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Research article

Towards sustainable energy: Implementation framework for a decentralized peer-to-peer transactive energy system

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Abstract: Power distribution infrastructures are deteriorating rapidly due to the geometric increase in electricity consumption, without corresponding infrastructural development. Distributed Energy Resource (DER) integration into energy distribution is increasingly important to address this energy shortfall, enhance grid reliability, and alleviate environmental concerns associated with non-renewable energy generation. An emerging energy solution, the Transactive Energy System (TES), enables customers with DERs to provide grid services to their peers within the network, thereby balancing the energy demanded and supplied. Adequate literature has reported on TES' theoretical background, but little has been done about its implementation; even the available work suffers from inadequate robustness, low reliability, and scalability at the communication layer. Integrating decentralized peer-to-peer (P2P) to TES is pivotal in resolving challenges associated with meeting energy demand, market efficiency, and grid reliability. Consequently, we proposed an implementation framework for decentralized P2P-TES to address identified challenges. The results obtained from the framework achieved a reliability rating of 89.71% and a 15% reduction in energy bill. The proposed framework fosters transparent and secure transactions within the TES. Moreover, we addressed the critical issues of data security, privacy, scalability, and long-term sustainability of the proposed system, which were enhanced through the framework. Additionally, we demonstrated the suitability of P2P-based TES in facilitating seamless interaction among components during energy exchange among peers using control and economic techniques. Furthermore, the economic viability of the developed system was assessed through a cost-benefit analysis. In conclusion, the implementation of this research has the potential to guide the TES experts in making informed decisions and advance technological knowledge for building more resilient and sustainable energy systems without expanding infrastructural capacity, thereby minimizing operation and investment costs.

Keywords: Distributed Energy Resources (DERs); Microgrid (MG); Peer-to-Peer (P2P); Renewable Energy Sources (RESs); Transactive Energy System (TES)

1. Introduction

Energy must be available, affordable, and sustainable for socio-economic development. Presently, human, economic, and technological development have heightened pressure on conventional power generation to meet energy demand, thereby creating an imbalance in the amount of energy demanded and energy supplied, and environmental deterioration through increased reliance on fossil fuels [1]. Therefore, there is a need to improve energy efficiency and affordability. Distributed Energy Resources (DERs) penetration is highly favored to address this energy shortage and carbon emissions [2]. However, DER generation suffers from operational difficulties in energy distribution systems; hence, the Transactive Energy System (TES) concept integration. Transactive Energy (TE) is a solution that enables the buying, selling, and distribution of electricity from consumers with DER in a decentralized manner using control and economic mechanisms [3,4]. The GridWise Architecture Council, with other researchers, describes TE as a combination of control and economic techniques that permits the dynamic equilibrium between supply and demand in a power system [5,6]. The TES is a flexible, self-governing system for making decisions and utilizing power from different Renewable Energy Sources (RESs) [2]. It is a market-based technique used to supervise the generation and electricity flowing through an electric energy system while considering grid reliability constraints [7,8]. Moreover, it gives room for negotiation for energy exchange among the two entities, supply and demand, in the energy market [9,10].

1.1. Concept of transactive energy system

The concept of a TES is an approach used to resolve dynamic exchange between buyers and suppliers using Information Communication Technology to provide control between components inside the system, where the energy exchange between participants is processed based on the agreement between prosumers [11,12]. In TES, there is a substantial demand for information exchange among market segments such as prosumers, storage devices, and control systems [13]. This information sharing occurs via communication channels and occasionally through the public internet, which builds the potential for increased threats or cyber-invasions/attacks. Attackers target weaknesses in the energy market in TES [14]. An intrusion detection system (IDS), Intelligent Priority Selection-based Reinforcement Learning, was proposed to mitigate cyberattacks in P2P energy trading. The performance of the proposed IDS was validated using three interconnected MGs deployed to test the system [15]. Hence, data exchange among prosumers and market agents is essential for a safe and stable communication system [15]. TES was described as an emerging system for the integration of DERs through distributed, agile, and scalable coordination and control schemes [16]. Advances in power electronics technologies and energy storage systems (ESS) gave birth to the discovery of microgrids (MGs), groups of interconnected loads, and DERs, within stated electrical limits [16]. DER generation requires a communication infrastructure to exchange data with each resource and optimize their operation locally. Similarly, an effective data communication system is a requisite for the continuous, fast, reliable, and successful transfer of information between sensors, local controllers, and the MG central controller [17]. In a centralized TES, the distribution system operator (DSO) handles the wholesale electricity market by aggregating all the DERs and MGs within the distribution layer [18].

1.2. Peer-to-Peer energy trading

A Peer-to-Peer (P2P) energy trading system is a mechanism that manages energy exchange between participants (i.e., peers) without any intervention by an intermediary [19,20]. Additionally, P2P is a market-based trading method that enables prosumers to sell excess energy to peers [12]. The P2P architecture permits prosumers (consumers with the capacity to produce or store energy) to directly participate in bilateral energy trading without an intermediary, aiming to maximize the social welfare of all participants [21]. This strategy enables energy trading among peers at a closer distance to ease or minimize network losses [22]. To enhance the efficiency of energy allocations, the P2P platform encourages prosumers to self-organize into coalitions and other community energy initiatives [23]. Market participants are typically grouped into buyers and sellers based on their total generation and consumption [24]. The framework promotes incentivizing participants or players to trade their energy with peers [25].

P2P model energy arrangement is a consumer-centric, decentralized energy market designed to overcome technical constraints associated with the physical electricity network [21]. In the planning of central distribution systems, controls are typically made at one location [26]. However, a decentralized platform permits prosumers and consumers to transact energy directly with one another in a TE market. In centralized planning, prosumers' comprehensive data is required for centralized management, which causes communication and computational bottlenecks and privacy concerns, whereas in decentralized planning, all market participants, including consumers and DSOs, make decisions on their own [26]. Another computational burden arises from energy transactions, which are shared among all the market participants in a centralized market. Similarly, a decentralized TES can facilitate decentralized energy trading by utilizing a centralized optimization algorithm; however, it requires a central node to handle all computational functions [27]. Additionally, the structure of operations in the energy market is shifting from centralized to more distributed and transactive decision-making. Decentralized decision-making is giving way to more distributed and transactive models in energy market operations [6].

1.3. Contribution and article organization

The primary goal of cost optimization in TES is to maximize the use of RESs, preserve grid stability, and reduce energy costs for both prosumers and consumers. The major drivers behind the adoption of TES in the energy sector are the convergence of technologies, policies, and economic factors within an active prosumer market (where prosumers include buildings, EVs, and MGs) [28]. The factors motivating TES include the increasing penetration of RES, alignment with the latest concepts, and innovations such as energy decentralization, energy marketing, modernization, digital transformation, consumer participation, grid operations influenced by advanced control and communication technologies, MGs, prosumer engagement (consumers who can produce energy), and grid modernization efforts supported by State incentives. Compared to traditional energy systems, TES provides greater customer satisfaction, lower energy costs, efficient energy usage, reliability, and operational cost optimization through decision making [29]. The advantage of participating in TES is that energy consumers can lower their electricity expenses by sourcing energy from neighbors, increasing their profits by selling excess energy to other customers without incurring grid service fees.

