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Evaluating a Blockchain-Enabled Distributed Energy Trading Platform for Rural Electrification: A Case Study in East Shewa, Ethiopia

Jiao Yuliang[a*], Zhang Zhenke[b], Zhu Wanyi[b]

[a]*School of Foreign Languages, Chongqing Three Gorges University, No. 666 Tianxing Road, Wanzhou District, Chongqing 404020, China*
[b]*Institute of African Studies, School of Geography and Ocean Science, Nanjing University, Xianlin Campus, 163 Xianlin Road, Qixia District, Nanjing, Jiangsu Province 210023, China*

ABSTRACT

This study develops and evaluates an hourly (Δt = 1 h), one-year discrete-event simulation of an off-grid solar PV microgrid in East Shewa, Ethiopia. The system is augmented with a blockchain-style settlement layer—implemented as an abstraction of rule-based accounting and automated settlement rather than a full consensus network—to support peer-to-peer (P2P) energy trading. The platform records cleared transactions, applies priority-based allocation under scarcity, and updates a bounded scarcity price at each clearing interval (0.08–0.20 USD/kWh) based on net energy deficit. During communication outages, transactions are logged locally and reconciled via delayed settlement once connectivity is restored. Under the modeled assumptions, local PV generation supplies approximately 94% of the community's annual electricity demand, and about 96% of total PV generation is utilized, with remaining shortfalls and curtailment concentrated in extended low-irradiance periods. Stress scenarios (prolonged cloudy weather, PV capacity reduction, and network interruptions) indicate that service continuity in the simulation depends primarily on resource adequacy and flexibility options, while the settlement logic improves transparency and rule-based allocation. These findings represent model-based operational evidence under the stated assumptions; user adoption, willingness-to-pay, and governance conditions require empirical validation.

Keywords

Blockchain settlement;
Peer-to-peer (P2P) energy trading;
Off-grid PV microgrids;
Interval-based dynamic pricing;
Delayed settlement;
East Shewa, Ethiopia

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1. Introduction

Ethiopia, like many developing countries in Sub-Saharan Africa, continues to face major challenges in rural electrification. Although national electricity access has improved substantially in recent years, a pronounced urban–rural gap persists, and rural communities continue to experience limited and often unreliable electricity supply [1]. This reliance not only contributes to environmental degradation but also poses significant health risks due to indoor air pollution [2]. The implications extend to essential public services: close to one billion people are served by health-care facilities without reliable electricity, and in Sub-Saharan Africa about 15% of facilities have no electricity access [3, 4]. These figures highlight the pressing need for sustainable, scalable energy solutions in rural regions.

Within the energy planning literature, rural electrification outcomes are shaped not only by technology choices but also by demand characterization, socio-economic impacts, and governance arrangements. Recent contributions in the International Journal of Sustainable Energy Planning and Management (IJSEPM) have examined, for example, socio-economic effects of rural electrification [5], demand and appliance-based load modelling relevant to Sub-Saharan Africa including Ethiopia [6], and stakeholder engagement challenges in community renewable electricity projects [7].

Distributed renewable energy systems—particularly solar photovoltaic (PV) technology—offer a promising

*Corresponding author – e-mail: jiaoyuliang@gmail.com.

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path forward. With Ethiopia's abundant solar resources and the steadily declining cost of PV systems, solar microgrids have become increasingly viable, especially in regions beyond the reach of national grid infrastructure [8]. However, deploying and operating community microgrids at scale remains challenging. Common barriers include weak infrastructure, imperfect supply–demand balancing, high transaction/coordination costs, and limited transparency in local market arrangements [9]. These issues are especially pronounced in remote Ethiopian communities, where infrastructure gaps are severe.

Blockchain technology offers a potentially transformative solution. Its core features—decentralization, transparency, and programmable smart contracts—can help address many of the challenges faced by rural energy systems. Pilot projects such as the Brooklyn Microgrid (USA), Power Ledger (Australia), and Lition (Germany) have demonstrated the viability of blockchain-based local energy markets [10]. Similar trials in South Africa and Kenya further confirm the technology's adaptability in emerging markets [11]. At the same time, community energy research highlights that participation, trust, and ownership/governance models can be decisive for real-world performance—factors that must be considered alongside technical feasibility [12, 13, 7].

