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RESEARCH ARTICLE

Decentralized Community Energy Management: Enhancing Demand Response Through Smart Contracts in a Blockchain Network

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ABSTRACT The integration of distributed energy resources (DERs) and digital technologies has accelerated the transition to decentralized energy systems. Among these technologies, blockchain stands out for its ability to facilitate peer-to-peer (P2P) energy trading efficiently and securely. This paper explores the concept of P2P energy trading within community microgrid systems, leveraging blockchain-based smart contracts. The proposed system integrates an incentive-driven demand response program directly into the smart contract framework, offering real-time rewards for load-balancing contributions. By incorporating the microgrid's Energy Management System (EMS) and transparently recording all transactions on the blockchain, the proposed platform provides detailed data and immediate reward distribution. At the core of our system lies the Supply to Demand Ratio (SDR), ensuring fair energy exchange within the community. Dynamic pricing, enabled by blockchain and Tether (USDT) cryptocurrency, adjusts to real-time market conditions, enhancing transparency and responsiveness in energy trading. This adaptive pricing model fosters a more equitable and efficient trading environment compared to static approaches. Moreover, this system is tailored for community microgrids, emphasizing a community-centric approach. Local prosumers serve as validators in the blockchain network, aligning energy management decisions with community needs and dynamics. This localized engagement promotes efficiency and participation, fostering resilient, sustainable, and user-centric energy landscapes. Through rigorous analysis, we demonstrate the system's effectiveness in optimizing economic efficiency, reducing operational costs, and increasing compliance rates. By combining blockchain technology with community-focused design principles, the proposed platform represents a significant advancement towards self-sufficiency and resilience in local energy systems.

INDEX TERMS Blockchain technology (BT), microgrid energy management system (MEMS), peer-to-peer (P2P) energy trading, prosumers, demand response (DR), smart contract.

NOMENCLATURE: VARIABLES AND PARAMETERS

P2P:	Peer to Peer.
BESS:	Battery Energy Storage System.
DER:	Distributed Energy Resource.
RES:	Renewable Energy Sources.
COP:	Conference of the Parties.
PCC:	Point of Common Coupling.
USDT (Tether):	Cryptocurrency.
$P = \{p_1, p_2, \ldots, p_n\}$:	Set of prosumers.
$C = \{c_1, c, \ldots, c_n\}$:	Set of consumers.

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$G_{p_i,h}$: Energy generation by prosumer p_i at time h.
$L_{c_j,h}$: Energy demand (load) of consumer c_j at time h.
$Cost_{p_i,h}$: Cost of energy generation for prosumer p_i at time h.
$Price_h$: Price of energy in the market at time h.
$E_{p_i \rightarrow c_j,h}$: Energy sold from prosumer p_i to consumer c_j at time h.
$MaxGen_{p_i}$: Maximum generation capacity of prosumer p_i.
$MaxCons_{c_j}$: Maximum consumption capacity of consumer c_j.
$G_{grid,h}$: Energy bought from the grid at time h.
$Price_{grid,h}$: Price of energy from the grid at time h.
$C_{p_i,h}$: The energy charged to the battery of prosumer p_i at time h.
$D_{p_i,h}$: The energy discharged from the battery of prosumer p_i at time h.
η_{charge}: The charging efficiency of the prosume r's battery (0.9).
$\eta_{discharge}$: The discharging efficiency of the prosume r's battery (0.9).
SDR: Supply to Demand Ratio
$USDT_{P2P}$: Trading Price for Individual Household who Participate in the P2P Energy Trading.
$USDT_{usell}$: Surplus Power Price Sold to the utility Grid.
$USDT_{ubuy}$: Utility Grid Price.

I. INTRODUCTION

A. MOTIVATION AND BACKGROUND

Distributed Energy Resources (DERs) and microgrids are increasingly recognized as key solutions to meet the growing energy demand, a result of global industrialization and urbanization. This shift aligns with global governmental initiatives to lessen dependence on fossil fuels. The 2021 COP-26 summit highlighted this trend, urging governments to propose bold emission reduction targets for 2030, aiming for net-zero carbon emissions by mid-century. Achieving these goals will require significant investment in Renewable Energy Sources (RESs), accelerated adoption of electric vehicles, and gradual phasing out of fossil fuel-based power generation. Microgrids (MGs) offer versatility in operation, capable of functioning independently in an isolated mode or integrating with the main grid in a grid-connected mode through a Point of Common Coupling (PCC). This dual functionality allows them to autonomously manage energy needs or exchange energy with the main grid following specific guidelines. As we move forward, an increase in microgrid installations is anticipated, which will play a crucial role in reducing dependency on high-voltage networks and fossil fuel-based power plants [1], [2], [3]. Several obstacles need to be addressed to facilitate broad market participation. These include (i) effectively incorporating the concept of local energy trading within the distribution network, (ii) ensuring robust communication channels between microgrid operators and Distribution System Operators (DSOs), and (iii) developing a user-friendly platform that encourages public engagement in energy trading. Additionally, if factors such as price-responsive loads and the principles of perfect competition are not considered while shaping the energy market in the distribution system, there's a risk of setting prices that are either excessively high or unduly low. Fostering intra-microgrid trading is a key strategy for minimizing reliance on the central utility grid. Community microgrid systems offer significant benefits for local energy needs. Nowadays, even in areas served by larger grids, community microgrids are being explored to enhance local energy independence and resilience. Peer-to-Peer (P2P) energy trading is a system that permits households to distribute excess energy among their neighbors once their personal energy needs have been satisfied, as noted in [4]. In the environment of a microgrid, transactions of energy can take place among individual community members or between these members and the utility grid. Each participant in the microgrid is identified as a peer, including both those who actively consume and generate energy and those who solely consume it, as mentioned in [5]. Active energy consumers, commonly known as prosumers, are characterized by their ownership of distributed energy resources (DERs) like rooftop solar systems or wind power installations.

B. RELATED WORKS

The research presented in [6] delves into optimizing power dispatch in microgrids, a crucial aspect of ensuring efficient and reliable energy distribution in isolated systems. Significant research has been conducted on the integration of Renewable Energy Sources (RES), battery storage, and electric vehicles into power grids, a topic extensively covered in reference [7]. The application of blockchain technology in smart grids, especially for improving the operational efficiency of microgrids, is a key area of focus, as described in [8]. Research trends are increasingly centered on demand-side management and the enhancement of microgrid operations. The use of blockchain technology as a coordination tool for Distributed Energy Resources (DERs) is discussed in [9], where it is recognized for providing a secure and transparent framework essential for maintaining the integrity and safety of DER operations. Munsing et.al [10] introduced a decentralized model for optimal power flow (OPF) aimed at effectively managing a variety of DERs within microgrids, focusing on optimization and control.

Additionally, the application of blockchain in demand-side management, as investigated in [11], has shown promise in reducing the peak-to-average ratio (PAR) and mitigating fluctuations in load profiles caused by supply constraints. A novel approach involving blockchain for link control in medium voltage DC systems is presented in [12], where the strategy focuses on allocating responsibilities between system operators and the energy network. Integrating a digital layer into the elements of the smart grid, as proposed in [13], blockchain technology can substantially improve grid functionality, allowing each component to have its individual ledger within a cohesive blockchain framework. The area of energy trading in microgrids and distributed generation systems is increasingly becoming a focal point, as noted in [14]. The influence of blockchain on P2P energy exchanges is significant, providing enhanced cyber-physical security and reducing the risk of fraudulent activities, as detailed in [15]. In P2P systems, blockchain records transactions instantaneously and autonomously, eliminating the need for intermediaries and empowering energy traders to make decisions based on their preferences, as observed in [16]. Optimization in P2P trading within blockchain networks, particularly in Optimal Power Flow (OPF) applications, is discussed in [13]. Globally, there are numerous blockchain use cases. A notable example is the Brooklyn microgrid project, facilitated by Power Ledger, an Australian firm enabling prosumers to transfer surplus energy to nearby users. Other companies like Grid+, SIEMENS, and LO3 Energy have also been instrumental in advancing peer-to-peer power trading in microgrid systems through blockchain technology, as discussed in [11].

Numerous recent studies have explored various optimization techniques applied in microgrids for Demand-Side Management (DSM), including dynamic programming, and mixed integer linear programming, as noted in references [17], [18], [19], [20]. This paper [21] introduces a multi-objective optimization approach to balance load flexibility. Prete et al. have utilized game theory to analyze incentive schemes that encourage participation in microgrid consumption [22]. A non-cooperative game framework has been adopted to study the integration of solar PV systems in microgrids among diverse consumer groups [23]. Research on integrating hybrid PV and wind systems into microgrids for size optimization is discussed in [24]. Various strategies aim to reduce the Peak-to-Average Ratio (PAR) and cost through pricing incentives, with DSM frameworks incorporating battery storage examined in [11]. The paper [25] explores distributed secondary control and management of islanded microgrids through dynamic weights. It addresses the complexities of managing energy flow and stability in decentralized grid systems.

The peer-to-peer transactive energy trading in a reconfigurable multi-energy network was explored in [26], emphasizing the role of decentralized trading mechanisms in modern energy systems. Khorasany et al. [27] present a framework for prosumers' participation in peer-to-peer energy trading and flexibility markets. This framework addresses the evolving landscape of energy markets and the role of distributed energy resources. A framework [28] for joint scheduling and power trading of prosumers in transactive markets was discussed which highlights the importance of efficient energy trading mechanisms in sustainable energy systems. The study in [29] proposes a risk-averse day-ahead bidding strategy for transactive energy-sharing microgrids, incorporating data-driven chance constraints to enhance decision-making in energy markets. The paper [30] explores demand response through the control of aggregated inverter air conditioners, showcasing the potential for demand-side management in optimizing energy consumption.

