusted and transferred to the next stage with target prices by applying CFs.

2.2 Automatic and Dynamic Pricing Proposal with CFs

The structure of automatic and dynamic pricing in the energy market is of significant importance in the proposed multi-stage network trading market. Therefore, this structure must first be defined. In this paper, the automatic pricing method of the double auction theory is used to enhance efficiency within the comprehensive and general mechanism design for network market trading, based on its unique characteristics, with the aim of improving the proposed efficiency and completing the usage cycle. This theory involves a market of buyers and sellers who interact with each other to exchange their goods. The double auction process is generally carried out in the following step-by-step stages:

- Submission of buy and sell offers (power and price) from producers and consumers.
- Organization of sales offers in an ascending price order and buy offers in a descending price order, applying an innovative and corrective coefficient.
- The intersection of the buy and sell curves was created.
- Finalizing the adjusted and equilibrium price for selected buyers and sellers based on the intersection point.

Considering the steps mentioned, if the proposed price of a consumer is higher than the proposed price of a producer, energy exchange between these two will take place, with the exchange being limited to the minimum power offered by both parties.

The competition in network energy exchange lies in the consumers' desire to buy energy at a lower price and the sellers' desire to sell energy at a higher price if they have excess capacity. Therefore, in the proposed multi-stage exchange, the lowest energy sale price in the local market C_i is equivalent to the maximum sale price range to the upstream distribution network $P_{i(grid)}$ and the energy production cost C_i by sellers. The price of buying energy l_j is equal to the energy supply price in the upstream distribution network $P_{d(grid)}$. These basic pricing relationships are shown in Eqs. 1 and 2.

$$c_i = max \ \{P_{i(grid)}, C_i\} \tag{1}$$

$$l_j = P_{d(grid)} \tag{2}$$

At the beginning of the pricing proposal process, each customer defines their initial bid price as the target price τ. Then, in subsequent iterations of the process, they update their bid price according to Eqs. (3) and (4) to reach a new target price.

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$$\mathrm{bid_i(k+1)}=\begin{cases} \mathrm{bid}_{i,max}\,(\mathrm{k})\ \text{-}(\mathrm{bid}_{i,max}\,(\mathrm{k})\ \text{-max}\left\{\mathrm{c_i}\ \&\ \mathrm{bid_{j,min}}\,(\mathrm{k})\right\}/\eta_{\mathrm{i}}),\mathrm{k}=0 \\ \mathrm{bid}_{i,max}\,(\mathrm{k})\ \text{-}(\mathrm{bid}_{i,max}\,(\mathrm{k})\ \text{-}\ ?_i\,(\mathrm{k})\,)/\eta_{\mathrm{i}},\mathrm{k}?1 \end{cases} \tag{3}$$

$$\mathrm{bid}_j\mathrm{(k+1)}=\begin{cases} \mathrm{bid_{j,min}}\,(\mathrm{k})\ \text{-}(\mathrm{bid}_{c,min}\,(\mathrm{k})\,\text{-min}\left\{\mathrm{l_j}\ \&\ \mathrm{bid_{j,min}}\,(\mathrm{k})\right\}/\eta_{\mathrm{j}}),\mathrm{k}=0 \\ \mathrm{bid_{j,min}}\,(\mathrm{k})\ \text{-}(?_{\mathrm{j}}\,(\mathrm{k})\ \text{-}\ \mathrm{bid_{j,min}}\,(\mathrm{k})\,)/\eta_{\mathrm{j}},\mathrm{k}?1 \end{cases} \tag{4}$$

In Eqs. (3) and (4), the following variables are defined: $bid_i\,(k)$ is the seller's bid price in round K. $bid_{i,max}\,(k)$ is the highest selling price in round K. $bid_{j,min}\,(k)$ is the minimum buying price in round K. $\boldsymbol{\eta}_i$ is the seller's income reduction rate. $\boldsymbol{\tau}_i\,(k)$ is the target price for seller i in round K (adjusted price at each stage). $bid_j\,(k)$ is the buyer's bid price in round K. $\boldsymbol{\eta}_j$ is the buyer's cost increase rate. $\boldsymbol{\tau}_j\,(k)$ is the target price for buyer j in round K (adjusted price at each stage).

To ensure the economic profit of each customer and to illustrate the varying inclinations of customers towards gaining or losing revenue, CF is introduced in Eq. (5). These correction factors are used in the construction of target prices τ at each stage of the exchange market.

$$\mathrm{CF_{i,j}\,(k+1)} = \begin{cases} \mathrm{CF_i\,(k+1)} = \mathrm{CF_i\,(k)} + \alpha\ [\delta\ (k) - \mathrm{CF_i\,(k)}]\ ; & for\ buyer\ (i) \\ \mathrm{CF}_j\,\mathrm{(k+1)} = \mathrm{CF}_j\,\mathrm{(k)} + \beta\ [\delta\ (k) - \mathrm{CF}_j\,\mathrm{(k)}]\ ; & for\ seller\ (j) \end{cases} \tag{5}$$

Where $\delta\,(k) = 1 + \lambda\,(k)$ is the adjustment factor dependent on the previous stage. It is worth noting that the value of δ(k) ranges from −0.5 to 0.5, and the values of α and β also range from 0 to 1.