Our main contributions of this article include:

i. Identifying obstacles associated with real-time data exchange, energy management, and smart pricing mechanisms in TES.
ii. Offering insight into how the implementation framework of a P2P-based TES can assist in resolving energy deficit through the effective use of DERs to overcome infrastructural limitations at the energy distribution layer.
iii. Addressing the critical issues of data security and privacy in the context of TES and the potential for scalability and long-term sustainability of the proposed system.
iv. Establishing the viability of applying multi-level communication features of TES to coordinate energy generation, consumption, and delivery, and to enhance grid reliability and make energy access more affordable by delaying the need for network expansion, thereby reducing operational and investment costs.
v. Demonstrating the suitability of TES in facilitating seamless interaction among various components during energy exchange among participants.

The article arrangement is as follows: In Section 2, we review related works to assess the level of work done on the title, identifying constraints of other studies and research gaps that have not been explored. In Section 3, the Methodology, we provide guidelines followed in bridging the identified gaps. In Section 4, we present the results and discussion, while in Section 5, we provide the conclusion, recommendations, and research outlook.

2. Review of related work

Current research entails centralized energy market planning, but there is limited attention to the communication framework for energy transactions in P2P arrangements. Communication technology plays a great role in the operation and management of networked MGs [30,31]. In recent times, smart grid systems have experienced rapid growth through IoT-based technology that uses cable and wireless communication protocols. This development has led to changing some power grids to two-way from one-way interconnections. This has also enhanced millions of DERs' participations in grid management and P2P energy trading [32]. The potential of distributed ledger technology (DLT) for the P2P-TE exchanges in local energy markets (LEM) was appraised in [33]. The researchers carried out thorough descriptions of DLT-based transactive management infrastructure. A P2P energy exchange in LEM was used to create a TES. A method for the design of TES for future distribution systems was introduced in [12]. The researchers established the importance of outlining energy trading techniques among participants in a distribution system. An independent economic entity (IEE) was employed as a third-party agent to facilitate clearing the LEM between the MG and the distribution system. Nonetheless, the authors failed to establish the role of IEEs in linking peers in a P2P transactive environment.

A control technique for TE storage service to tackle the challenge of optimal scheduling of energy, managing, and sharing by a set of prosumers is presented in [34]. The team proposed a coordinated and an uncoordinated game-theoretical control formulation for two unique resolution algorithms used interchangeably, depending on the grid's underlying communication architecture. The methods were validated through realistic cases on a numerical simulation platform. In related studies, the researchers in [35,36] presented intelligence-based algorithms to distinguish the prosumer's data using a compression algorithm and blockchain approaches, respectively. Two data compression algorithms were presented for bandwidth capacity reduction and minimization of space for storage and communication. The authors probed the challenge of transmitting big data and information over TES, which often leads to complexity in communication algorithms and wide-bandwidth channels. The performance of the algorithms was evaluated using a simulated prosumers dataset, including residential and industrial consumers. In the result obtained, 46% bandwidth and 53% storage space were saved with improved accuracy. An investigation on P2P transactive energy (P2P-TE) trading on multiple MGs was carried out by [37]. A P2P trading model within MGs was constructed while considering renewable energy uncertainties. The authors proposed the Wasserstein distance approach optimization method for optimal scheduling to solve the power fluctuation issues in the renewable energy system.

Furthermore, an Advanced metering infrastructure (AMI) with two-way communication (TWC) networks was presented for the monitoring and management of DERs and grid edge devices [38]. The authors explored the choice of downstream communication for meter pinging from the utilities to smart meters. The authors reported that upstream communication, that is, smart meters to electric utilities (meter reading), has been extensively discussed by other researchers. The researchers highlighted the advancement of AMI to automatic meter reading. The proposed TWC enables sending control commands to smart meters and devices to support advanced applications such as TES. The network calculus method was used to evaluate the effect of the TWC on the AMI network. The gap in the work is that the researchers established only the interaction between two-way communication and smart meters. However, the team failed to consider TWC between DERs and the distribution system. A P2P distributed TE management method with product differentiation and distribution network constraints was considered by [39,40]. In [41], a model was designed to moderate the optimal set of energy commands in a DER network for operational cost minimization over a time horizon. The authors employed Gurobi optimization software to figure out the model to facilitate rapid responses (which ensure real-time decision-making) and enhance efficient control of the DER network within a three-days' rolling horizon. The P2P energy trading model was numerically analyzed on IEEE 33-bus and 141-bus distribution systems to validate the impact of the method in ensuring reduced data communication and data privacy protection. The authors developed a decentralized alternating direction method of multipliers to clear P2P transactions. However, the authors did not consider renewable energy uncertainties, as they affect the output.

A P2P-TE trading scheme based on distributionally robust optimization was proposed in [37]. The team considered the uncertainties of renewable energy in their investigation based on the Wasserstein distance for multiple MGs. Additionally, an alternating direction multiplier algorithm was adopted to solve the energy-sharing model of MGs for privacy protection. According to the authors, the results obtained from the numerical analysis of P2P-TE trading improve the profitability of MGs. The researchers in [42,43] investigated the practicability of solar energy for 320 buildings, which include electric vehicle (EV) charging and residential load functionality. The HOMER software was used to estimate the system performance to address the peak load challenge. In their discovery, transactive energy management systems (TEMS) depict that an entire system load with a localized grid offers better system performance. The integration of prosumers with EVs and battery storage to TE was presented by [44]. A swarm optimization based on the honeybee mating algorithm was proposed for optimal scheduling and management of units (solar, wind, and EVs) in the MGs. The researchers discovered that smart charging is capable of mitigating system costs when the uncoordinated plan increases it [45]. The inter-communication structure was used to assist the electric utilities in identifying the negative effects of integrating EVs and local DERs to provide voltage support. It was noted that increasing the service voltage increases the earnings for homeowners through the energy trade, without sacrificing their convenience. In addition, it reduces voltage imbalance and lengthens the transformers' lifespan.

A group of researchers presented privacy-preserving energy transactions (PETra) by leveraging a decentralized IoT for TE to address the new risk posed to trading [46]. In order to meet security, safety, and privacy criteria, the authors used PETra to build on decentralized ledgers, like blockchains [46]. However, the authors failed to quantify their results based on the metric used to evaluate the proposed technique. In [47], reactive power control was designed to stimulate DERs to assist with reactive power for enhancing voltage profiles, allowing extra customer load restoration during power outages. In the results obtained, the reliability of critical load, under the transactive control, improved by at least 30% with the non-utility owned DERs. The researchers used a probabilistic distribution model, Monte Carlo, for simulations to provide multiple possible outcomes. The limitation of Monte Carlo is that one can sample only the input data to establish correlation, which may reduce the accuracy of the obtained results. Hence, there is a need to use a more advanced method, such as machine learning, which can accept both input and output data. The researchers in [31,48] and present a structured TE market in a community with multiple prosumers to enhance P2P energy trading. In the suggested method, the authors achieved a reduction in the community energy bills. When compared with the conventional peer-to-grid market under different scenarios, the bill reduction ranges between 18% and 52% in the P2P marketplace. A unifying approach for TES to resolve the DERs' market-based coordination issue was presented in [49]. The work limitation is that the authors do not provide sufficient information on implementing TES, which requires a combination of skills from an economist and a control engineer. Table 1 presents a summary of literature focusing on the Aim, Method, Results, and Limitations.