Peer-to-peer (P2P) energy trading facilitates the swift incorporation of Blockchain Technology (BT) into microgrid operations, enabling direct transactions between participants without intermediaries. P2P trading allows electricity exchange among consumers and prosumers, leveraging a cost-effective settlement system. This system benefits participants by monetizing surplus power, reducing electricity bills, and improving returns from distributed generation [31]. Users can regularly switch energy providers and trade electricity based on their preferences. In such systems, BT can track the amount of electricity sold and provide a transparent, automated payment method. Smart meters and IoT-connected devices offer a secure platform for monitoring and managing energy usage within microgrids through BT. Blockchain-based systems in community microgrids could significantly boost the efficiency of distribution systems [32]. Demand-side management via BT exemplifies this, where smart contracts on the BT network determine customer interactions. These contracts facilitate direct transactions, eliminating the need for intermediaries. BT networks aim to reduce overall energy demand and costs [33]. The decentralization provided by BT enhances system transparency and security, utilizing SHA-256 encryption [34]. Energy trading is conducted through automated smart contracts, which outline the terms for transactions. Unlike traditional energy trading, where consumer choice is limited, P2P trading offers greater control to peers involved in energy exchange [35].

The different types of consensus mechanisms commonly used in blockchain networks are shown in Table 1, along with their limitations [36], [37], [38]. In the domain of peer-to-peer (P2P) energy trading, various consensus mechanisms are employed to guarantee the secure and transparent functioning of blockchain platforms [33], [35], [36]. The proposed framework operates on the Ethereum blockchain platform, offering a secure and efficient transaction environment for community microgrid systems involving consumers, and prosumers. To enhance energy efficiency and scalability, the framework adopts the proof of stake consensus mechanism [39], recognized for its reduced energy consumption compared to proof of work [40]. In proof of stake, transaction validation is assigned to nodes based on their stake in the network, eliminating the need for energy-intensive competition in solving complex mathematical problems. This transition holds

TABLE 1. Types of consensus mechanisms in blockchain [36], [37], [38].

Consensus Mechanism	Description	Limitation
Proof of Work (PoW)	Miners compete to solve complex mathematical puzzles to validate transactions and add new blocks to the blockchain.	High energy consumption, scalability issues due to computational requirements, potential for centralization as mining becomes dominated by entities with significant resources.
Proof of Stake (PoS)	Validators are chosen to create new blocks based on the amount of cryptocurrency they hold and are willing to 'stake' as collateral.	Potential for centralization as validators with higher stakes have more power, reduced energy consumption compared to PoW, but still faces scalability challenges.
Delegated Proof of Stake (DPoS)	Token holders vote for delegates responsible for validating transactions and creating new blocks.	Susceptible to collusion among delegates, potential centralization as voting power may be concentrated among a few entities chosen as delegates.
Proof of Authority (PoA)	Trusted nodes are granted authority to validate transactions and create new blocks based on their reputation or identity.	Sacrifices decentralization for efficiency and security, as the network relies on a central authority or a limited number of trusted nodes.
Proof of Burn (PoB)	Validators 'burn' cryptocurrency tokens to earn the right to validate transactions and create new blocks.	Reduces overall supply of the cryptocurrency, potentially affecting liquidity and value, may not be sustainable in the long term.
Proof of Elapsed Time (PoET)	Validators wait for a randomly generated time period before being eligible to validate transactions and create new blocks.	Relies on trusted hardware for randomness, potential point of vulnerability if compromised, may not be suitable for all blockchain applications.
Practical Byzantine Fault Tolerance (PBFT)	Validators agree on the validity of transactions through a series of rounds of communication and voting.	Requires a predetermined number of known and trusted nodes, may not be suitable for permissionless and decentralized networks, limited scalability due to communication overhead.
Proposed Modified Proof of Stake (MPoS)	Local prosumers are chosen as validators to create new blocks, improves network efficiency, and fosters trust among microgrid participants, thereby paving the way for the widespread adoption of P2P energy trading in microgrids.	Based on historical performance only prosumers with high reputation scores will be preferred in validating the transaction which helps to avoid the centralization of stakes. However, scalability remains a challenge, but it's suitable for small network requirements like community microgrid systems.

promise for more eco-friendly and scalable energy trading systems [41].

In response to the distinctive challenges posed by peer-to-peer (P2P) energy trading within microgrid environments, we introduce the Prosumer-Powered Modified Proof of Stake (MPoS) consensus mechanism, specifically tailored for such ecosystems. Unlike traditional Proof of Stake (PoS) protocols, MPoS harnesses the active participation and stake of prosumers—individuals or entities who both consume and produce energy—to validate transactions and create new blocks within the blockchain network. By integrating prosumers into the validation process, MPoS enhances decentralization, resilience, and transparency in microgrid energy trading. Smart contracts are deployed to enforce the rules of MPoS, ensuring transparency, immutability, and integrity in energy transactions, while facilitating real-time settlement between prosumers and consumers. This approach streamlines the validation process, improves network efficiency, and fosters trust among participants, thereby paving the way for the widespread adoption of P2P energy trading in microgrids. Prosumers as validators [42], [43] can significantly enhance the performance and security of blockchain-based energy trading systems. Their proximity to end-users reduces latency and enhances security. Moreover, prosumers are more likely to be motivated to protect the system because they are more likely to be affected by any disruptions to the system.

C. CONTRIBUTIONS

Despite the extensive research on Peer-to-Peer (P2P) energy trading within blockchain platforms, there remains a gap in developing a comprehensive decentralized energy trading platform. To promote the adoption and robust operation of the blockchain within the community microgrid, engaging local prosumers as validators is a pivotal strategy. Validators play a crucial role in verifying and validating transactions on the blockchain, ensuring the integrity and security of the entire decentralized energy management system. The microgrid Energy Management System (EMS) serves as the backbone of the energy infrastructure, promoting the efficient distribution of power among local prosumers and consumers. Integrating blockchain technology into this EMS empowers the local community with a transparent, secure, and decentralized platform. Smart contracts, programmed with predefined rules and conditions, enable the automated and secure execution of agreements, ensuring a fair and reliable energy exchange within the community. The collaboration between local prosumers and the microgrid EMS using blockchain smart contracts creates a dynamic ecosystem for load and generation balancing. Prosumers, acting as validators, contribute to the decentralization and security of the blockchain network, fostering a sense of community ownership. The smart contracts embedded in the microgrid EMS automate tasks such as energy transactions, demand response events, and incentive mechanisms, streamlining operations and enhancing overall efficiency.

This paper seeks to fill these gaps, with the following key contributions:

1. Development of a Local Energy Trading Platform: We have created a platform that facilitates local energy trading among consumers, and prosumers, integrating seamlessly with a blockchain network. This platform is designed with straightforward implementation steps in mind.
2. Calculation of Local P2P Energy Trading Prices: The trading prices within this platform are determined using the Tether (USDT) cryptocurrency, based on a supply-to-demand ratio method. This approach ensures transparent and fair pricing aligned with current market dynamics.
3. Implementation of an Incentive-Based Demand Response Program: An incentive scheme is incorporated into the platform to maintain the balance between load and generation within the community microgrid, enhancing overall efficiency and sustainability.
4. Integration of Local Validators in Blockchain: Validators are selected from among the local consumers and prosumers using Proof of Stake (PoS) consensus mechanism. This approach not only provides them with an opportunity to benefit financially but also contributes to making the local community microgrid more self-sufficient within the blockchain network.
5. Smart Contract: Implementation of automated smart contracts to achieve the desired energy demand profiles enrolled in the DR programs by each participant (consumers and prosumers).

D. PAPER ORGANIZATION

Section I provides a detailed literature review and background of the research. In Section II, we present a comprehensive design framework for decentralized Peer-to-Peer (P2P) energy trading in microgrids, along with mathematical modeling that employs Tether (USDT) cryptocurrency. The methodology, including an algorithm for P2P energy trading using Blockchain Technology (BT) smart contracts, is elaborated in Section III. Section IV is dedicated to discussing the results and analyses of the study. Finally, the conclusions drawn from the research are discussed in Section V.

II. DECENTRALIZED P2P ENERGY TRADING DESIGN AND MODELLING

Microgrid energy management system must ensure that energy balance is maintained within the community microgrid. Here, excess electricity generated by members of the community is sold to the utility grid at a predefined rate, while any additional energy required to meet the community's demand is procured from the grid at standard prices. This system necessitates processes for developing energy trading strategies, setting local electricity tariffs, and calculating energy expenses. Accordingly, Figure 1 illustrates the Peer-to-Peer (P2P) energy trading structure in a grid-connected Microgrid Energy Management System (EMS), featuring prosumers (denoted as p^{th}), and consumers (denoted as c^{th}). In this schematic, solid-colored arrows indicate the physical flow of electricity, whereas dashed arrows represent the flow of information. The presence of Distributed Energy Resources (DERs) on the prosumers' side allows for bidirectional electricity exchange between prosumers and the consumers. This dynamic ensures a flexible and efficient management of local energy resources, optimizing both consumption and generation within the community microgrid. Any surplus generation is first utilized to meet local needs, and then any remaining excess energy from the microgrid is sold to the utility grid. Local prosumers can engage in Peer-to-Peer (P2P) energy trading, supplying energy to other consumers and even neighboring microgrids.