By considering the updated equations with correction factors at each stage of the network energy exchange market, the target prices of interest between producers and consumers are obtained. These are shown in Eqs. (6) and (7).

$$?_{\mathrm{i}}\mathrm{(k+1)}=\begin{cases} \mathrm{bid}_i\,(\mathrm{k}) + (\mathrm{bid}_i\,(\mathrm{k})\ \text{-}\ \mathrm{c_i}) * \mathrm{CF_i\,(k)}\,,\mathrm{CF_i\,(k)} \in (\text{-}1,0] \\ \mathrm{bid}_i\,(\mathrm{k}) * (1\text{-}\mathrm{CF}_i\,(\mathrm{k})\,),\mathrm{CF_i\,(k)} \in (0,1) \end{cases} \tag{6}$$

$$?_{\mathrm{j}}\mathrm{(k+1)}=\begin{cases} \mathrm{bid}_j\,(\mathrm{k}) + (\mathrm{bid}_j\,(\mathrm{k})\ \text{-}\ \mathrm{l_j}) * \mathrm{CF\,(k)}\,,\mathrm{CF}_j\,(\mathrm{k}) \in (\text{-}1,0] \\ \mathrm{bid}_j\,(\mathrm{k}) * (1\text{-}\mathrm{CF}_j\,(\mathrm{k})\,),\mathrm{CF}_j\,(\mathrm{k}) \in (0,1) \end{cases} \tag{7}$$

These target price update equations are central to the optimization process, dynamically adjusting bids to converge towards a market equilibrium price that maximizes social welfare the collective benefit of all buyers and sellers.

2.3 Decentralized Settlement Mechanism

Given that the energy market is a closed auction market, the market expiration time (Du and Li 2018) and the method for settling the market through the smart contract network settlement program are examined. Market settlement is crucial because it reflects the difference between the predicted market price and the actual production or consumption price. As recommendations from sellers and buyers directly impact the results of the energy market, determining the difference between actual and predicted values after-market expiration, which leads to the payment of rewards or penalties for local sellers and buyers, is essential for the continuation of energy trade trends.

Settlement in the market reflects the difference between predicted electrical energy and the actual electrical energy produced or consumed, making the bidding process economically binding. Since the proposals from sellers and buyers influence the auction outcomes, after the energy transaction period, each participating party is responsible for the quantities of energy that were either not delivered or not consumed. In other words, the way the discrepancy between actual and predicted values is determined is important because it leads to the transaction payment and amounts receivable, which act as incentives for local sellers and buyers to continue trading. Various methods of energy market settlement have been proposed for this purpose, and this paper will use the pairwise settlement (PS) method (Du and Li 2018). The mechanism of this settlement is such that if a seller fails to deliver the auctioned quantity of power or a buyer fails to consume the auctioned quantity, they must pay penalties corresponding to the price difference between the auction price and the retail price. The settlement process described can be illustrated as shown in Table 2.

In Table 2, rP_b is retailer price for buyers, rP_s is retailer price for sellers, aP is the auction price, abQ_j is the auctioned buying quantity of buyer *j*, asQ_i is the auctioned selling quantity of seller *i*, cQ_j is the consumed quantity of buyer *j*, dQ_i is the delivered quantity of seller *i*, ncQ_j is the non-consumed quantity of buyer *j*, ndQ_i is the non-delivered quantity of seller *i*, *m* and *n* are the number of buyers and sellers respectively, B_i^{pen} is the penalty of buyer *j*, S_i^{pen} is the penalty of seller *i*, B_j^{pay} is the payment of buyer *j* and S_i^{en} is the encashment of seller *i*.

The proposed settlement is automatically done through Ethereum-based smart contracts on the Ganache blockchain and eliminates centralized intermediaries. Key features of this type of settlement include:

- Immutable transactions: each transaction is recorded in a chain in each block, and its immutability is ensured by the unique transaction hash.