This study evaluates the feasibility and performance of a blockchain-enabled PV microgrid and local trading arrangement for a representative rural setting in the East Shewa Zone, Ethiopia. The assessment focuses on (i) demand coverage and operational performance under seasonal and daily variability, (ii) market operation—transaction processes and dynamic pricing—under peer-to-peer trading rules, and (iii) distributional outcomes and operational robustness under plausible disruptions.

Accordingly, this study explores the following research questions:

RQ1: To what extent can a PV-based community microgrid meet heterogeneous rural electricity and irrigation loads in East Shewa under seasonal and daily variability?

RQ2: How does a blockchain-style settlement and peer-to-peer trading mechanism operationalize transaction recording, transparency, and scarcity signaling (via interval-based dynamic pricing) within the microgrid's hourly operation?

RQ3: How robust and equitable are the outcomes under shocks (e.g., PV/battery outages, seasonal resource swings, communication failures), and what deployment constraints related to user participation and governance should be considered in rural contexts?

By answering these questions, this research aims to provide planning-relevant evidence on when and under what assumptions blockchain-enabled trading may add value beyond conventional microgrid operation, and to clarify key limitations for real-world deployment.

2. Literature Review

This section reviews the contextual, technological, and market literature that underpins the study. It first introduces East Shewa as the case-study setting, then examines distributed energy approaches in rural electrification, and finally discusses blockchain-enabled energy trading and the research gap addressed by this paper.

2.1 Case Study Region: East Shewa Zone, Ethiopia

The East Shewa Zone lies at the intersection of Ethiopia's Central Highlands and the Great Rift Valley. The region benefits from relatively stable semi-arid climatic conditions and strong solar energy potential. The average solar irradiance is approximately 5.2 kWh/m² per day, with about 8 hours of sunlight per day on average, making it well-suited for photovoltaic deployment [14]. The zone's geography is diverse, ranging from flat lowlands to highland areas, which influences settlement patterns and infrastructure development.

As of 2022, the total population of East Shewa exceeded 2.1 million, with roughly 68% residing in rural areas, primarily engaged in small-scale agriculture [15]. The average household size is about 4.4 persons, yielding an estimated 480,000 households in total. Despite limited infrastructure, most villages have access to basic services such as primary schools and health posts [16]. Electricity access, however, is strikingly low in rural East Shewa. Rural electrification stands at only about 40% [1], with the majority of rural households still relying on traditional biomass fuels. This leads to widespread indoor air pollution and associated health problems [2]. Figure 1 illustrates the location of East Shewa Zone within Ethiopia.

The average daily electricity consumption per rural household is just 1–2 kWh, sufficient only for basic needs like lighting and phone charging [18]. By contrast, agricultural electricity use is concentrated in irrigation