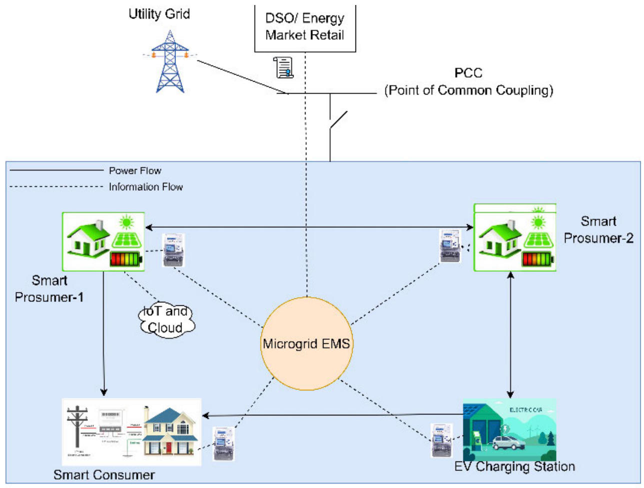

FIGURE 1. Design of peer-to-peer (P2P) trading for energy transactions within a microgrid energy management system (EMS).

This approach significantly modifies the existing peer-to-grid model, also known as the grid feed-in system, where surplus generation is typically sold back to the grid. Under this new paradigm, consumers transform into energy producers, actively participating in the energy market. Households have the opportunity to buy and sell energy at locally determined prices, facilitating energy exchanges within their community. Before initiating energy trades, the original scheduling, including adjustments based on consumer load demands, is communicated across the Blockchain network. This ensures a more effective match between supply and demand, catering to the energy requirements of the community more efficiently.

The flowchart as shown in Figure 2 outlines a blockchain-based energy management and trading process within

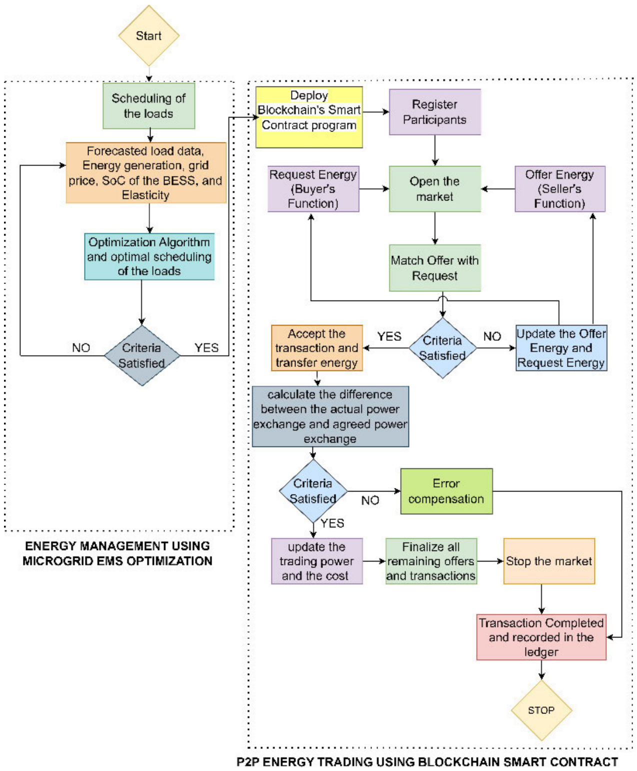

FIGURE 2. Flowchart illustrating energy management and P2P energy trading in a community microgrid.

a community microgrid. It begins with gathering data on forecasted loads, energy generation, pricing, and battery storage, followed by an optimization algorithm that schedules loads for efficient energy distribution. If the optimization criteria are met, the energy management phase concludes. Simultaneously, the energy trading phase communicates excess power availability to buyers through an energy management system, initiating smart contracts on the blockchain to facilitate transactions. Sellers and buyers engage in a process where offers are made, transactions are accepted, and power is exchanged. The system calculates any discrepancies between actual and agreed exchanges, applying error compensation when necessary. Finally, the trading details are updated, ensuring a seamless flow of energy and financial settlement within the microgrid, leveraging the security and efficiency of blockchain technology.

A mathematical formulation for cost optimization in a decentralized energy management system involving prosumers and consumers to focus on balancing energy supply and demand while minimizing the costs of community microgrids [17], [18], [19], [20]. This formulation will consider key constraints such as energy balance, generation, battery storage and consumption limits, and grid constraints.

Objective Function:

Equation (1) represents a mathematical formulation for the minimization of total energy costs in a microgrid system involving peer-to-peer (P2P) energy trading and grid interactions.

$$\boldsymbol{min} \sum_{h\in H} \left(\sum_{c_j\in C} \sum_{p_i\in P} \boldsymbol{Price_h . E_{p_i\rightarrow c_j,h}} + \boldsymbol{Price_{grid,h} . G_{grid,h}} \right) \tag{1}$$

Constraints

1. Energy Balance:
   Equation (2) represents a balance constraint of a microgrid system that involves peer-to-peer (P2P) energy trading and interactions with an external power grid. It ensures that for each hour, the total energy produced and consumed within the microgrid, including any exchanges with the external grid, is balanced.

$$\sum_{p_i\in P} \left(\boldsymbol{G_{p_i,h}} - \sum_{c_j\in C} \boldsymbol{E_{p_i\rightarrow c_j,h}} \right) + \boldsymbol{G_{grid,h}} = 0 \quad \forall \boldsymbol{h} \in \boldsymbol{H} \tag{2}$$

2. Generation Limits: $\boldsymbol{MaxGen_{p_i}}$ is a predefined maximum limit of energy that prosumer $\boldsymbol{p_i}$ can generate in an hour. This limit is determined the capacity of their energy generation equipment (like solar PV panels).

$$0 \leq \boldsymbol{G_{p_i,h}} \leq \boldsymbol{MaxGen_{p_i}} \quad \forall \boldsymbol{p_i} \in \boldsymbol{P},\ \forall \boldsymbol{h} \in \boldsymbol{H} \tag{3}$$

3. Consumption Limits: $\boldsymbol{MaxCons_{c_j}}$ is a predetermined maximum limit of energy that consumer $\boldsymbol{c_j}$ can consume in an hour. This limit is based on the consumer's historical consumption patterns and the capacity of their electrical installation.

$$0 \leq \boldsymbol{L_{c_j,h}} \leq \boldsymbol{MaxCons_{c_j}} \quad \forall \boldsymbol{c_j} \in \boldsymbol{C},\ \forall \boldsymbol{h} \in \boldsymbol{H} \tag{4}$$

4. Trading Limits: The constraint ensures that the traded amount is greater than zero but less than the minimum of either the energy generated by the prosumer $\boldsymbol{G_{p_i,h}}$ or the energy consumption need of the consumer $\boldsymbol{L_{c_j,h}}$ during that hour.

$$0 \ll \boldsymbol{E_{p_i\rightarrow c_j,h}} \ll \min(\boldsymbol{G_{p_i,h}}, \boldsymbol{L_{c_j,h}}) \quad \forall \boldsymbol{p_i} \in \boldsymbol{P},\ \forall \boldsymbol{c_j} \in \boldsymbol{C},\ \forall \boldsymbol{h} \in \boldsymbol{H} \tag{5}$$

5. Grid Trading Limits: Limits for energy bought from or sold to the utility grid:

$$\boldsymbol{G_{grid,h}} \geq \_\boldsymbol{MaxGridFeedIn} \quad \forall \boldsymbol{h} \in \boldsymbol{H} \tag{6}$$

$$\boldsymbol{G_{grid,h}} \leq \_\boldsymbol{MaxGridWithdrawal} \quad \forall \boldsymbol{h} \in \boldsymbol{H} \tag{7}$$

6. State of Charge (SoC) Limit: Equation (8) is a constraint related to the state of charge (SoC) of the battery energy storage systems (BESS) owned by prosumers within a microgrid. This constraint ensures that the SoC of each prosumer's storage system remains within specified minimum and maximum limits at all times.

$$\boldsymbol{MinSoC_{p_i}} \leq \boldsymbol{SoC_{p_i,h}} \leq \boldsymbol{MaxSoC_{p_i}} \quad \forall \boldsymbol{p_i} \in \boldsymbol{P}, \forall \boldsymbol{h} \in \boldsymbol{H} \tag{8}$$

7. SoC for the next time interval: Equation (9) is used to calculate the state of charge (SoC) of the BESS for each prosumer in a microgrid from one hour to the next. This equation takes into account the charging and discharging activities within each hour.

$$SoC_{p_i,h+1} = SoC_{p_i,h} + \left(C_{p_i,h} \cdot \eta_{charge}\right) - \left(D_{p_i,h} \cdot \eta_{discharge}\right) \quad \forall p_i \in P, \forall h \in H \tag{9}$$

In the decentralized energy management system within a community microgrid, a prosumer's Battery Energy Storage System (BESS) is designed with sophisticated logic to enhance energy utilization and contribute to the overall resilience of the microgrid. A pivotal element of this logic involves the management of the State of Charge (SoC), particularly focusing on optimal actions during periods of peak demand within the community as shown in Figure 3.