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Table 2 The process considered for the settlement of the network smart contract market

Seller (*i*)	Buyer (*j*)
For i in range (1 , n):	*For j in range (1 , m):*
IF $dQ_i < asQ_i$:	*IF* $cQ_j < abQ_j$:
$ndQ_i = \lvert asQ_i - cQ_i \rvert$	$ncQ_j = \lvert abQ_j - cQ_j \rvert$
$S_i^{pen} = ndQ_i \times (rP_b - aP)$	$B_j^{pen} = ncQ_j \times (aP - rP_s)$
$S_i^{en} = dQ_i \times aP - S_i^{pen}$	$B_j^{pay} = cQ_j \times aP + B_j^{pen}$
ELIF $dQ_i > asQ_i$:	*ELIF* $cQ_j > abQ_j$:
$S_i^{en} = (asQ_i \times aP) + (dQ_i - asQ_i) \times rP_s$	$B_J^{pay} = (abQ_i \times aP) + \left(cQ_j - abQ_j\right) \times rP_b$
ELIF $dQ_i = asQ_i$:	*ELIF* $cQ_j = abQ_j$:
$S_i^{en} = asQ_i \times aP$	$B_j^{pay} = abQ_j \times aP$

- Penalty and reward system: participants who fail to deliver or consume their committed energy will be penalized based on the price difference of retail and will be automatically enforced by smart contracts.
- Gas consumption optimization: settlement execution in the Ganache environment reduces transaction costs by 18–25% compared to Main-net and Test-net environments, which is critical for small-scale transactions.

2.4 The Developed Web environment, Test Networks and Functional Plugin in Executing

In the implementation of smart contracts in various domains, including electrical energy and its connection to the blockchain, digital currency funding, and internet server connectivity, transaction fees in the form of the respective cryptocurrency must be paid. Therefore, this section introduces the developed web environment and experimental networks to enable the execution and result evaluation of program codes free of charge. In this paper, the Visual Studio Code (VSC)-based development environment is used to code the equations mentioned in previous sections. In the VSC environment, users can create, edit, and use programming codes and also generate project outputs in text file format. For implementing smart contracts, this software environment is utilized due to its support for multiple programming languages such as Solidity and JavaScript (). Furthermore, this paper uses the Ganache Ethereum test network to test decentralized applications for smart contract execution and transaction validation. The Ethereum Ganache blockchain test network is selected because it creates a balance between network security, decentralization, scalability, and high transaction speed and allows the creation of multiple user addresses (up to 10 users) with free virtual Ethereum tokens ranging from 100 to 1000 in the Metamask wallet, as shown in Fig. 2. It also supports private keys, making it a more suitable choice compared to other available networks (;.;.).

In the Ethereum Ganache blockchain network and smart contracts, an electronic wallet is assigned to each market participant, and the producer receives cryptocurrency or electronic money from the consumer for the energy sold. In this way, after receiving the information, a bill with transaction details for the energy exchange of each customer is generated, and a payment request is issued. Metamask, the official and trusted Ethereum wallet, operates as a browser extension for Chrome and Firefox. This software easily stores Ethereum cryptocurrency and enables interaction and transactions with other users on the Ethereum blockchain network, allowing users to send or receive Ethereum. This extension provides a platform for decentralized applications to interact with smart contracts, and Ethereum developers use it extensively for their projects (…).

3 Optimization Model

The model is a mixed-integer linear programming (MILP) problem whose main objective is to maximize social welfare (the collective economic profit of all buyers and sellers in the distribution network market) while ensuring that operational constraints are met.

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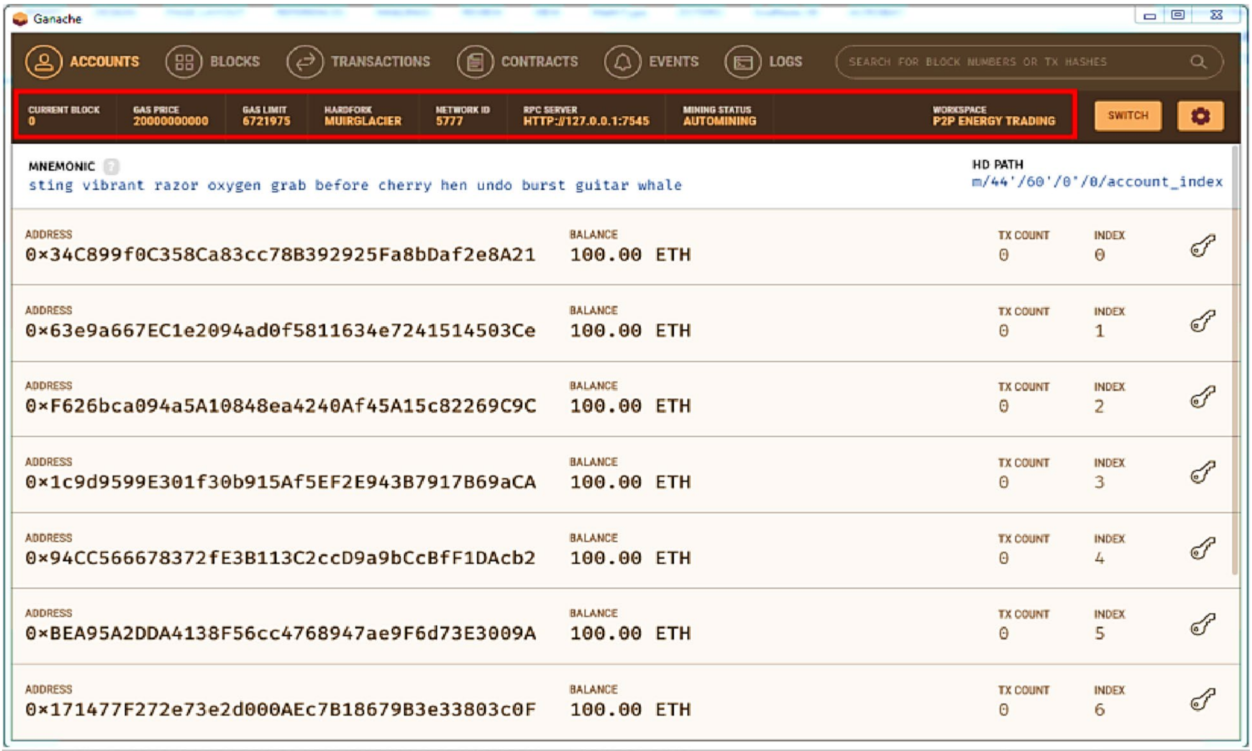