In reference to the reviewed articles, it was observed that there is little direction on the communication framework to enhance secure and transparent transactions between decentralized P2P participants. Accordingly, we gave more attention to solving challenges associated with identified obstacles of real-time data exchange, energy management, and smart pricing mechanisms. The proposed TES finds a solution to meeting energy demand linked to infrastructure limitations at the energy distribution layer. The approach ensures system reliability and affordable energy access, thereby delaying network expansion, minimizing operation and investment costs. Furthermore, we present a technique to enhance the communication framework that can be integrated into TES. We also address the critical issues of data security and privacy in the context of TES and the potential for scalability and long-term sustainability of the proposed system.

Table 1. Summary of related work.

Authors	Research aim	Method	Results	Limitation
Nie et al., 2023	P2P Transactive Energy (P2P-TE) exchange in local energy markets	Distributed Ledger Technology (DLT)	Designed TES with a DLT-based transactive management system	Democratic features of DLT affect the security of peers
Jalali et al., 2021	Third-party agent to facilitate local energy markets (LEM)	Independent Economic Entity (IEE)	Outlined energy trading technique among participants	Role of IEE in linking peers not established
Mignoni et al., 2023	Coordinated and uncoordinated control in TES	Two unique resolution algorithms	Validated through numerical analysis	Low-reliability analytical method
Zamani et al., 2022	Reduction of bandwidth capacity and minimization of storage space	Dynamic intelligent algorithm	A 46% bandwidth and 53% storage saved	
Huang et al., 2022	Explored downstream communication	Two-way communication (TWC) technique	A network calculus method was used to evaluate the system	No link between DERs and utilities.
Zhou et al., 2023	P2P distributed TE management	Developed a decentralized alternating direction	Not reported clearly	Some uncertainties are not considered
Laszka et al., 2017	Privacy-preserving energy transactions	Decentralized IoT for TE	Not reported clearly	Performance metrics not quantified.
Dong et al., 2022	Reactive power control to stimulate DERs to enhance voltage profile	Probabilistic distribution model (Monte Carlo)	Reliability of critical load improved by 30%.	Only input data was sampled for correlation
Rao & Selvan, 2020	P2P energy trading enhancement within a community	Structured TE market	Reduction in the community energy bills	Insufficient information on implementation

3. Methodology

In TES, various architectures such as 3-Layer, 5-Layer, and 7-Layer have been proposed to manage energy generation, consumption, and power flow, ensuring a dynamic balance between demand and supply while considering network constraints. The three-layer architecture includes an aggregator, communication, and user layers. The five-layer model adds two extra layers: Market and regulation. The seven-layer version improves upon the previous models by adding network and distribution line layers. This seven-layer architecture was adapted for this research, as shown in the Block diagram in Figure 1, illustrating how the components interact within the system. The architecture highlights the role of prosumers in enhancing the overall reliability and sustainability of the grid. The P2P-based TES architecture proposed here is decentralized to meet operational and economic goals, facilitating coordinated integration of utilities, prosumers, and DERs. P2P enables participants to engage in the market without intermediaries directly. Energy transactions occur at the user layer, while the communication layer is used for data analysis related to energy exchange. With fast communication and data measurement, and a market-clearing mechanism involving TE, bidirectional information and power flows are enabled. In this section, we outline the detailed procedures used to address challenges associated with centralized power systems, such as high energy consumption, wastage, maintenance costs, and environmental impact. We further considered MGs with various local energy sources such as solar, wind turbines, biomass, and energy storage systems (ESS) to make up the renewable energy sources (RES) farm. In this setup, the ESS stores excess energy, which is later used during the peak period. The system adopts a decentralized MG model to distribute energy production and consumption across nodes. Each node within the MG acts autonomously, contributing to the overall economic viability of the system. The major components of the TES, showing the decentralized MGs, DERs, and cloud servers for data storage, are illustrated in Figure 2.

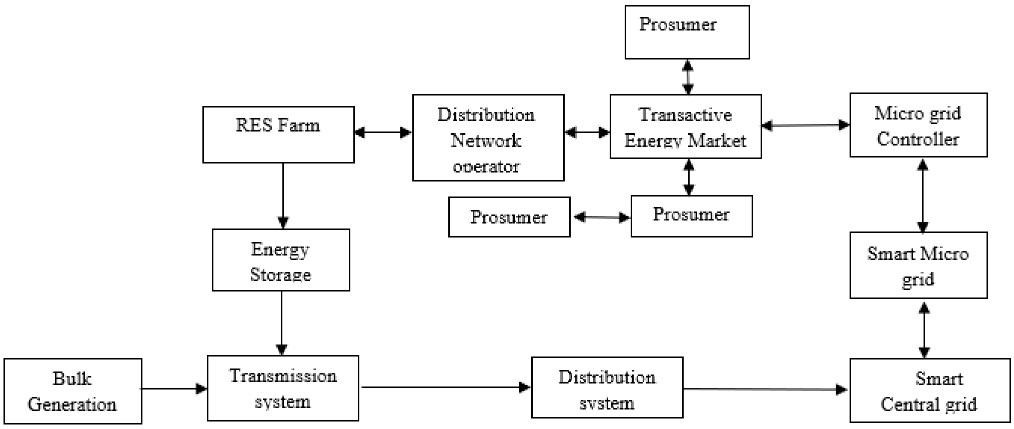


Figure 1. Block diagram of TES architecture.

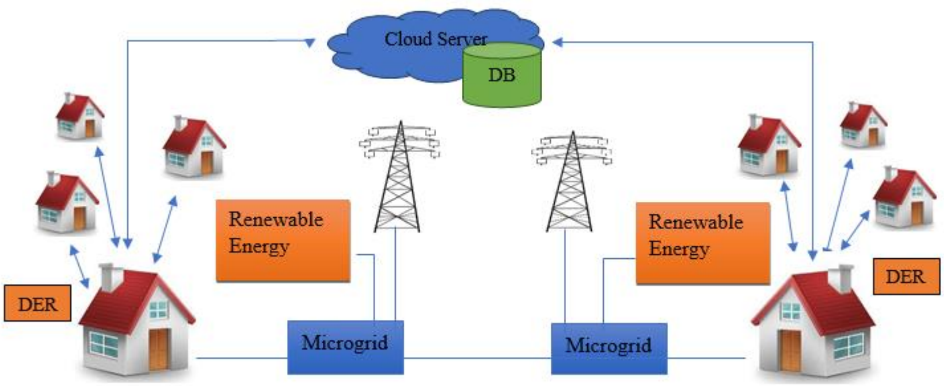


Figure 2. Decentralized microgrid architecture.