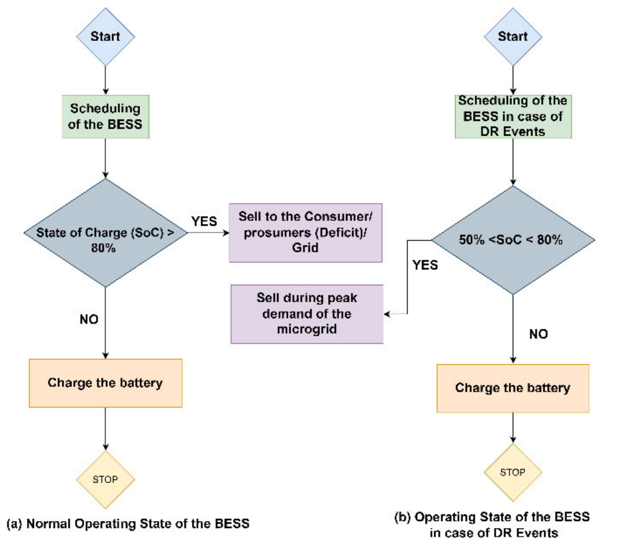

FIGURE 3. Flow chart for prosumer's BESS discharging logic in case of DR events.

When the prosumer's BESS observes that its State of Charge exceeds the 50% threshold, a strategic decision is made to commence the discharge of the battery. This threshold is carefully chosen to strike a balance between retaining a reserve within the battery for potential future needs and actively supporting the community microgrid during times of heightened demand. The logic effectively utilizes the stored energy in the battery precisely when the community microgrid experiences peak demand, marked by elevated energy consumption. By discharging the battery when the SoC surpasses 50%, the prosumer actively contributes additional power to the community microgrid when it is most required.

A. MARKET TRADING PRICE USING SDR METHOD

When formulating energy pricing strategies, we considered three essential economic principles:

- Price Boundaries Based on Utility Rates: In line with fundamental economic principles, the prices in Peer-to-Peer (P2P) trading should be bounded by the utility's purchase price and the grid feed-in tariffs. This ensures that P2P prices remain competitive and fair within the existing energy market structure.
- Inverse Relationship with Supply-Demand Ratio (SDR): The P2P pricing is inversely proportional to the SDR. This means that as the SDR increases (indicating a surplus of supply over demand), the P2P price tends to decrease, and vice versa. This relationship helps in aligning P2P prices with current market conditions, reflecting the balance of energy supply and demand.
- Economic Equilibrium in P2P Trading: It is crucial to maintain an economic balance in P2P transactions within the microgrid. The objective is to ensure a sustainable and equitable trading environment where all participants, both buyers and sellers, find value in their transactions.
- Economic Equilibrium in P2P Trading: It is crucial to maintain an economic balance in P2P transactions within the microgrid. The objective is to ensure a sustainable and equitable trading environment where all participants, both buyers and sellers, find value in their transactions.

In the microgrid P2P trading system utilizing the Ethereum blockchain, the unique aspect is the use of Tether (USDT), a stable coin, as the medium of exchange. This system operates without a central regulatory authority, relying instead on the Supply-Demand Ratio (SDR) method to autonomously determine P2P prices based on the dynamics of supply and demand. The use of Tether within the Ethereum network brings stability to the trading process, as it is pegged to the US dollar, reducing the volatility often associated with cryptocurrencies. Utility reference prices serve as benchmarks for energy exchanges within the microgrids. Consumers prefer to purchase energy from neighboring prosumers when their offering prices are lower than the utility grid's prices. On the other hand, prosumers with excess energy find it more profitable to sell to other consumers within the microgrid at higher prices than to sell back to the grid. As a result, the P2P price using Tether is strategically set between the utility's buying price and the grid-feed-in price. In this framework, the P2P trading price for each participant in the energy trading is denoted ***USDT_P2P***. This pricing structure can be represented as follows:

$$USDT_{usell} < USDT_{P2P} < USDT_{ubuy}$$

Here:

- $USDT_{usell}$ is the price at which prosumers sell their excess energy to the utility.

- $USDT_{P2P}$ represents the P2P trading price within the microgrid.
- $USDT_{ubuy}$ signifies the utility's buying price at that time.

This arrangement ensures a stable, balanced, and economically viable trading environment within the microgrid, leveraging the stability of Tether (USDT) on the Ethereum network to facilitate efficient and transparent energy transactions.

B. MARKET TRADING PRICE DETERMINATION

The market price of energy at time 'h' denoted as $Price_h$, is determined by applying a function f to the SDR value:

$$Price_h = f(SDR) \tag{10}$$

The function f is designed to translate the SDR into a corresponding price. This function must capture how changes in the balance between supply and demand (as reflected by the SDR) influence the price of energy. The SDR at a given time interval 'h' is defined as the ratio of the total energy supply to the total energy demand within the microgrid. Mathematically, it is represented as:

$$SDR_h = \frac{\sum_{p_i \in P} G_{p_i,h}}{\sum_{c_i \in C} L_{c_j,h}} \tag{11}$$

The pricing model can be developed based on the SDR method, as previously discussed, considering the inverse proportional relationship between SDR and P2P trading prices. The market trading price for P2P transactions within the microgrid is determined using the formula presented in Equation (4), as established in reference [44]:

$$Price_h = \begin{cases} \dfrac{USDT_{ubuy} \times USDT_{usell}}{\left(USDT_{ubuy} - USDT_{usell}\right) .SDR_h + USDT_{usell}}, & 0 \leq SDR_h \leq 1 \\ USDT_{usell}, & SDR_h > 1 \end{cases} \tag{12}$$

In decentralized energy trading, the SDR value plays a crucial role in determining the market price of energy. An appropriately designed function f translates the SDR into a market price, reflecting the current balance of supply and demand. The pricing mechanism, therefore, remains responsive and adaptable to the changing dynamics of the microgrid's energy ecosystem.

C. INCENTIVE-BASED DEMAND RESPONSE (DR) PROGRAM FOR CONSUMERS

It is presumed that all the consumers participating in Demand Response (DR) have a certain portion of their load that is adjustable. Due to pricing incentives, these consumers might opt to alter their power consumption patterns, leading to deviations from their originally planned power usage. Recent trends indicate that the readiness of users to shift their load is becoming a key consideration in demand-side energy management, as users exhibit varying levels of willingness to adjust their load [45]. For consumers, using shiftable appliances without regard for DR incentives may result in no perceived inconvenience, leaving their original load profiles unchanged. However, if they choose to modify their shiftable load in reaction to price signals, this decision could impact their convenience, potentially causing delays in appliance use or necessitating usage at earlier times than initially planned. The inconvenience caused by such load shifting is more precisely quantified by considering the frequency and timing adjustments of these shiftable appliances. The cost equivalent to this inconvenience formulated as follows:

$$inc_n = \alpha_n \sum\nolimits_{h=1}^{H} \left(L'_{c_j,h} - L_{c_j,h}\right)^2 \tag{13}$$

where inc_n is the inconvenience cost for consumer n, The sensitivity coefficient for consumer n, denoted as α_n is utilized to measure the consumer's readiness for load shifting, while $L'_{c_j,h}$ reflects the modified load consumption of the consumer. When choosing α_n ($\alpha_n > 0$), a higher value suggests that the consumer is more sensitive to the discomfort caused by shifting their load and is therefore less inclined to alter their load usage.

By combining the inconvenience cost with the electricity costs of the consumer, we can establish the following cost function for their optimal operation:

$$\begin{aligned} C_n^h(L'_{c_j,h}) &= Price'_h . \sum\nolimits_{h=1}^{H} \left(L'_{c_j,h} - L_{c_j,h}\right) \\ &\quad + \alpha_n \sum\nolimits_{h=1}^{H} \left(L'_{c_j,h} - L_{c_j,h}\right)^2 \end{aligned} \tag{14}$$

$$C_n = C_n^h(L'_{c_j,h}) \tag{15}$$

where $C_n^h(L'_{c_j,h})$ can be separated into two parts: the cost of using electricity $Price_h . \sum_{h=1}^{H} (L'_{c_j,h} - L_{c_j,h})$ and the equivalent cost of adjusting flexible power $\alpha_n \sum_{h=1}^{H} (L'_{c_j,h} - L_{c_j,h})^2$. These two parts constitute the cost function in both economy and users' willingness. $Price_h$ is the price at time slot 'h' for consumer 'n', which can be the selling price or buying price, and decided by the net power:

$$SDR'_h = \frac{\sum_{p_i \in P} G_{p_i,h}}{\sum_{c_i \in C} L'_{c_j,h}} \tag{16}$$

$$\begin{aligned} Price'_h &= f'\left(SDR'_h\right) \\ &= \begin{cases} \dfrac{USDT_{ubuy} \times USDT_{usell}}{\left(USDT_{ubuy} - USDT_{usell}\right) .SDR'_h + USDT_{usell}}, & 0 \leq SDR'_h \leq 1 \\ USDT_{usell}, & SDR'_h > 1 \end{cases} \end{aligned} \tag{17}$$

III. IMPLEMENTATION OF BLOCKCHAIN FOR PEER-TO-PEER ENERGY TRADING USING SMART CONTRACT

A smart contract is essentially a set of predefined rules for interaction among parties, crafted using a high-level programming language like Solidity on the Ethereum platform.