Fig. 2 The Ganache blockchain network with users' account information, addresses and private keys

3.1 Objective Function

The objective function maximizes total social welfare (SW) across all market participants over the trading horizon, which is defined as the difference between consumers' total utility and producers' total cost.

$$Max\ SW = \sum_{k=1}^{n}\left[\sum_{j=1}^{N_b}\tau_j(k) * E_{b,j}(k) - \sum_{i=1}^{N_s}\tau_i(k) * E_{s,i}(k)\right] \quad (8)$$

Where:

- K is the total number of trading stages.
- N_b and N_s are number of buyers and sellers.
- $E_{b,j}(k)$ is the energy purchased by buyer j at stage k (kwh).
- $E_{s,i}(k)$ is the energy sold by seller i at stage k (kwh).

3.2 Operational and Technical Constraints

The proposed optimization framework considers the following constraints to ensure market efficiency and maintain grid stability:

- Supply-demand equilibrium: $\sum_{i=1}^{N_s} E_{s,i}(k) = \sum_{j=1}^{N_b} E_{b,j}(k) \quad \forall k \in \{1,2,\ldots,K\}$
- Capacity limitations: $0 \le E_{s,i}(k) \le Q_{p,i}(k) \quad \forall i \in \{1,2,\ldots,N_s\}$ & $0 \le E_{b,j}(k) \le Q_{c,j}(k) \quad \forall j \in \{1,2,\ldots,N_b\}$ where $Q_{p,i}(k)$ denotes the maximum available energy from seller i and $Q_{c,j}(k)$ represents the maximum demand of buyer j at stage k.

4 Results and Discussion

This section focuses on the evaluation and review of the new mechanism presented in this paper for local energy exchange in a multi-stage network electricity market based on smart contracts on the blockchain platform. In this context, a case study is used to assess the proposed mechanism. The case study involves the implementation of a multi-stage network smart energy exchange market in a 33-bus IEEE distribution network, as shown in Fig. 3. The implementation is carried out on a desktop computer with an Intel Core i7 processor and 8 GB RAM. The smart contract is extended in an Ethereum JVM browser and a VSC version 4.5 development environment.

In Fig. 3, the single-line diagram of the assumed network with 10 participating nodes in the proposed market is shown.