3.1. Description of the system components

Energy producers generate and supply energy within a MG. These encompass a variety of sources, each contributing to the overall energy mix. The key source of energy for the producers is solar panels, which capture solar energy and transform it into electrical power for consumption within MGs. The wind turbines operating harness wind energy to produce electricity, contributing to the power supply of the MG, while power sources from conventional electricity generation facilitate support for the MG's energy needs to ensure a reliable and diversified energy production profile. Residential areas consist of households actively using the MG, consuming, and generating energy through rooftop solar panels. A decentralized control network facilitates communication among MG components. The architecture integrates wireless and secure IoT protocols to boost seamless communication between smart devices, energy meters, and the central control unit. On the P2P, the system employed blockchain technology to ensure transaction transparency, security, and traceability. The smart contracts govern the execution of transactions, enabling prosumers to engage in P2P energy trading securely. The energy management system (EMS) oversees the MG's operation. It includes an energy market platform, data analytics tools, and an administrative interface for monitoring and managing MGs. Machine learning algorithms are employed to optimize energy distribution and predict demand patterns.

3.2. Transactive energy model

In the proposed TES framework, several variables were used to ensure its functionality and efficiency. These variables collectively represent the energy generation, storage, consumption, and transaction mechanisms within the P2P-based TES. These variables were integrated into models for optimization, value mapping, profit sharing, and economic assessment to evaluate the technical and economic feasibility of TES.

Variables

C_{MG} = Energy Surplus (kW)

${C_{t,\omega}}^{ET}$ = Energy Transaction within Electrical Energy Network (kW)

${C_{i,t}}^{E,L}$ = Electrical Energy Demand (MW)

${C_{h,t}}^{ESS,C}$ = ESS Electrical Energy Charging

${C_{h,t}}^{ESS,G}$ = ESS Electrical Energy Discharging

${C_{h,t}}^{LtH}$ = Transmitted Electrical Energy (kW)

${e_i}^{Min}$, ${e_i}^{Max}$ = Min & Max Energy Consumption (kW)

${C_{h,t}}^{Wind}$,${C_{h,t}}^{PV}$ = Electricity generated from PV & wind (kW)

${C_{h,t}}^{ET}$ = Energy Transaction (kW)

${C_t}^{Buy}$, ${C_t}^{Sell}$ = Bid and Offer Energy Quantity (kW)

${C_{i,t}}^{Inj}$ ${D_{i,t}}^{Inj}$ = Injected Power (Active and Reactive in kW)

$Qp_{t,\omega}^{PGP}$ = Fuel consumed by PGP

φ_{ω} = Probability of Scenario ω

${\delta_t}^{Pr}$ = Forecasted Wind Speed (km/h)

Electricity constraint

The electrical energy constraint was modeled as:

$$\sum_{i=1}^{J_i} C_{h,t}{}^{E,L} \forall t = \sum_{h}^{J_h} \begin{Bmatrix} C_{h,t}{}^{PGP} + C_{h,t}{}^{PV} + C_{h,t}{}^{Wind} + C_{h,t}{}^{ESS,D} + C_{h,t}{}^{LtH} + \eta_{h,t}{}^{ESg} \\ -C_{h,t}{}^{ET} - C_{h,t}{}^{HtL} \frac{C_{h,t}{}^{ESS,G}}{\eta_h{}^{ES}} \end{Bmatrix} \quad (1)$$

PV constraint

The PV constraint were modeled using:

$$C_{h,t}{}^{PV} \le \eta_h{}^{PV} \times R_t{}^{PV} \times S_h{}^{PV} \forall h, \forall t \quad (2)$$

Wind-energy constraint

The total generated energy from the PV and winds hangs on Sun radiation and the wind speed. Hence, the energy outputs were obtained as:

$$C_{h,t}{}^{Wind} = \begin{Bmatrix} 0 & \delta_t{}^{Pr} < \delta_h{}^{k.in}, \delta_t{}^{Pr} > \delta_h{}^{k.out} \\ \bar{C}_h{}^{wind} \cdot \left(\frac{\delta_t{}^{Pr} - \delta_h{}^{k.in}}{\delta_h{}^{RWS} - \delta_h{}^{k.in}}\right)^3 & \delta_t{}^{k.in} \le \delta_t{}^{Pr} \le \delta_h{}^{RWS} \\ \bar{C}_h{}^{wind} & \delta_t{}^{Pr} < \delta_t{}^{Pr} > \delta_h{}^{k.out} \end{Bmatrix} \quad (3)$$

ESS constraints

The power output of RESs depends on climate and geographical location [50]. Therefore, the ESS was modeled as;

$$C_{h,t}{}^{ESS} = \Delta t\{C_{h,t}{}^{ESS,G} - C_{h,t}{}^{ESS,D}\} + ESS_h{}^{In} \ \forall h \text{ for } t = 1 \quad (4)$$

$$C_{h,t}{}^{ESS} - C_{h,t-1}{}^{ESS} = \Delta t\{C_{h,t}{}^{ESS,G} - C_{h,t}{}^{ESS,D}\} + \forall h, \text{ when } \forall t \ge 2 \quad (5)$$

Communication system model for information flow

The information flow is carried out by modeling the communication system to reflect how information is exchanged between different entities in the TES, which relies on MG parameters. The whole cost of the MGs' communication system was developed based on the principle proposed in [13], as

$$\mathrm{J_{l,n}} = \varepsilon_{c1} \mathrm{z_{m,n}} + \varepsilon_{c2} (\mathrm{z_{c,m,n}})^2 \quad (6)$$

ε_{c1} and ε_{c2} = The cost of communication and the penalty for the Cloudlet, respectively, and $\mathrm{z_{c,l,n}}$ = the rate of utilization of the cloudlet.

Cloudlet utilization rate for communication power, $\mathrm{PC_{m,n}}$, and the System's Bandwidth, $\mathrm{BW_{m,n}}$, are expressed as;

$$\mathrm{y_{c,m,n}} = \varepsilon_s \frac{\mathrm{PC_{mn}}}{\mathrm{PC_{n,max}}} + \varepsilon_t \frac{\mathrm{BW_{m,n}}}{\mathrm{BW_{n,max}}} \quad (7)$$

where ε_s and ε_t are coefficients of the resources that satisfy the condition $\varepsilon_s + \varepsilon_t = 1$. If the noise in the communication channel is white noise, the best achievable rate is

$$N_{m,n} = BW_{T,n} \log_2 \left(1 + \frac{\sigma_{m,n} \cdot PC_{T,n}}{BW_{T,n}}\right) \tag{8}$$

where, $\sigma_{m,n}$ = Bit-rate coefficient, $PC_{T,n}$ = Total sum of communication power, and $BW_{T,n}$ = Total sum of the bandwidth.

The price estimation through the capital investment for installed RES is calculated based on the investment boundary (IB). This was derived in reference to the foundation laid in [34]. The IB is expressed as:

$$IB = \frac{CI + IC + MC}{AV_{PG}} \tag{9}$$

where CI = Capital Investment
IC = Inverter Cost (applicable to solar panel system)
MC = Maintenance Cost
AV_{PG} = Average of the power generated.

Calculating the profit of the energy supplier is given by

$$D_{pa} = \sum_b (R_{ab} \times \gamma_{ab} - R_{ab} \times H_{Yab}) + (P_a^K - P_a^{MK}) * H_V + C \tag{10}$$

where, R_{ij} = Cost of Energy Transferred (from seller *a* to buyer *b*), γ_{ab} = LMP, H_{Yab} = Transaction fee paid by buyer *a* to seller *b*, H_V = Utility Price, P_a^K = The demand of the seller during the generating period, and P_a^{MK} = The demand of the seller during the non-generating period, while C = Other market constraints.