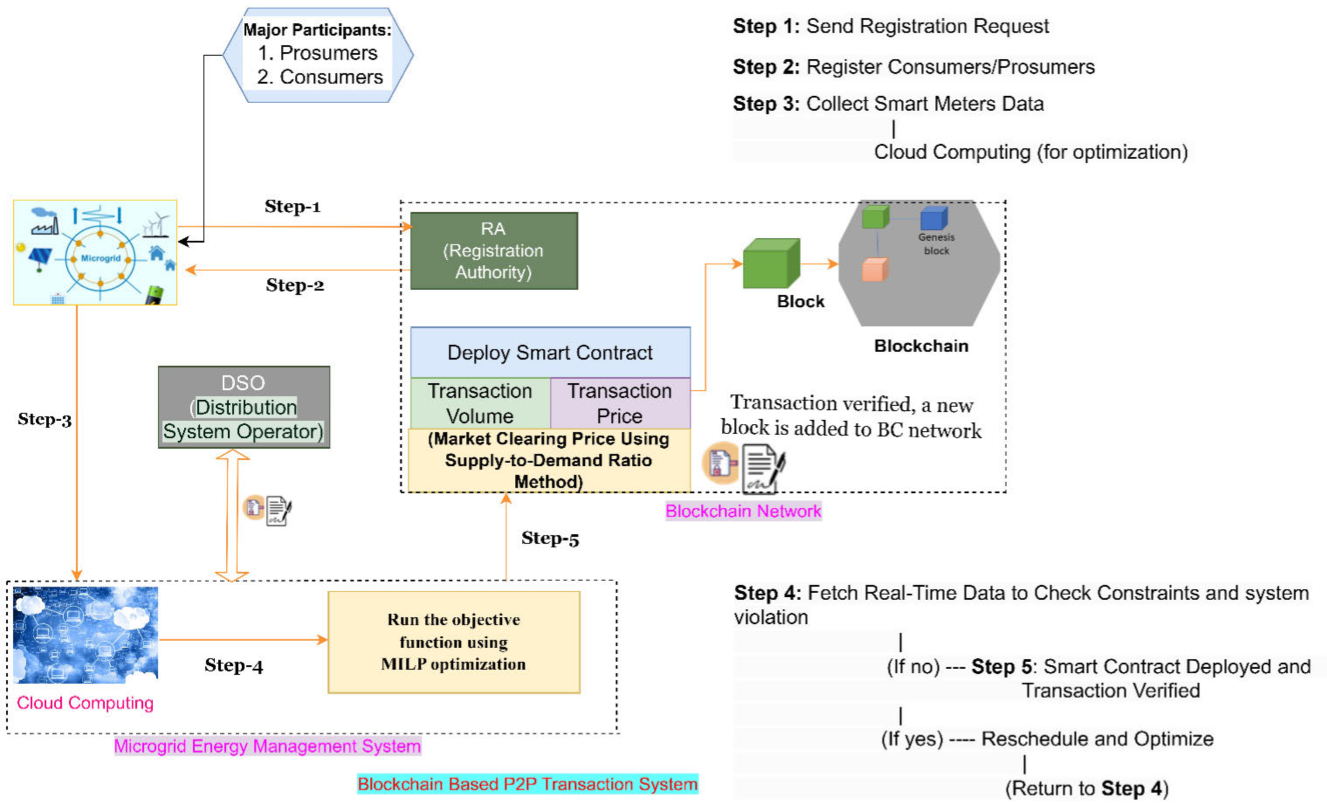

FIGURE 4. Design framework of peer to peer blockchain transactions integrated with microgrid EMS.

This contract is designed to automatically execute once its specified conditions are met. Participants in the contract, such as prosumers, consumers, and RES owners, can engage with its functionalities and initiate transactions that are then broadcast across the Ethereum Blockchain Technology Network. For a smart contract to become operational, it must first be created and then uploaded to the blockchain. Figure 4 shows a detailed design framework for integrating the Microgrid EMS to the blockchain which demonstrates the implementation steps from the beginning of a transaction to its conclusion. Initially, in step 1, all microgrid participants submit requests to the registration authority (RA). Step 2 ensures that only registered participants with public keys can take part. Step 3 involves storing all transaction requests in the cloud. Step 4 follows the Microgrid Energy Management System (MEMS) performs microgrid cost optimization analysis on the data provided by prosumers, and consumers to evaluate system parameters and optimize costs. In case of a generation shortfall, transaction requests are sent to consumers with an initial incentive rate to solicit Demand Response (DR) resources. This process is iterative, adjusting the incentive rate as needed. This approach employs elasticity-based DR modeling to simulate scenarios. If no violations occur, the requested transaction is broadcast to all peers, as shown in Step 5, and the smart contract is deployed with DR elements to determine the transaction price using Supply-to-Demand Ratio (SDR) method. This transaction is then validated by miners. Upon validation, a new blockchain block is created and appended to the existing chain, and complete with a new hash. If violations occur, reschedule the dispatch and run the optimization, repeat the step 4.

The coordination between a Microgrid Energy Management System (EMS) and a Blockchain smart contract for effective peer-to-peer (P2P) energy trading involves a seamless integration of optimized data transmission. The Microgrid EMS serves as the central intelligence, continuously collecting real-time data on energy production, consumption patterns, and storage levels within the microgrid. Employing sophisticated optimization algorithms, the EMS analyzes this data to determine the most efficient allocation of energy resources. Subsequently, it generates a transaction proposal that encapsulates the optimal energy distribution, including details such as participating parties, amounts, and pricing.

The interaction with the Blockchain smart contract is a critical aspect of this coordination. The Microgrid EMS communicates with the smart contract by submitting the generated transaction proposal. Specifically, designed functions within the smart contract handle these proposals, ensuring secure and transparent execution. The smart contract validates the proposed transactions based on predefined rules, leveraging the inherent trust and transparency of blockchain technology. Once validated, the optimized data is securely stored on the blockchain, forming an immutable record of P2P energy transactions. This integrated approach enhances

Algorithm 1 Market Trading Price and Demand Response Program

P2P Market Trading Price:
Calculate SDR: $$SDR_h = \frac{\sum_{p_i \in P} G_{p_i,h}}{\sum_{c_i \in C} L_{c_j,h}}$$ from Equation (11)

Market Clearing Price:

$Price_h = f(SDR)$ from Equation (12)

Initiate DR Signal:

Load Shifting Initiated

Run load optimization and minimize the cost for individual consumers/ prosumers as $C_n^h(L'_{c_j,h})$ from Equation (14)

Calculate modified SDR and price setting:

$$SDR'_h = \frac{\sum_{p_i \in P} G_{p_i,h}}{\sum_{c_i \in C} L'_{c_j,h}}$$

$Price'_h = f(SDR)$ from Equation (17)

if $\|Price'_h - Price_h\| \leq \varepsilon$ then
stop iteration
end if

Algorithm 2 Smart Contract for the Decentralized Energy Management

// Participants and transactions
mapping(address => Participant) participants; Transaction[] pendingTransactions;

// Initialize the contract
function initializeContract(float initialBuyPrice, float initialSellPrice) {gridBuyPrice = initialBuyPrice; gridSellPrice = initialSellPrice; currentSDRPrice = (initialBuyPrice + initialSellPrice) / 2; currentDREvent = DemandResponseEvent(0, 0, false);}

// Update energy data for a participant
function updateEnergyData(address id, float consumption, float generation) { participants[id].hourlyConsumption = consumption; participants[id].hourlyGeneration = generation; calculateSDRPrice(); createOrUpdateTransactions(id); checkAndRespondToDREvent(id);}

// Calculate Supply-Demand Ratio (SDR) Price
function calculateSDRPrice() {// Implement the logic to calculate SDR based on current supply and demand using equation (11); currentSDRPrice = // Calculation logic as defined in equation (12)
}

the efficiency and transparency of energy trading within the microgrid, providing a secure foundation for decentralized and optimized energy management.

The smart contract for the microgrid encompasses key components that define the participant structure, incorporating both consumers and prosumers with detailed attributes such as energy consumption, generation, and financial balances. Crucial to the contract is the Demand Response (DR) event management system, designed to balance energy demand and supply during peak periods by adjusting consumption patterns and providing incentives for flexibility. Managing pricing parameters like grid buy and sell prices, along with a dynamically calculated Supply-Demand Ratio (SDR) price, ensures fair and market-reflective pricing for energy transactions.

The functionalities of the smart contract include initialization and participant registration, energy data management, DR event handling, transaction creation and execution, as well as incentive distribution and event finalization. Through these features, participants register, update their energy data, engage in DR events, and partake in efficient energy trading with the contract ensuring fair compensation and event settlement.

The Algorithm-2 is designed the smart contract structures with key functions to facilitate decentralized energy management, incorporating features such as participant registration, real-time energy data updates, and the calculation of the Supply-Demand Ratio (SDR) Price. The contract defines two essential data structures: "Participant" encapsulates information about each participant, including their Ethereum address, hourly energy consumption, generation, balance, and flags indicating whether they are a prosumer and currently participating in Demand Response (DR) events. The "DemandResponseEvent" structure captures details of ongoing DR events, specifying the required adjustment in energy demand, the incentive rate for participant involvement, and a boolean indicating the event's activation status.

The contract initializes with parameters for grid buy and sell prices, setting the initial SDR Price as the average of these values. The current DR event is initialized with default values, signaling no active event at the contract's onset. The participant mappings store detailed information about each participant, while an array of transactions keeps track of pending energy transactions.

The contract defines various functions to interact with its functionalities. The "initializeContract" function sets initial pricing parameters and initializes the DR event. "registerParticipant" enables the addition of participants to the system, initializing their data structures. The "updateEnergyData" function allows participants to dynamically update their energy consumption and generation, triggering the recalculation of the SDR Price and updating transactions accordingly.