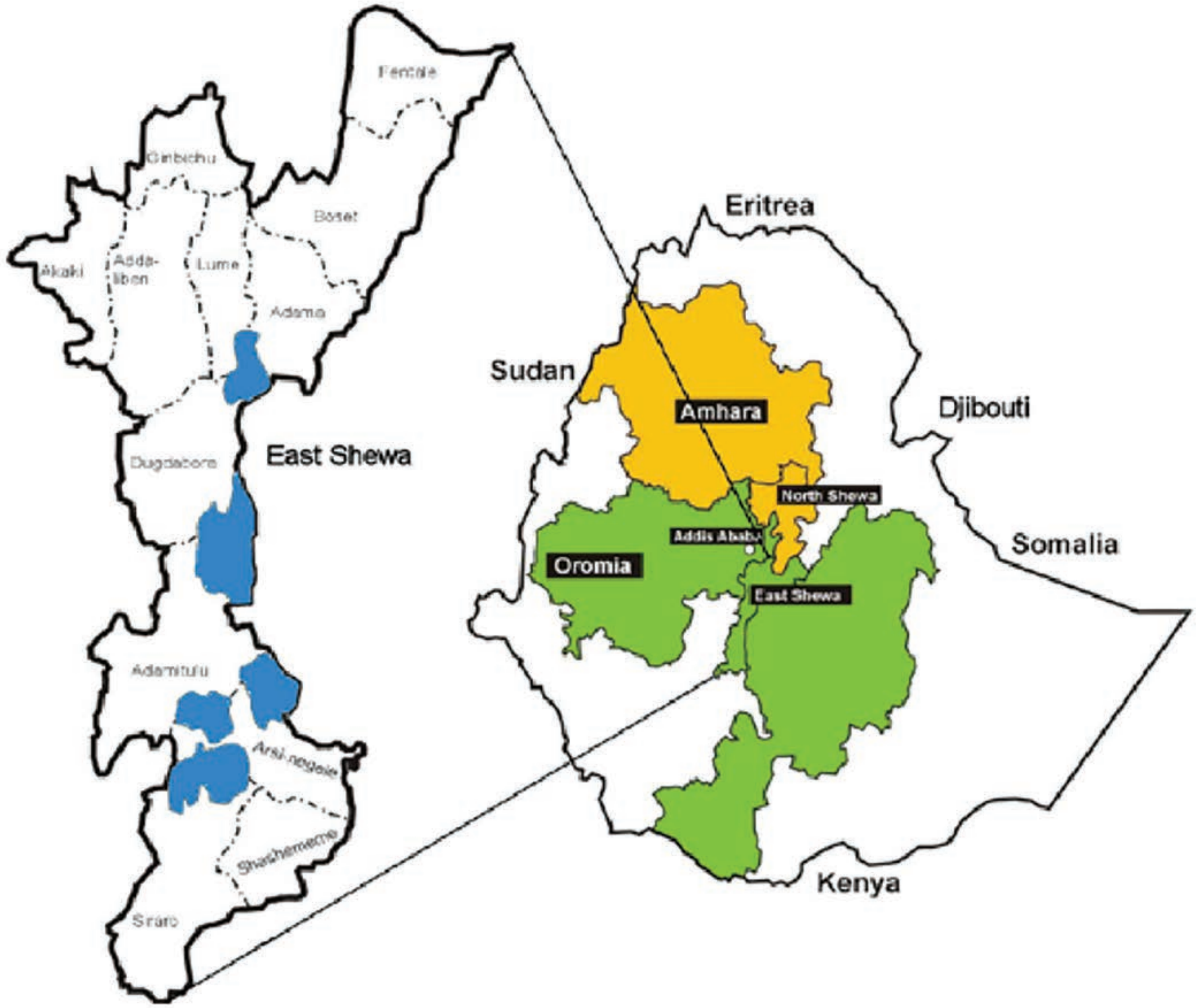

Figure 1: Map of Ethiopia highlighting East Shewa Zone. (Source: Adapted from Wikimedia Commons [17].)

pumps and is highly seasonal. During the dry season, a typical irrigation pump (3–5 kW) operating for extended hours can drive per-household daily electricity demand up to 25–30 kWh; in the rainy season, when irrigation is minimal, household demand drops to around 4–6 kWh per day [19, 20]. Likewise, public facilities such as rural health posts and primary schools consume on the order of 5–10 kWh daily (with peak power demands of 1–2 kW for equipment) [19]. This energy landscape of East Shewa reflects the typical challenges of rural electrification and provides a realistic data foundation for the modeling efforts in this study.

2.2 Distributed Energy in Rural Electrification

From an energy planning perspective, the performance of distributed systems in rural electrification depends not only on technology choice but also on financing, operations and maintenance, demand profiles, and local governance arrangements. Distributed energy systems—particularly solar home systems and micro-grids—are considered key strategies for improving electricity access in rural areas of developing countries [21]. Experiences from other regions provide useful lessons. In East Africa, Kenya has pioneered the “pay-as-you-go” (PAYG) financing model, which significantly reduces the upfront cost of solar home systems by allowing users to pay in small installments via mobile money platforms like M-Pesa [22]. This model often integrates remote monitoring and automatic disconnection features, enhancing payment compliance and reducing default risk [23]. These PAYG experiences also illustrate that transaction mechanisms in low-income rural settings must align with available payment channels (e.g., mobile money), metering/monitoring capabilities, and intermittent connectivity—constraints that are directly relevant when considering blockchain-enabled trading. By lowering financial barriers, PAYG has accelerated the adoption of solar lighting systems among low-income rural households.