The first term of the equation represents income realized from selling, the second term is the renewable generation pay-off for the user, and the third term is a constant to factor in some other market constraints not captured in the first and the second parts of the equation:

$$E_{pb} = \sum_a \left(R_{ab}^{RES}(\gamma_{ab} + H_{Yab})\right) + (P_{ab}^V) * H_V + C \tag{11}$$

where R_{ab}^{RES} = The total quantity of energy purchased from the buyer b, from the RES with price of H_{Yab}, and P_{ab}^V = The total quantity of energy bought from the utility.

The price per unit of energy is given as

$$H_{Yab} = \sum_{L=1}^{M} \tau_L \frac{P_L}{P_{Max}} \tag{12}$$

where τ = utilization fee for the line L, P_L = line flow, and P_{Max} = line maximum capacity.

Since the distribution system is a three-phase load, system imbalance occurs between the prosumers connected to different phases. Therefore, transaction reliability was considered to authorize energy transactions among the prosumers. The voltage imbalance metric (VIM) was applied to address the voltage constraints. The percentage VIM was given by;

$$VIM(\%) = \frac{\text{Average of Maximum Deviation}}{\text{Phase Average-to-phase voltages}} \tag{13}$$

The system design encompasses two segments: The development of the EMS utilizing the C#, and NET programming language and the concurrent creation of the cloud side of the TES. Each stage plays a role in the overall architecture, contributing to the system's efficiency and functionality. The Flowchart of the P2P energy transaction is shown in Figure 3. The flowchart illustrates the sequential order followed in achieving P2P-based energy trading. The first step is to determine the price based on available energy and the time of the day. Prosumers decided whether to buy for storage using ESS/EVs or sell surplus energy to neighboring consumers/peers. The prosumer's balance in the wallet was used to determine eligibility for participation in the energy trading. The same process was repeated for the consumers. After this, the transaction was updated to reflect the energy availability. The following steps outline the algorithm for calculating energy consumption within the EMS:

To determine the power usage of each electrical component:

$$Power\ (W) = Voltage\ (V) \times Current\ (A) \tag{14}$$

For devices with constant power ratings, the energy consumption is defined as:

$$\text{Energy (kWh)} = \left(\frac{\text{Power (Watts)} \times \text{Time (hours)}}{1000}\right) \tag{15}$$

where energy is in kilowatt-hours (kWh).

The power rating of the electrical device in kilowatts (kW).

Time is the period the device was in use in hours.

The energy consumption is in kilowatt-hours (kWh) based on the power rating of appliances in watts and the number of hours it is used. To calculate the cost of using a device;

$$\text{Cost (NGN)} = \text{Energy(kWh)} \times \text{Tariff Rate (NGN/kWh)} \tag{16}$$

The tariff rate is the cost per kWh, which is determined by the electricity provider. Additionally, some providers have different tariff rates for different times of the day and locations for different levels of consumption.

The energy efficiency is expressed as

$$\text{Efficiency (\%)} = \left(\frac{\text{Useful Output Energy}}{\text{Input Energy}}\right) \times 100 \tag{17}$$

The process efficiency is given as

$$\text{Process Efficiency (\%)} = \left(\frac{\text{Useful Output Power}}{\text{Input Power}}\right) \times 100 \tag{18}$$

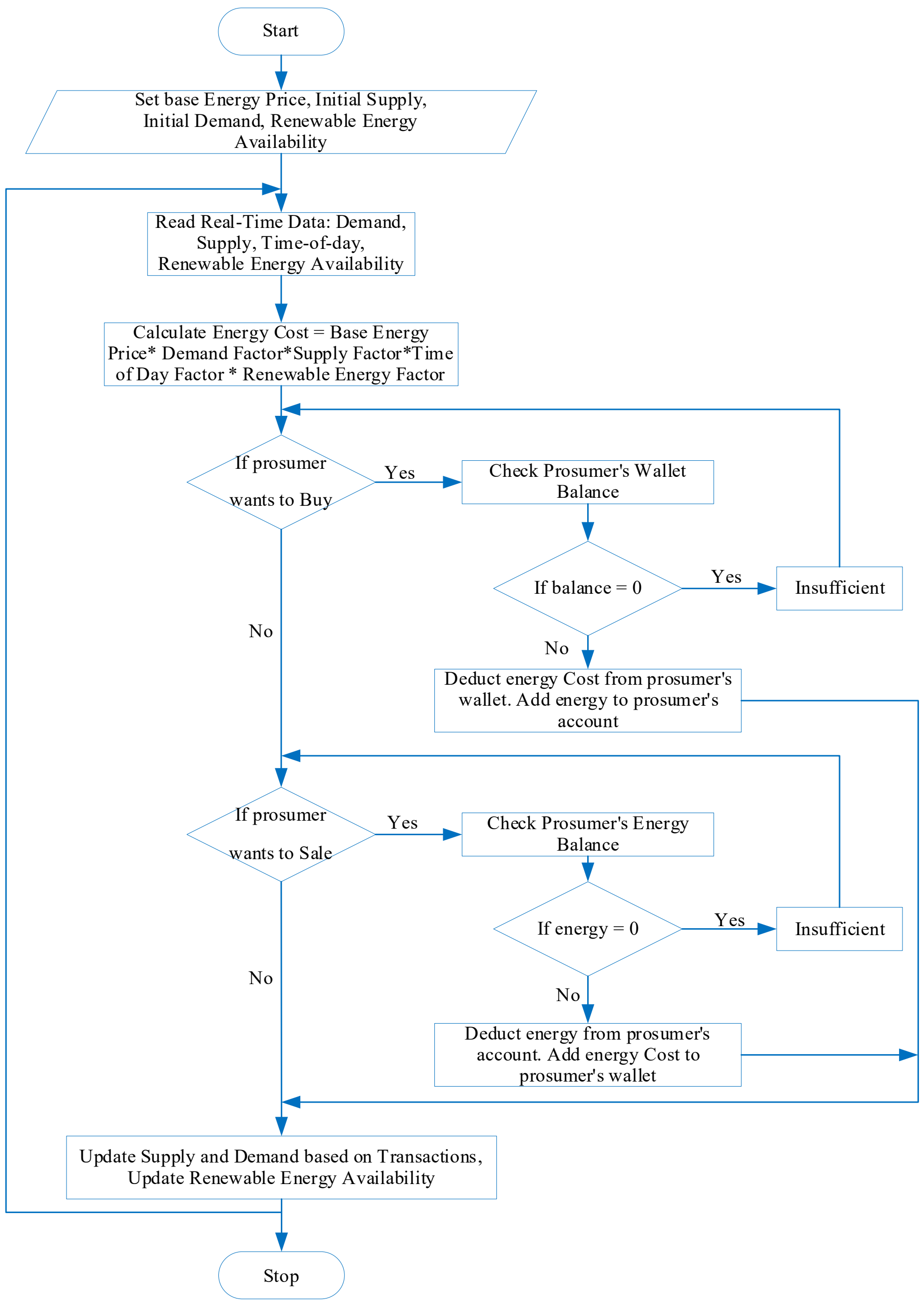
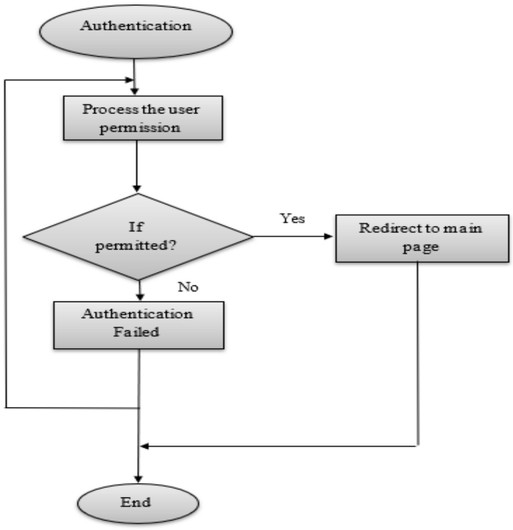