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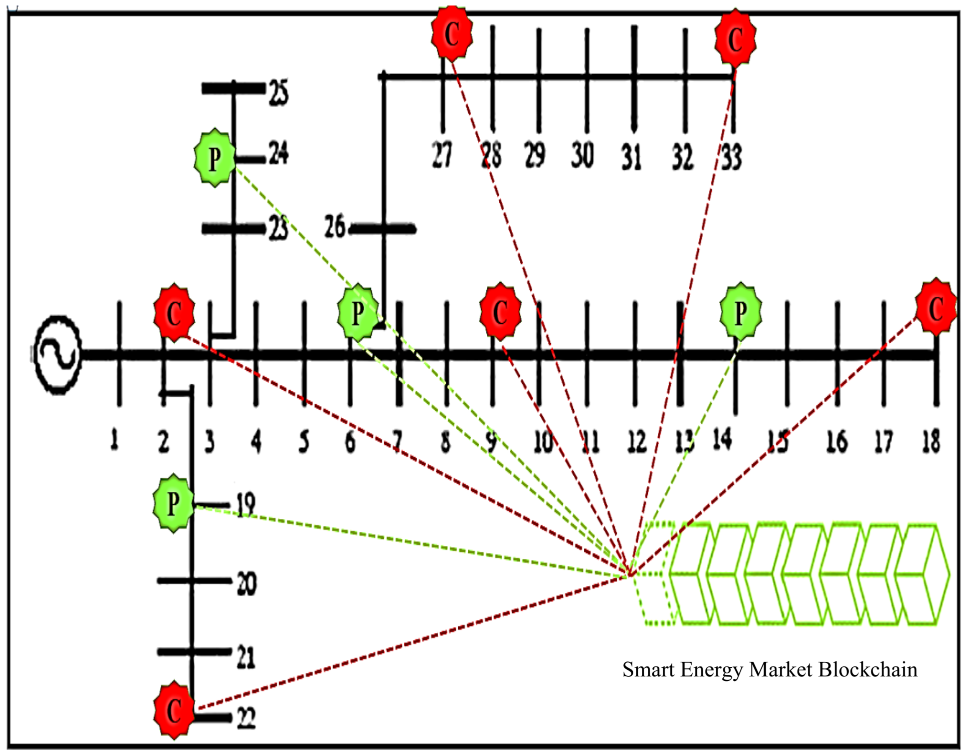

Fig. 3 Single-line diagram of the IEEE 33-bus network with the representation of seller and buyer nodes

Table 3 Indices and price parameters of sellers with correction factors

Node	CF_i	$Q_{p,i}$ (kw)	$bid_{i,max}$ $(\$/kwh)$	τ_i (\$/kwh)	c_i (\$/kwh)	η_i
6	0.1	100	0.04	0.04	0.03	5
12	−0.1	75	0.03	0.03	0.03	4
15	0.1	75	0.05	0.05	0.035	3
19	0	100	0.04	0.04	0.035	3

Table 4 Indices and price parameters of buyers with correction factors

Node	CF_j	$Q_{c,j}$ (kw)	$bid_{j,min}$ (\$/kwh)	τ_j (\$/kwh)	l_j (\$/kwh)	η_j
9	0	100	0.05	0.05	0.062	3
18	−0.5	45	0.045	0.045	0.062	4
22	−0.5	45	0.045	0.045	0.062	4
24	0.5	30	0.06	0.045	0.062	5
30	0	100	0.06	0.06	0.062	6
33	0	30	0.06	0.06	0.062	6

The Ganache blockchain can support 10 nodes in exchange for a charge of 100 Ethereum per cycle (all the color-coded points marked in Fig. 3). According to this figure, four green points correspond to the producer group (sellers), and six red points represent consumers (buyers) in the electrical network. In Tables 3 and 4, the indices and price parameters of the sellers at nodes [6, 12, 15, 19] with correction factors, as well as the indices and price parameters of the producers with correction factors at nodes [9, 18, 22, 24, 30, 33], are provided for use in Eq. (3) to (7) in the VSC environment.

At this stage of the proposed market idea for the studied network, the necessary indices and parameters for each of the consumers and producers, as well as the required software platform, have been determined. Now, it is possible to evaluate and examine the new mechanism presented in this paper for energy exchange in a multi-stage network electricity market based on smart contracts within the blockchain environment, using the VSC development platform.

In this context, by executing the commands NPM INSTALL, NPM RAN GANACHE, and NODE MAIN in the Terminal toolbar of the VSC development environment, the Ganache blockchain is run with the website connected to the server on Port 5000, listening for smart contract interactions, as shown in Fig. 4. This allows for retrieving

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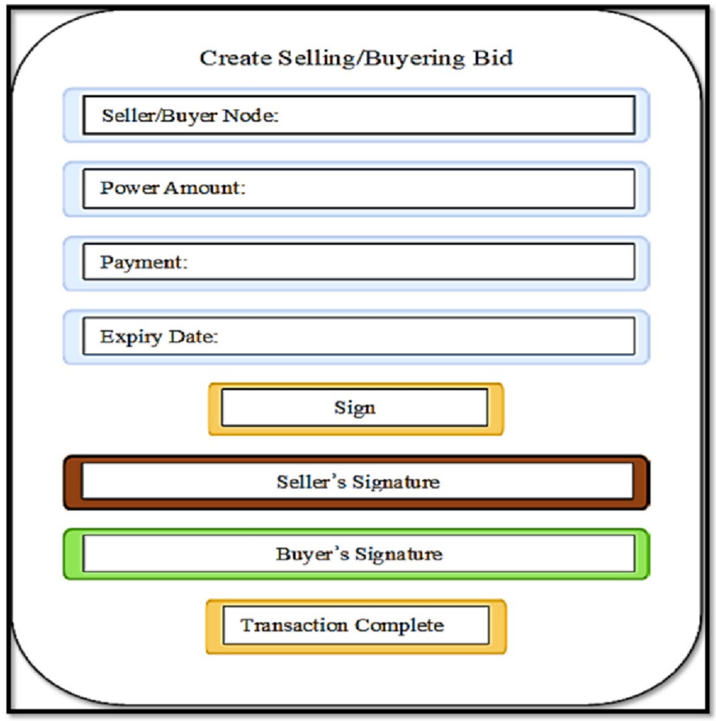