The "calculateSDRPrice" function, although represented as a placeholder, is designed to implement the logic for

Algorithm 3 The Logic for Participants to Adjust Their Energy Usage Based on the DR Event Requirements

```
function adjustEnergyForDREvent(address id) {
  require(currentDREvent.isActive, "No active DR event");
  Participant storage participant = participants[id];
  float adjustment = currentDREvent.requiredAdjustment;
  if (adjustment > 0) {
    // Implement logic for participants to reduce energy consumption
    participant.hourlyConsumption -= adjustment;
  } else if (adjustment < 0 && participant.isProsumer) {
    // Implement logic for prosumers to increase energy generation
    participant.hourlyGeneration -= adjustment;
  }
    // Calculate and update participant's balance based on DR incentives
    participant.balance + = adjustment * currentDREvent.incentiveRate;
    // Notify participant of successful adjustment
    emit AdjustmentComplete(id, adjustment);
  }
```

computing the SDR Price based on the current supply and demand. This function forms a crucial component in the contract, influencing pricing dynamics within the decentralized energy management system.

The smart contract function "adjustEnergyForDREvent" is a crucial component within the Decentralized Energy Management smart contract, designed to facilitate dynamic adjustments to the energy consumption and generation of individual participants in response to an active Demand Response (DR) event as explained in Algorithm-3. The function takes the Ethereum address (id) of a participant as input and ensures that there is an ongoing DR event by checking the boolean status of "currentDREvent.isActive". If there is no active DR event, the function exits with an appropriate error message to maintain the integrity of the process.

Upon verifying the presence of an active DR event, the function proceeds to retrieve the relevant participant data, stored in the participants mapping, specifically focusing on their hourly energy consumption "hourlyConsumption", energy generation "hourlyGeneration", and current balance "balance". The adjustment parameter (adjustment) is then extracted from the global DR event parameters "currentDREvent.requiredAdjustment".

The subsequent conditional statements play a pivotal role in determining the type of energy adjustment needed based on the sign of the adjustment parameter. If adjustment is positive, implying an increased demand, the function implements logic to reduce the participant's hourly energy consumption proportionally. Conversely, if adjustment is negative (indicating a reduced demand) and the participant is identified as a prosumer, the function executes logic to increase the prosumer's energy generation.

Algorithm 4 Pseudo Code for the Modified PoS Consensus Within the Smart Contract

```
// Define structures for Validators, Peers, and Transactions
Structure Validator: id, reputation

// Define mappings for validators, peers, and transactions
Mapping validations maps Address to Validator
Mapping peers maps Address to Peer
Mapping transactions maps uint256 to Transaction

// Functions for smart contract operation
Function addValidator(Address validatorAddress):
    Create new Validator with given address
    Initialize reputation based on historical performance
    Add Validator to validations mapping

Function updateReputation(Address validatorAddress, Performance performance):
    Retrieve validator's historical performances
    Update reputation based on the latest performance and past records
    Store the updated reputation

Function proposeTransaction(uint256 transactionId, Transaction details):
    Validate transaction details
    If valid, add Transaction to transactions mapping
    Update validator's reputation who proposed the transaction
```

Following the adjustment of energy consumption or generation, the participant's balance is recalculated to incorporate the financial incentives associated with their response to the DR event. The adjustment amount is multiplied by the incentive rate "currentDREvent.incentiveRate" to determine the monetary reward, which is then added to the participant's balance.

Finally, to provide transparency and real-time updates, the function emits an "AdjustmentComplete" event, notifying the participant of the successful execution of the energy adjustment. This event can serve as a trigger for external systems or user interfaces to respond to the dynamic changes in participants' energy profiles during DR events.

Algorithm-4 details the essential components and functionalities of a modified Proof of Stake (MPoS) consensus algorithm implemented within a smart contract. Firstly, it defines important structures and mappings to organize data within the contract. The validators are mapped to their addresses using the "validations" mapping, allowing for easy retrieval and management. Additionally, the "peers" mapping associates each peer's address with relevant information. Secondly, the pseudocode outlines several key functions responsible for managing validators and transactions. The "addValidator" function facilitates the addition of new validators to the network by initializing their reputation and integrating them into the validations mapping. The "updateReputation" function plays a pivotal role in maintaining the reputation of validators, utilizing historical performance data to adjust reputations based on recent activities. Lastly, the "proposeTransaction" function handles the submission of new transactions to the network, ensuring their validity before adding them to the transactions mapping. Furthermore, this function triggers reputation updates for validators who propose transactions, contributing to the dynamic nature of the consensus process. The pseudocode also incorporates additional consideration of reputations. The "historicalPerformance" mapping tracks past performances of validators, serving as a basis for reputation calculations.

IV. RESULTS AND DISCUSSIONS

The dataset utilized for this study is sourced from the Pecan Street Project and encompasses the energy usage and production records of 244 residential households in Austin, Texas. Within this community, there are 119 prosumers equipped with solar photovoltaic (PV) and wind generation capabilities and 125 consumers [46], [47], [48], [49]. For the purpose of our analysis, we have aggregated this data into a more manageable form by modeling the community as composed of 5 prosumers and 5 consumers. The model retains the fundamental characteristics of the original community, reflecting the energy exchange patterns and interactions that occur within a peer-to-peer (P2P) energy trading network.

The optimization experiments utilized a computer system equipped with an Intel Core i7-10700K processor, 32GB DDR4 RAM, with the software programming used Python 3.8 and the Gurobi v10 solver for Mixed-Integer Linear Programming (MILP) optimization. The optimization algorithm, using Gurobi solver for MILP, arrived at an objective function value of 1993.6296 US$ in 12 seconds, indicative of the community microgrid's total cost optimization. This value represents the total cost optimization for the community microgrid, the overall economic efficiency achieved through the P2P energy transactions between prosumers and consumers, incorporating the SDR based market clearing pricing.

Each household was assigned an account on Ganache, a personal blockchain for Ethereum development. The data for each household includes an hourly records of consumption and generation, alongside grid feed-in rates for prosumers (for surplus generation) and utility grid prices for consumers (when facing a shortfall in generation). As outlined in section III, the P2P trading price is set to be within the range of grid buying and selling prices to encourage participation in the microgrid's decentralized market. This approach also aims to reduce reliance on the utility grid, fostering community self-sufficiency through local distributed generations and blockchain-based trading platforms. Each account in the system posts a bid if it has surplus energy and requests energy if there is a deficit. The Supply-Demand Ratio (SDR) method is then applied to establish a market clearance price, with transactions occurring on an hourly basis. This price, positioned between the grid's selling and buying prices, is set using dynamic grid pricing (USDT_p2p). Bids and asks are then matched to fulfill customer needs. The total energy cost is calculated in Wei, and the equivalent amount in USDT cryptocurrency is transferred from the buyer to the seller.

Surplus energy post local P2P trading is sold to the utility grid, and in cases of a microgrid generation deficit, additional energy needs are met by the utility grid.

This study presents an efficient, secure, and self-sustaining microgrid system for addressing local community energy needs through P2P energy trading. It examines the impact of the proposed market structure combined with Blockchain Technology (BT). Pricing for various energy sources significantly influences the optimization and comparison of the proposed market architecture. All other variables are tied to the dynamic pricing set for the grid using the SDR method. In the absence of local trades, the P2P price should mirror each prosumer's willingness to sell power at a reduced rate.

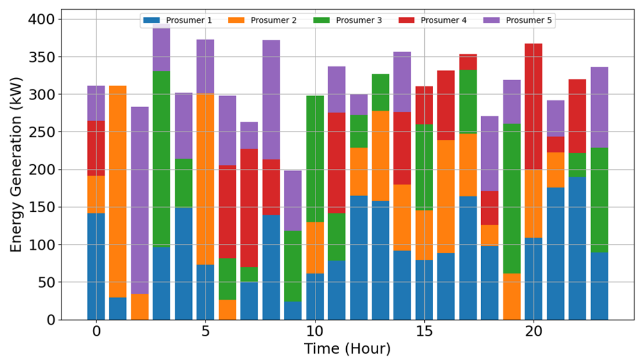

FIGURE 5. Energy allocations by five prosumers over 24 hours time-period.

Figure 5 bar chart illustrates the optimized results of a peer-to-peer (P2P) energy trading system showing the amount of energy allocated by five prosumers over 24 hours period of time, segmented into hourly intervals. From the chart, we observe that each prosumer has contributed to the energy allocations in varying amounts depending on their generation capacity, indicated by the different colored segments within each bar. Prosumer 1, represented by the color blue, appears to consistently contribute a significant portion of the energy traded across most hours. Prosumer 2 (orange) and Prosumer 3 (green) also demonstrate considerable activity in the market, with their contributions showing some variation over time. Prosumer 4 (red) and Prosumer 5 (purple) add to the diversity of the market with their shares, although they seem to contribute less energy than the others in certain hours.

The overall pattern of trading is dynamic, with the total energy sold each hour fluctuating, indicating variable production or availability of energy from prosumers, which could be due to the intermittent nature of renewable energy sources, solar PV. The peaks and troughs in the bar chart suggest that at certain times during daylight hours, there is a surplus of energy from solar generation, while at other times, the energy sold decreases, which could correspond to periods of lower generation capacity or higher self-consumption by the prosumers.

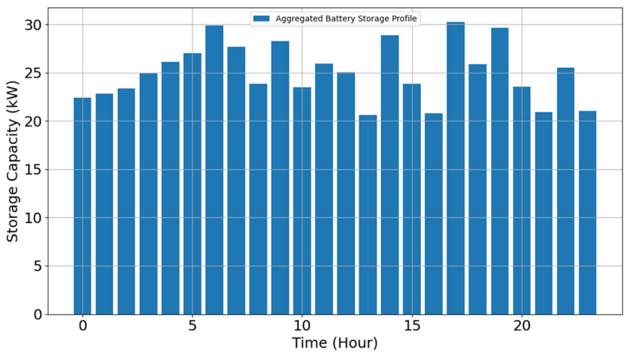

FIGURE 6. Aggregated battery storage capacity over 24 hours time-period.