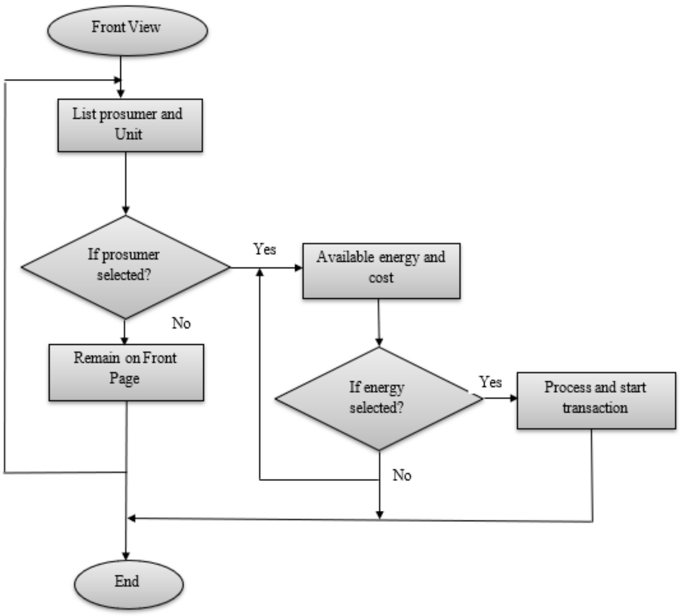
Figure 3. Flowchart of the decentralized P2P energy transaction framework.

3.3. Communication and integration

In the communication layer, participants were interconnected for data exchange. Communication channels between EMS components were carefully planned and implemented. The design incorporated asynchronous communication to enhance system responsiveness. Integration points with external systems were seamlessly integrated to ensure cohesive functionality. The logging mechanisms and error-handling strategies were embedded within the EMS to capture system activities and manage exceptions effectively. C# logging libraries, NLog, and log were employed. The flowchart diagrams for the Authentication and TES User interface for the proposed communication framework are shown in Figure 4a,b, respectively.



(a)



(b)

Figure 4. (a) User login and authentication flowchart; (b) User environment flowchart.

3.4. Cloud-Side of the Transactive Energy System (TES)

3.4.1. Cloud infrastructure

The TES is on the cloud side. It leverages cloud infrastructure for scalability and accessibility. Cloud services are considered a platform for managing controllable assets and the regional wholesale energy market. The TES architecture was designed to manage transactions related to energy consumption. It incorporates features for monitoring and analyzing energy transactions within a decentralized MG.

3.4.2. Communication with EMS

The communication links between the EMS and TES were established to ensure real-time data exchange. The design incorporates asynchronous communication to enhance system responsiveness. Integration points with external systems that are application programming interface (API) were integrated into the framework to ensure cohesive functionality. The API calls were forwarded to the server for secure communication protocols and efficient interaction. The TES serves as a repository for historical data to analyze energy consumption. It generates reports and notifications, contributing to facilitating energy management.

3.5. Programming

The EMS and communication framework for the TES, three programming Languages, Python, C#, and MySQL, were used in developing the backend. Python was used for data analysis and simulation. Pandas and NumPy from Python libraries were applied to analyze energy consumption patterns and simulate MG behavior. For the Web Interface Development, Django from Python was used to develop a web-based interface for monitoring and controlling MG components. C# was employed to develop the backend services. The backend services were designed to handle communication protocols, manage distributed systems, and coordinate TE transactions. MySQL stores energy consumption patterns, pricing information, and system configuration data. The integration of Python, C#, and MySQL for web interface development using Django in Python interacts with C# backend services to retrieve data from the MySQL database for real-time monitoring and control.

3.6. Database design for the transactive energy system

A well-designed database schema was implemented to store and manage relevant data. The suitable database technology selection was based on compatibility with C# NET (MySQL), ensuring integration and optimal data handling. It is a multi-threaded server-based application that permits users to have access to the thread or process participants' requests. In response to changes in the information system and the correction of errors in the current schema, the database schema (a formal structure) is used for querying, updating, integrating, and converting data of participants in P2P-based TES. The schema is vital for the system's reliability, especially when improving the TES database or adding new constraints and reorganizations aimed at optimizing the execution of important queries, which generally involve modifications to the database structure. The database schema was designed with features that permit new schema components to be added, modified, dropped, split, or merged with existing ones. Therefore, efforts were made to prevent schema changes without data loss, as such tasks are time-consuming, prone to errors, and require advanced skills for correction.

3.7. Case study

The decentralized TES was used for the case study of a community of 246 consumers connected to the grid, with 14 prosumers. The trading interval of 150 minutes was considered. The prosumers were designed to sell excess energy to consumers and other prosumers within and outside the local community. These energy transactions among the participants were implemented using the P2P market structure. The framework studied energy consumption through TES under various scenarios and conditions. It enabled the assessment of the system's responsiveness and ability to adapt to different scenarios, including changes in energy demand, pricing, and external factors.

3.7.1. User table attributes and transaction record

The database was designed to comprise users (prosumer and consumer), energy, prices, units, and balance as shown in Tables 2 and 3. In the context of a TES, the user table plays a pivotal role in storing information about prosumers and consumers. This sub-section outlines the detailed design considerations for the user table, emphasizing the attributes and functionalities essential for managing prosumer and consumer records effectively. The user Table encompasses a set of defined attributes to capture pertinent information about both prosumers and consumers. Key attributes include User ID (UID), a unique identifier assigned to each user, to facilitate efficient record retrieval and management. The username and password credentials are for secure user authentication and access to the system. There is a designated role to indicate whether the user is a prosumer or consumer, enabling role-based access control. The personal information fields include name, contact details, and address for comprehensive user identification. The energy production/consumption data are recorded to give values of energy produced or consumed to track individual contributions to the energy ecosystem. The billing information system is for billing and financial transactions to ensure accurate invoicing and financial transparency. The Meter ID is for the identification of the energy meter associated with each user for precise tracking of energy consumption or production. Furthermore, the connection status indicates whether users are actively contributing to the grid or solely consuming energy.

Table 2. User record.

S/N	Field	Data type	Size
1	User Id	Int	10
2	Full name	Varchar	150
3	Username	Varchar	150
4	Password	Varchar	150
5	Transaction Category	Varchar	20
6	Energy	Int	100
7	Date Registered	Varchar	150

Table 3. Transaction record.