Fig. 4 Price offer information between the buyer and seller at each stage of the energy market execution

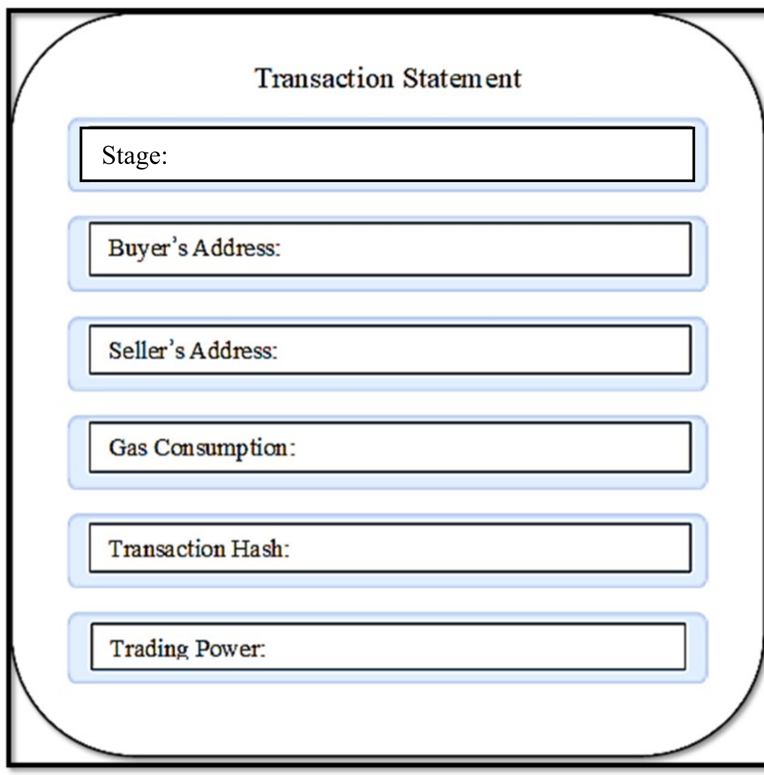

Fig. 5 Invoice information and transaction details of the energy exchanged between the buyer and seller at each completed stage of the energy network market

information such as the buyer and seller addresses, the required exchange energy and power, the target price for buying and selling power, the relevant factors, and the market expiration time based on the price offer. Once this information is received, the smart contract is executed by signing it on behalf of each buyer and seller, connecting to the MetaMask wallet. The transaction details, including the buyer and seller addresses, are then recorded, and the transaction fees are captured on the Ganache blockchain.

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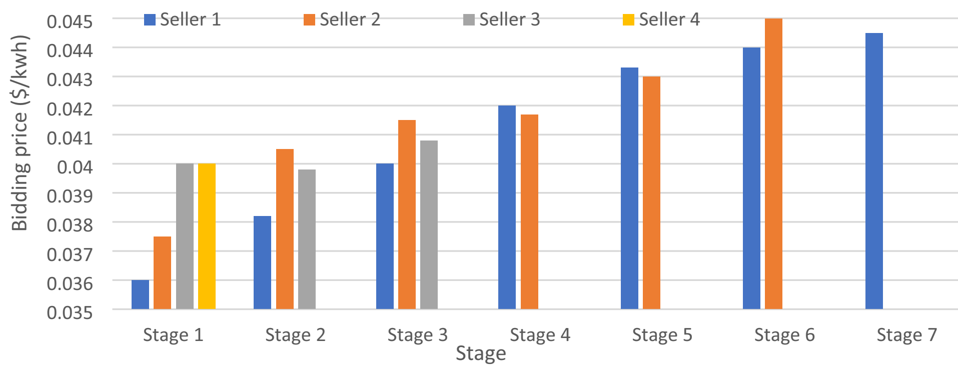

Fig. 6 Adjusted proposed prices with correction factors applied by sellers at each stage of the energy market