Figure 6 represents the aggregated battery storage capacity profile across a community of prosumers. The profile indicates the total energy storage available at different hours throughout the day. Each bar represents a specific hour, and the height of the bar indicates the total storage capacity in kilowatt-hours (kWh) at that time. The relatively uniform distribution of the bars suggests that the battery storage system has been designed to maintain a consistent level of storage capacity throughout the day, which can help to buffer against variability in solar PV generation and to ensure a steady supply of energy.

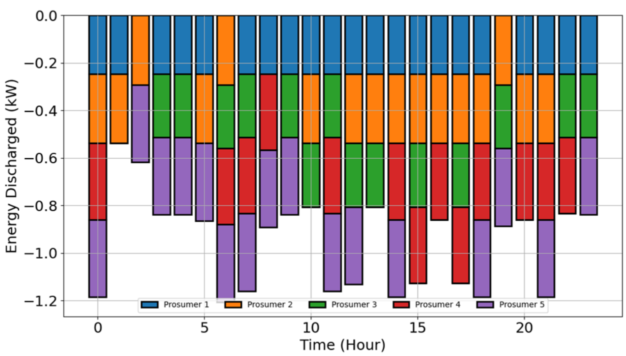

FIGURE 7. Battery discharging profiles of the five prosumers over 24 hours time-period.

Figure 7 illustrates the discharging profile of batteries for each prosumer in the community. Negative values indicate energy being discharged from the battery to meet demand or to sell into the P2P energy trading market. Each color in the stacked bars represents a different prosumer, and the length of each colored segment indicates the amount of energy that prosumer's battery is discharging at that hour. This profile demonstrates how each prosumer's battery discharges at different rates and times in response to their individual energy generation and consumption patterns, as well as their participation in energy trading. It is an essential aspect of managing the microgrid's overall energy balance, ensuring that excess generation can be stored and used when generation is low or demand is high.

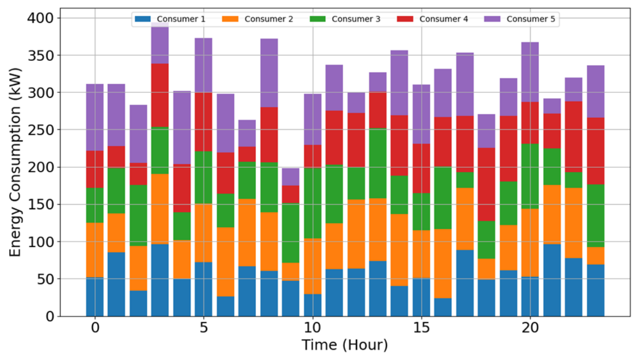

FIGURE 8. Energy allocations for five consumers over 24 hours time-period.

Figure 8 bar chart showcases the energy consumption patterns of five consumers over a 24-hour period. Each bar represents an hour in the day, and the stacked colors within each bar depict the individual energy consumption for each consumer. The varied height of each color segment within the bars indicates the fluctuating demand for energy by each consumer throughout the day. From the chart, we can see that all consumers exhibit similar patterns of energy consumption, with varying levels of demand. The presence of all five colors in most bars suggests that every consumer is active in purchasing energy at most hours. There are peaks and troughs which likely correspond to typical daily activities, with higher energy consumption during the day and evening hours, and lower consumption overnight.

The distribution of energy consumption among the consumers appears to be relatively balanced, with no single consumer consistently dominating energy purchases. This could imply a well-integrated demand-side management system that allows for equitable energy distribution and reflects the effectiveness of a demand response program that encourages consumers to shift their energy usage to off-peak times or to times when renewable energy generation is high. The aggregation of such detailed consumption data can be pivotal for the microgrid manager or utility provider to understand demand patterns, which can inform strategies for energy distribution, pricing models, and energy storage requirements. It also provides insights into the success of energy efficiency measures and demand response initiatives within the community.

The line graph in Figure 9 illustrates the impact of a demand response (DR) program on the microgrid load profile over a 24-hour period. The blue dashed line represents the load profile before the implementation of the DR program, while the orange solid line shows the load profile after the program has been put into effect. From the graph, it is apparent that the DR program has led to a modification of the load profile across the day. Before the DR program, the load profile exhibits significant fluctuations, with peaks likely

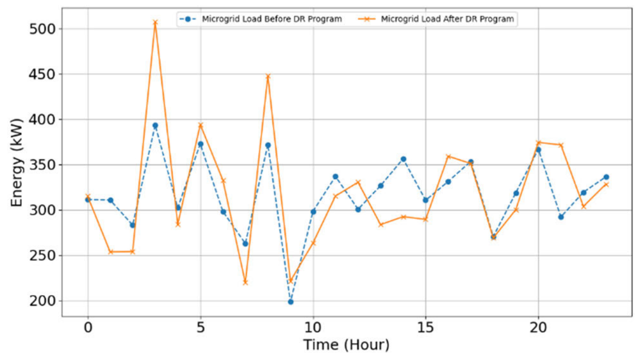

FIGURE 9. Microgrid overall profile before and after Demand Response (DR) program over 24 hours time-period.

corresponding to high-use periods during the evening time. These peaks are interspersed with valleys, possibly indicating lower energy usage during late-night or mid-day periods.

After the implementation of the DR program, the load profile changes markedly. The peaks and valleys appear to be smoothed out, suggesting a shift in energy consumption from high-peak periods to other times of the day. This shift could be attributed to time-of-use based DR pricing strategy where energy costs are more during peak hours and less during off-peak hours, encouraging consumers to use less energy when it is more expensive.

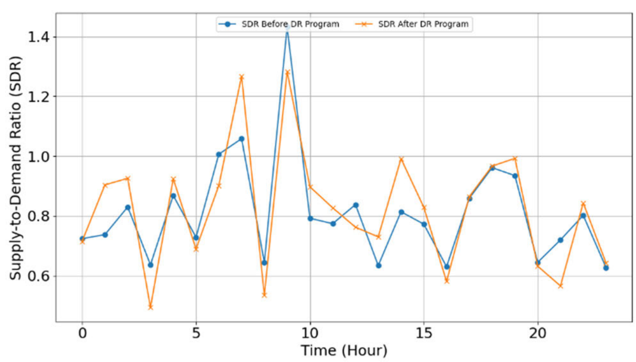

FIGURE 10. Microgrid Supply to Demand Ratio (SDR) profile before and after Demand Response (DR) program over 24 hours time-period.

The graph presented in Figure 10 depicts the Supply-Demand Ratio (SDR) before and after the implementation of a Demand Response (DR) program over a 24-hour period. The SDR is a metric that quantifies the balance between energy supply and demand, with higher values indicating a surplus of energy supply relative to demand, and lower values suggesting a closer balance or even a shortfall. The blue line with circular markers represents the SDR before the implementation of the DR program. It fluctuates over the course of the day, which is typical in residential areas due to varying consumption patterns. The peaks may correspond to times when energy supply from renewable sources like solar PV systems is high, or when consumer demand is low. Conversely, the troughs suggest periods when demand is higher relative to supply, possibly during early morning and evening hours when residential energy use typically increases. The orange line with cross markers shows the SDR after the DR program has been applied. Notably, the SDR still fluctuates, but the peaks and valleys are less pronounced, indicating that the DR program has succeeded in flattening the demand curve. This could be due to load shifting based incentivizing DR strategy to consumers to reduce consumption during peak periods. One notable feature is the sharp peak in the orange line towards the end of the period, which suggests a significant surplus of supply or a substantial drop in demand. This could indicate that the DR program has aggressively moved loads out of this period, or that there was a substantial increase in renewable generation that was not matched by demand.

Overall, the SDR graph indicates that the DR program has made an impact on energy consumption behavior, smoothing out the extremes of energy supply and demand. This is beneficial for the stability of the grid and can lead to cost savings for both utilities and consumers. It also highlights the potential for DR programs to enhance the integration of renewable energy sources into the grid by managing when and how much energy is used, contributing to a more sustainable energy system.

TABLE 2. Comparative analysis of microgrid financial metrics before and after the implementation of a demand response program.

Description	**Before DR Program (US$)**	**After DR Program (US$)**	**Savings (US$)**	**Total Cost Savings (%)**
Cost of Energy Sold by Prosumers	1,950	2,200	250	
Cost of Energy Bought by Consumers	2,500	2,200	300	
Total Cost of Microgrid Load	1,993.63	1,794.27	199.36	
Inconvenience Cost for Consumers	0	150	-150	6.36
Total Operational Costs	4,700	4,094.27	605.73	
Aggregated Cost of Battery Storage	100	90	10	
Total Cost Savings	11,244	10,529	715	

Table 2 gives the comparative performance of the Microgrid Financial Metrics before and after the Implementation of a Demand Response Program. Before the DR program was enacted, the cost of energy sold by prosumers was $1,950, which increased to $2,200 after the program, resulting in savings of $250. Similarly, the cost of energy bought by consumers decreased from $2,500 to $2,200, yielding a savings of $300. The total cost of the microgrid load before the DR program stood at $1,993.63, and the implementation of the DR program led to a reduction in this cost, bringing it down to $1,794.27, which translates to savings of $199.36. It's worth noting that an inconvenience cost of $150 was incurred due to the DR program, which provides incentives to the consumers for the shift of their load patterns. The overall operational costs of the microgrid before the DR program were $4,700, and after the program, these costs were reduced to $4,094.27, marking a substantial saving of $605.73. Additionally, cost savings were also realized in aggregated storage costs, which dropped from $100 to $90, contributing another $10 to the total savings. Taking all these factors into account, the total cost savings realized from the DR program amounted to $715 with overall 6.36 % cost saving of the microgrid. This highlights the direct financial benefits of the program, highlighting the efficacy of DR initiatives in optimizing energy costs within a microgrid setting. It is important to underline that these savings must be carefully weighed against the inconvenience costs to ensure that the DR program delivers net positive value to all stakeholders involved.