S/N	Field	Data type	Size
1	Transaction Id	Int	10
2	User Id	Varchar	10
3	Message	Varchar	246
4	Energy	Varchar	100
5	Date Registered	Varchar	150

3.7.2. User table relationships

Establishing relationships between the user table and other pertinent tables is essential for maintaining a well-structured database. The key relationship, the prosumer-consumer Relationship, is a one-to-many relationship where a prosumer has multiple associated consumers (households or businesses connected to a prosumer's energy production). On the transaction history, a one-to-many relationship between the user table and the transaction history table captures the details of energy transactions initiated by both prosumers and consumers. Furthermore, the meter readings table ensures real-time synchronization of energy consumption.

3.7.3. Functionalities

The user Table supports various functionalities to enhance the TES reliability in terms of user registration and authentication for secure processes to safeguard system integrity. The role-based access control ensures that prosumers and consumers have access to relevant data and functionalities. The billing and invoicing function automates the generation of bills and invoices based on energy consumption records. It is also the transaction tracking for tracking energy transactions initiated by the participants (prosumers and consumers). In addition, the real-time update feature is integrated with energy consumption reading.

3.8. Experimentation process

The experimentation concept involves creating diverse scenarios that mimic real-world conditions, such as peak demand periods, fluctuating energy inputs from renewable sources, and unexpected changes in consumption. In the developed framework, the MGs were incorporated for real-time monitoring mechanisms to track and analyze energy consumption patterns continuously.

4. Results and discussion

4.1. Results

The results demonstrated that the system is robust at encrypting sensitive information, securely storing credentials, and including features for regular security audits to ensure the confidentiality and integrity of user data. In implementation, scalability features enable the TES to support a growing user base without sacrificing performance. The database within the TES efficiently manages prosumer and consumer records. After integrating the EMS into the framework, it enables real-time monitoring of energy consumption, which optimizes the distribution and management of energy resources within the system. The EMS permits real-time energy consumption monitoring, manages energy flow within the grid infrastructure, maintains system stability, and reduces losses. The system employs data analytics and machine learning to forecast future energy consumption patterns and supports proactive decision-making, optimizing energy use based on predictive insights. The graphical interface is shown in Figure 5. The TES was designed to enable a dynamic, two-way flow of electricity and value between energy producers and consumers. The graphical interface of the developed TES framework is shown in Figure 6. The system provides information for 246 customers, available energy, total energy sold, total revenue, and generates transaction records for customers. Using advanced technologies, the TES framework monitors the implementation of market mechanisms and real-time communication to optimize energy exchange among stakeholders. Data collected during a 150-minute trading period is plotted in Figure 7.

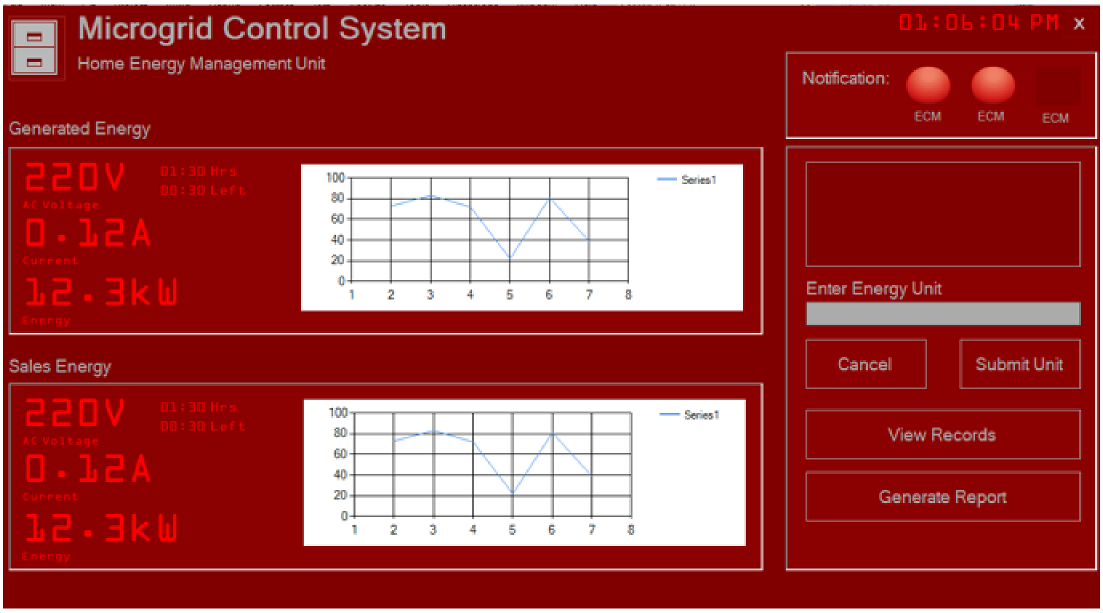


Figure 5. Energy Management System (EMS)

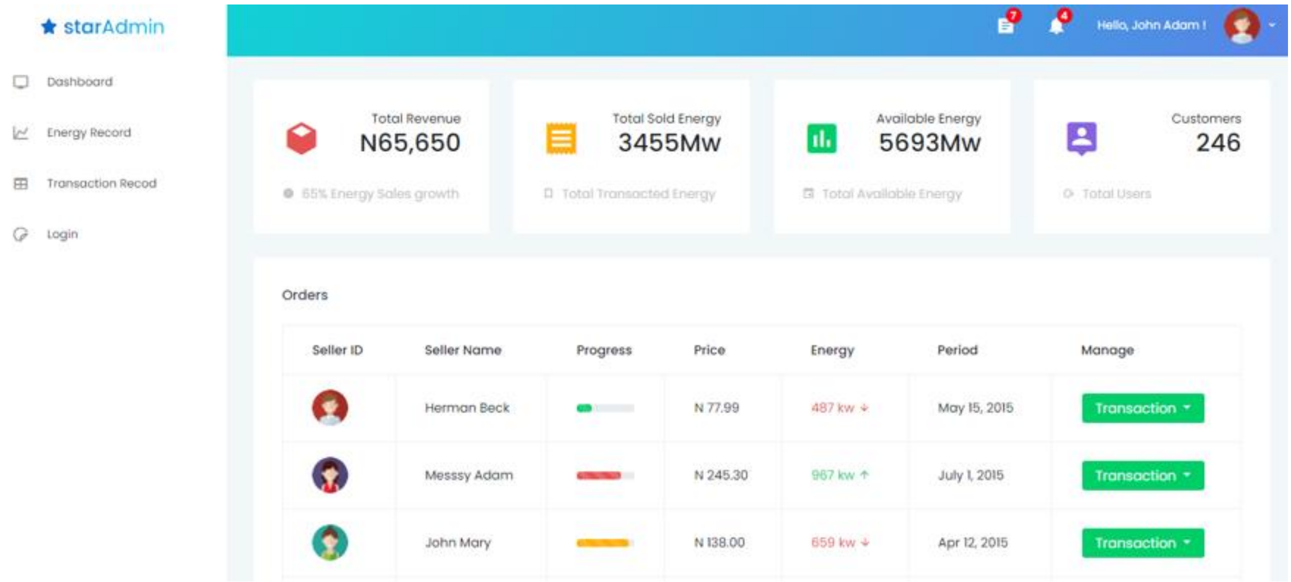


Figure 6. TES interface.