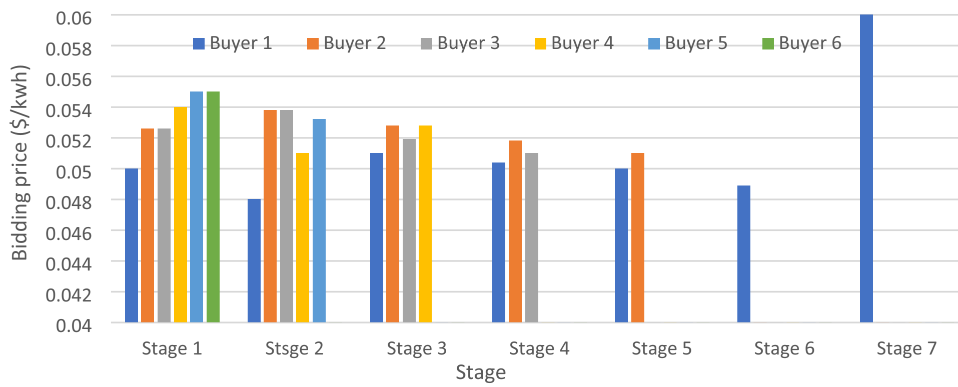

Fig. 7 Adjusted proposed prices with correction factors applied by buyers at each stage of the energy market

Subsequently, with the confirmation of the smart contract signatures recorded on the Ganache blockchain and the appearance of the message "Transaction successfully recorded on the VSC website server," the first cycle of the multi-stage market execution takes place. The specified energy between the seller and buyer is exchanged using the designated addresses. Then, an invoice, as shown in Fig. 5, is generated containing the market cycle number, buyer and seller addresses, transaction cost, transaction hash, and the amount of energy exchanged during this stage, all of which are stored in the current block of the Ganache blockchain.

The process of market execution continues with the exchange and update of accounts in the MetaMask wallet for later phases. Price proposals for buying and selling are updated with other network nodes based on the requested or supplied electricity until a supply-demand balance is achieved. In the execution of the smart market in the investigated network, it can be noted that buyers and sellers (players) in different cycles, using price offer methods based on the correction factor, alter and adjust their target price offers to maximize economic profit and produce more income. This is done to ensure that the existing trading opportunity is used as quickly as feasible and that the best potential optimization of buying and selling occurs in accordance with the techniques indicated in Figs. 6 and 7.

In layman's terms, each seller or buyer participating in the multi-stage energy network exchange based on smart contracts on the Ganache blockchain exits the market exchange cycle in the next stage after meeting the requested or delivered power at the optimized and updated target price, as shown in Fig. 8. The market flow continues for the remaining players until supply and demand are balanced or until the market expires. Finally, once the energy market is complete, the transferred power amounts, as well as transactions and customer invoices, are saved in the personal accounts of each supplier and buyer within the blockchain blocks and made visible.

It has also been observed that some sellers and buyers, after successfully selling their excess energy (energy delivery) or purchasing the required energy (energy supply) at any stage, exit the market exchange in the next stage of the price offer process, leaving the market with a price of zero while retaining the income generated. This phenomenon is depicted in Fig. 8, which shows information about energy exchange quantities from the first stage to the supply and demand equilibrium stage (seventh stage). Based on the traded energy, each energy block acts in the opposite manner (buy and sell), with any unexchanged energy being passed to the next stage or cycle.

In this article, the results of a comparative execution of the proposed multi-stage energy market on the IEEE 33-bus network with 10 nodes (including 4 sellers and 6 buyers) with targeted and dynamic prices, as well as the adjustment coefficients compared to the single-stage market with fixed prices and no matching, as reported in references (Hasan

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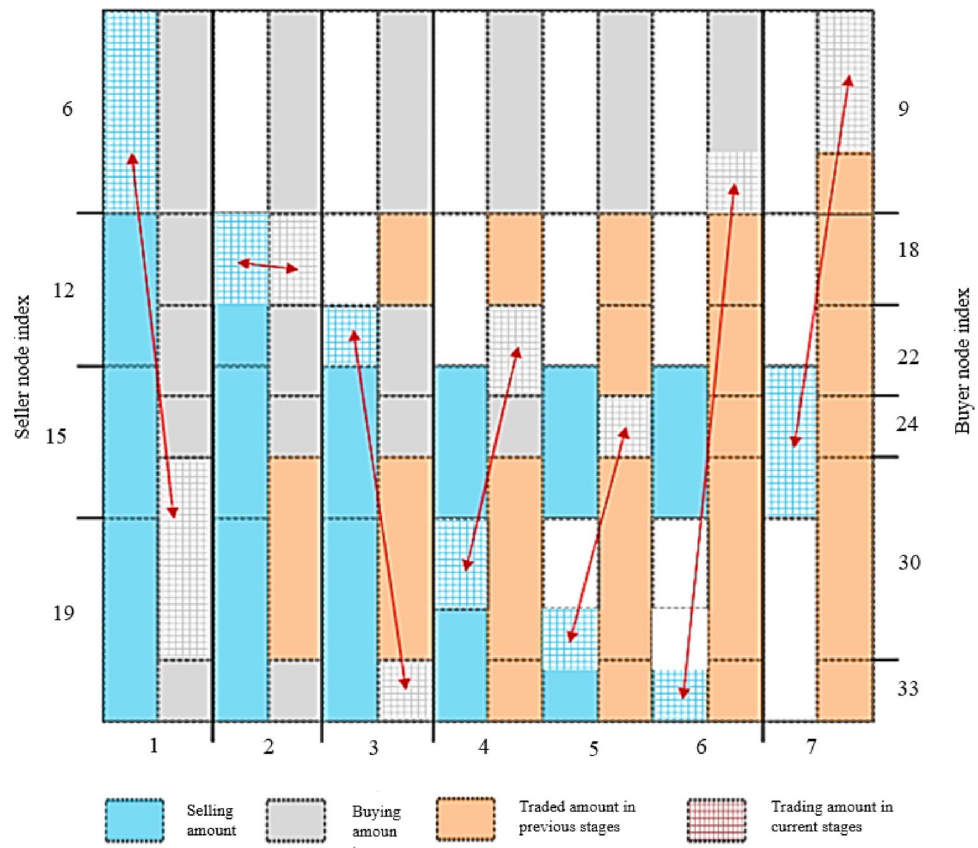