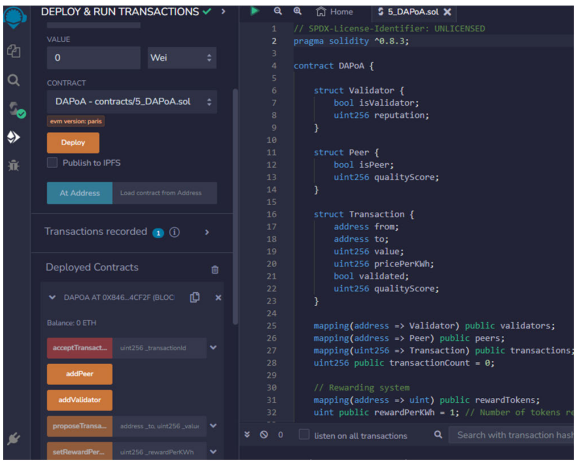

FIGURE 11. Proof of Stake (PoS) consensus mechanism transaction validated through Remix Ethereum.

We designed and implemented the Modified Proof of Stake (MPoS) consensus mechanism on a private Ethereum platform, specifically tailored for the decentralized community microgrid P2P energy trading. This platform enabled peer-to-peer energy trading between prosumers and consumers. Using Ganache for setting up a private Ethereum blockchain, MetaMask for managing accounts and transactions, and Remix Ethereum for developing, testing, and deploying Solidity smart contract as shown in Figure 11.

Figure 12 displays the user interface of a smart contract deployment on an Ethereum blockchain platform, illustrating the smart contract's interactive functions tailored for the energy trading system. The functions visible at the left side indicate a dynamic marketplace where users can trade energy. On the right, a transaction record confirms the smart

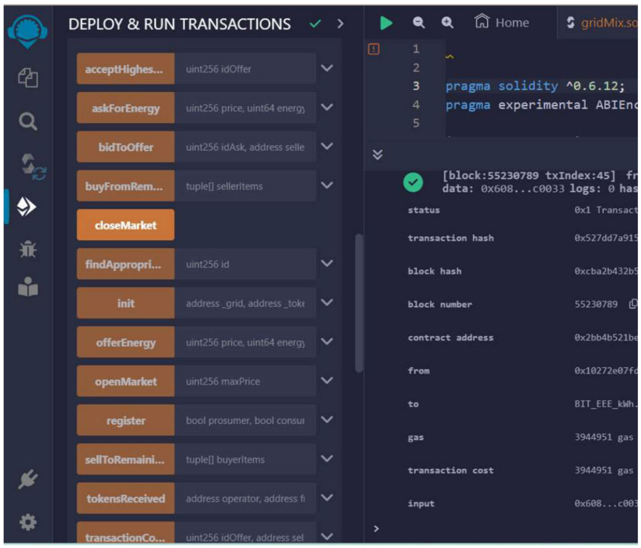

FIGURE 12. Smart contract deployment showing functions and the transaction record.

contract's operations, detailing the unique transaction hash, the contract address, and the associated transaction costs. This figure captures both the functionality designed to facilitate energy trades and the inherent transparency of blockchain transactions.

TABLE 3. Key performance metrics.

Metric	Value
Execution Time	12 ms (milli-seconds)
Transaction Cost	0.0005 USDT
Compliance Rate (Adhere to the network rules)	99.5 % (May vary significantly in real time implementation)
Energy Cost Savings	715 US$ (6.36%)

The PoS consensus mechanism allowed validators, who were pre-registered peers among the consumers and prosumers on the network, to propose and validate energy transactions. Furthermore, the contract regulated the trading of energy units between prosumers and consumers, ensuring secure and transparent transactions. This successful implementation of the MPoS consensus mechanism for energy trading demonstrates its potential for real-world applications in decentralized energy markets.

The efficacy of the smart contracts in the blockchain-integrated microgrid system was rigorously evaluated using key performance metrics. These metrics were carefully chosen to reflect the system's operational efficiency, cost-effectiveness, compliance with network rules, and environmental sustainability. Detailed results, illustrated in Table 3 and Figure 13, showcase significant improvement in the system's performance.

TABLE 4. Hourly consumer and prosumer energy transaction results using blockchain with energy volume (kWh) and price (US$).

Logic Description	Consumer's transaction	Prosumer's transaction
Selected house with hour	House_10:19th Hour	House_4:19th Hour
Consumer's/ Prosumer's public address	"0x10272E.......5E1ba"	"0x327618...........38691"
Generation	0 kWh	6.76 kWh (Solar)
Demand	4.35 kWh	2.79 kWh
ShortageofEnergy	4.35 kWh	Null
ExcessEnergy	false	True
Hasbattery	false	True
batteryPercentage	0	85.46
SurplusEnergy	–	3.97 kWh
Task	'AskForEnergy'	'OfferEnergy'
P2PEnergyTrading	True	True
BuyFromMainGrid	False	–
SellToMainGrid	–	False
EnergyVolume	3.97 kWh	3.97 kWh
DemandResponse	True (Adjusted 0.38 kWh)	False
Price	0.00 US$ (Main Grid)	0.337 US$ (P2P)
DR_Reward	True	False

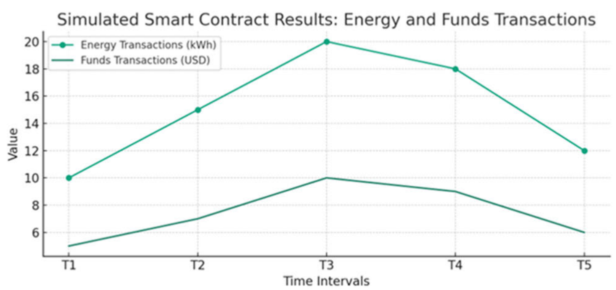

FIGURE 13. Simulated smart contract results for energy and funds transactions between prosumers and consumers.

Table 3 shows the transaction cost of successful contract deployment. At a minimal cost of 0.0005 USDT per transaction, the system demonstrates the cost-effectiveness. This low transaction cost is vital for ensuring the economic feasibility of the microgrid, particularly for frequent, small-scale energy trades typical in a residential community setting. The execution time for the successful energy trading and fund transfer is simulated in Figure 13.

Measured at an average 12 milliseconds, the execution time metric highlights the swift processing capabilities of the deployed smart contracts. This rapid execution is crucial for real-time energy trading and demand response scenarios, ensuring that energy transactions are promptly and efficiently handled within the microgrid. As shown in Table 3, with a compliance rate of 99.5%, the system exhibits a high level of adherence to predefined network rules. This metric is indicative of the robustness and reliability of the smart contract implementation, ensuring that all energy transactions are conducted in a transparent and trustworthy manner. However, historical performance indices of the network participants (consumers and prosumers) will be more indicative of this metric in real time implementation. The introduction of a Demand Response (DR) program in the microgrid system has led to substantial energy cost savings, as evidenced by the comparative analysis of financial metrics before and after the implementation of the DR program. The net total cost savings realized from the DR program amounted to 6.36%. This figure represents a significant economic benefit, highlighting the DR program's role in optimizing energy costs within the microgrid.

The smart contract deployment results are shown in Table 4 which illustrates the P2P energy trading among prosumer and consumers. In the 19th hour, Consumer House_10, with a deficit of 4.35 kWh and no battery storage, engages in P2P energy trading, interacting using 'AskForEnergy' function due to their shortfall. Meanwhile, Prosumer House_4, with a surplus of 3.97 kWh from solar generation, utilizes 'OfferEnergy', selling excess energy to this consumer. The transaction reflects active P2P trading at a price of 0.337 USD, with the consumer additionally benefiting from a demand response adjustment and reward.

V. CONCLUSION

This paper presents a detailed examination and practical application of a decentralized community microgrid system integrated with blockchain technology, drawing insights from data collected as part of the Pecan Street Project involving 244 households situated in Austin, Texas. The study focuses on a selected group of 5 prosumers and 5 consumers equipped with solar photovoltaic (PV) generation and battery storage capabilities, aiming to assess the viability of peer-to-peer (P2P) energy trading within residential communities. The supply-demand Ratio (SDR) plays a pivotal role in ensuring fair energy exchange within the community, while the deployment of blockchain technology through smart contracts, underpins the security of these transactions.

Through the combination of SDR for equitable trade and blockchain for secure transactions, our system fosters a reliable and fair energy trading environment. Furthermore, the proposed incentive-based demand response program is integrated directly within the smart contract framework, offering real-time rewards for load-balancing contributions, which could be more responsive than incentive mechanisms in other systems. Statistical analyses reveal a notable overall cost reduction of 6.36% following the introduction of the demand response program. Local prosumers' active involvement as validators in the blockchain network further reinforces community engagement and fosters resilience and sustainability in local energy systems.

CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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