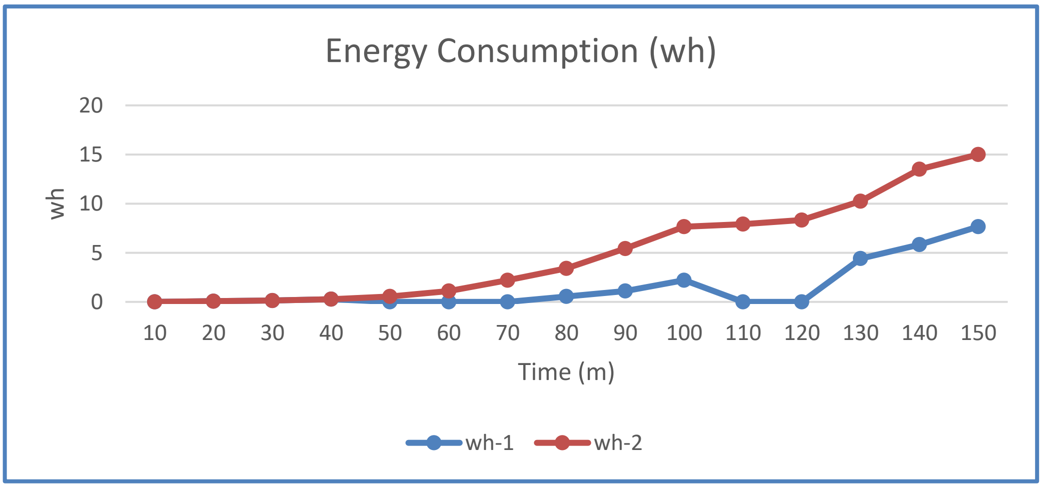


Figure 7. Duration of energy trading.

4.2. Discussion

The monitoring capabilities are tested, enabling a robust evaluation of its performance in different operational contexts. The developed framework ensures real-time monitoring mechanisms to track and analyze energy consumption patterns. The system was assessed for its adaptability to varying consumption patterns and sudden changes in energy demand. This aspect gauges the flexibility in responding to dynamic conditions, ensuring its effectiveness in optimizing energy distribution and resource utilization. The performance validation confirmed that the developed system performs better and effectively monitors and responds to energy consumption. The experimentation process helps identify operational challenges the system encountered. Uncovering potential difficulties, the system refines and enances its resilience and reliability under various scenarios. The system monitors consumption, optimizing the allocation of energy resources. This optimization contributes to energy efficiency, cost-effectiveness, and the overall sustainability of the system operation. In essence, subjecting the system to experimentation in simulations validates the current capabilities and positions it for continuous improvement, adaptability, and scalability in the ever-evolving energy landscape.

It can be deduced from the framework that the developed system provides insights into energy usage, facilitating informed decision-making. On the cost-benefit analysis of TE trading, the Transactive Coordination System communicates with local supply through two major signals: The Transactive Incentive Signal (TIS), which gives details of energy costs (₦/kWh), and the Transactive Feedback Signal, forecasting aggregated power flow (kW) between the two Transactive Nodes. This ensures that the total energy consumers use matches what the DSO wants. The TIS and TFS, transactive signals, are traded between the neighboring TNs.

4.3. Performance evaluation

A comparative evaluation was carried out to validate the performance of the proposed framework. The proposed work was compared based on reliability, security, privacy, and scalability. The researchers in [46] considered three of the metrics but failed to quantify the results. However, in this work, we quantified all the results obtained from the considered metrics. The other two references considered energy bill reduction from their results. The scalability was measured by analyzing the change in the performance with an increase in the number of customers to obtain the system response to resource utilization under different load patterns. This gives the system a comparative advantage over other methods presented by researchers in the reviewed articles. Moreover, this validation instills confidence in the framework, establishing its potential for real-world implementation. The analysis is shown in Table 4.

Table 4. Comparative analysis of the performance metrics.

S/N	Performance metrics	[46]	[47]	[34]	Proposed framework
1	Reliability	√	×	×	89.71%
2	Security	√	×	×	High
3	Privacy	√	×	×	High
4	Scalability	×	×	×	High
5	Energy Bill Reduction	×	√	√	15% Reduction

In TES, the integration of small-scale prosumers and highly variable intermittent DERs introduces challenges and uncertainties. The uncertainties of DERs and the participants' behavior have an impact on the economics of scheduling and the stability of TES. Here, we focused on the intermittent and predictable nature of RES and cybersecurity risks. In addressing these uncertainties, prosumers were credit-rated to incentivize/motivate credible participants through savings on their electricity bills. Additionally, penalizing bad behavior is done by increasing the energy price for participants with a low reputation. Regarding the optimality of this proposed framework, it guarantees that it yields the best result and fulfills the objective function of profit maximization or cost minimization. Achieving high computing efficiency, decentralized operations, and solution optimality simultaneously is difficult for this P2P-based TES. Nonetheless, the decentralized system's optimality was sustained.

5. Conclusions

In this work, we present a compelling vision for the future of energy distribution. We proposed the robustness and efficiency of the TES framework, which facilitates seamless interaction among components of the TES for energy exchange between participants. The significance of this paper lies in its potential to revolutionize the current power infrastructure, introducing a more resilient and efficient system. The challenges associated with real-time data exchange and energy management in TES were identified through the review of related work. The research offers an insight into how the implementation framework of a P2P-based TES can assist in resolving energy shortfalls through the effective use of DERs to overcome infrastructural limitations at the energy distribution layer and addresses the critical issues of data storage, security, and privacy of participants in the context of TES and the potential for scalability and long-term sustainability of the proposed system. Additionally, we show the viability of applying multi-level communication features of TES to coordinate energy generation, consumption, and delivery.

The research findings emphasize the importance of a complete transition to decentralized MGs to enhance energy accessibility. Through detailed simulations and analysis, it was discovered that adopting the framework will result in reduced energy losses, improved reliability, and the establishment of a sustainable energy ecosystem. The adoption of this framework will increase energy security, reduce dependency on centralized grids, and a more equitable distribution of resources. We recommend a multi-stakeholder approach to foster partnerships in solving energy distribution issues using TES. We also present an implementation framework rather than a model, focusing on the structured approach designed to support a theoretical understanding of the Decentralized P2P-based TES. Therefore, there is a limitation on the analysis of the model’s sensitivity to changes in computational parameters. In the future, we plan to investigate the cyber vulnerability of TES and develop an intrusion detection monitoring solution for identifying malicious activities on the network. Additionally, to further demonstrate the system’s robustness and efficiency, we plan to validate the proposed P2P-based TES using Lab-scale test instances and varying conditions in the future.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

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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.

Author contributions

Oluwaseun Tooki: Writing—Original draft, Visualization, Software, Methodology, Formal analysis, editing. Olawale Popoola: Conceptualization, Supervision, Investigation, and review. Jeremiah Pam: Writing, Coding and Review.

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