Fig. 8 Amounts of electrical energy exchanged at each stage of the energy market execution

Table 5 Comparative results from multi-stage market implementation

Parameters	Proposed Model	Single-Stage (Hasan et al. 2022)	Static Pricing (Hou, et al. 2023)
Transaction Cost (ETH)	0.0021	0.0027	0.0031
Settlement Time/Stage (s)	4.2	7.1	6.8
Profit Fairness Index	0.89	0.67	0.72

et al. 2022; Hou et al. 2019) and Huang et al. (2020) are described as follows in Table 5:

- 25% reduction in transaction costs and gas consumption from 0.0027 Ether per trade to 0.0021 Ether per trade compared to the single-stage market model (Hasan et al. 2022), due to an agreement on setting and adjusting proposed prices.
- 40% increase in the speed of settlement of intelligent transactions from 7.1 s (Hou et al. 2023) to 4.2 s at each stage is critical for markets sensitive to instant supply.
- 33% increase in convergence rate and a reduction in the number of steps required to achieve supply-demand balance compared to the static pricing model (Hou et al. 2019) due to the mechanism of corrective factor and adaptive price discovery for critical loads with load sensitivity index (LSI = 1) and prices close to retail prices (0.058 $/kwh).
- Load management by considering the prioritization of load sensitivity (LS) for access to reliable energy throughout all stages of market implementation compared to markets without prioritization (Huang 2020) even in times of energy supply shortages.

The Profit Fairness Index (PFI) is a quantitative metric used to assess the equity of profit or economic benefit distribution among participants in decentralized energy markets. It is particularly relevant in peer-to-peer (P2P) energy trading systems, where ensuring fairness is essential to encourage participation, prevent exploitative behavior, and promote the sustainable utilization of energy resources. The PFI takes into account a variety of parameters, including energy participation levels, bidding and selling techniques, and load priority rankings, to determine the level of profitability balance between energy buyers and sellers (Zhang et al. 2017). The index normally varies from 0 to 1, with 1 representing total fairness, indicating that all participants obtain profits proportionate to their market contributions, and 0 representing complete inequality, where profits are concentrated among a small subset of players. In the proposed multi-stage market

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model, the computed PFI value of 0.89, compared to 0.67 observed in conventional single-stage models, demonstrates a more equitable distribution of profits among both sellers (e.g., small-scale solar and wind producers) and buyers (e.g., households and vital loads). This higher index value confirms the superior fairness and inclusivity of the multi-stage market mechanism in allocating economic benefits across participants.

5 Conclusion

In this paper presented a novel blockchain-based framework for a multi-stage local electricity market. The three core contributions: (1) the dynamic CF-based auction mechanism, (2) the cost-effective decentralized settlement on Ganache, and (3) the critical load prioritization algorithm collectively address key challenges of high transaction costs, inefficient pricing, and lack of fairness and resilience. The results demonstrate a 25% reduction in transaction costs, a 33% improvement in convergence speed, a 92% market efficiency, and superior fairness (PFI = 0.89) compared to existing models. This work provides a viable and scalable model for integrating small-scale renewables and empowering prosumers in the future smart grid.

6 Future Directions

While the model showcases scalability for up to 10 nodes, testing on larger networks (100 + nodes) and integration with energy-rich blockchains (e.g., Polkadot) could further validate robustness. Future work will explore hybrid consensus mechanisms to reduce time overhead and expand the LSI framework to incorporate dynamic network conditions. Policymakers and utilities are urged to pilot this approach in rural networks, where decentralized trading can accelerate energy equity and decarbonization.

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Data Availability No datasets were generated or analysed during the current study.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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