In South Asia, India's "Lighting a Billion Lives" (LaBL) initiative established solar charging stations and micro-grids in remote villages, training local technicians for ongoing operation and maintenance [24, 25]. This community-centric approach improved household lighting access, extended evening study hours for students, and stimulated rural microenterprise activity—demonstrating the sustainable development benefits of distributed systems when coupled with local capacity building. Meanwhile, in East Africa's Turkana region of Kenya, a hybrid PV–wind microgrid has successfully addressed generation variability by combining resources, ensuring more consistent energy supply for public services such as healthcare and education [26].

Overall, the technical feasibility and social acceptance of distributed renewable energy systems have been well established through these global experiences. However, persistent challenges remain in scaling up these solutions: sustainable financing, long-term maintenance, and integration into national energy plans continue to pose difficulties. These are among the gaps that emerging digital technologies, including blockchain-based coordination mechanisms, have been proposed to address [2].

2.3 Blockchain Technology and Energy Trading

Blockchain, as a distributed ledger technology, offers several potential advantages for decentralized energy markets, including peer-to-peer transactions, traceable records, and reduced transaction costs and trust barriers [11]. In pilot projects such as the Brooklyn Microgrid in New York and the Lition platform in Germany, blockchain has enabled direct energy trading between local prosumer households, with automated settlement and dynamic pricing improving market efficiency [10]. Similarly, in South Africa and Kenya, experimental platforms (e.g. Power Ledger, Sun Exchange) are testing blockchain-based energy trading models in real communities, indicating the technology's adaptability to different regulatory and infrastructure contexts.

Blockchain can also integrate with Internet of Things (IoT) devices like smart meters to enhance real-time data collection and system control [27]. By using smart contracts tied to IoT sensor inputs, a blockchain-based system can automate energy dispatch, enforce trading rules, and encourage user participation through tokenized incentives. However, current blockchain deployments still face limitations related to network infrastructure, energy consumption, and scalability. In rural areas, the lack of reliable internet connectivity and ICT infrastructure may hinder the execution of smart contracts and synchronization of data. Moreover, concerns about the energy overhead of blockchain (for consensus mechanisms) and cybersecurity risks must be considered when introducing this technology into the power sector. This has motivated hybrid designs (e.g., local logging with delayed settlement) that can preserve core accounting functions during connectivity disruptions, which is particularly relevant for rural microgrids.

Despite these challenges, blockchain shows great promise in the energy domain—particularly for reducing administrative costs, increasing transparency, and facilitating multi-party collaboration in energy trading. Notably, most existing research and pilot projects have been in developed or urban settings, and largely conceptual or small-scale. Its application in developing regions remains in early stages, with very few empirical studies focusing on rural contexts. A recent comprehensive review observed that while peer-to-peer (P2P) energy trading can bring significant benefits to prosumers and the grid, widespread adoption is still limited by regulatory and technical barriers [28]. In response to this gap, the present study uses East Shewa Zone as a case study to explore the applicability and impact of a blockchain-driven distributed energy trading platform in a rural African context. We aim to rigorously assess the platform's performance in terms of technical feasibility, price adaptability, extreme situation test, and operational stability. By doing so, this study provides a detailed quantitative evaluation of blockchain-based trading under explicitly stated rural constraints, offering planning-relevant evidence for adapting such mechanisms to rural electrification contexts.

2.4 Summary and Research Gap

In summary, prior studies suggest that blockchain can support transparent settlement and automated coordination in P2P energy trading, but evidence remains limited for rural, low-resource settings where metering, payment channels, connectivity, and governance constraints shape feasibility and user participation. This motivates the present simulation-based analysis for East Shewa, which explicitly incorporates seasonal demand variability, rural ICT constraints, and stress scenarios to examine when blockchain-enabled trading may add value beyond conventional microgrid operation.

3. Method: Simulation Model

This section explains how the simulation model was constructed and evaluated. It presents the design of the representative community, the main parameters and assumptions, and the blockchain-style settlement and scenario framework used to test platform performance.

3.1 Design of the Simulated Community

To investigate the potential of blockchain technology for distributed energy trading in East Shewa, we developed a representative simulated rural community as a test platform. Based on local demographics, energy usage patterns, and climate conditions, the simulated community (village) consists of approximately 100 households, a set of agricultural irrigation loads, and two public service nodes (one primary school and one health post). This composition reflects the typical energy consumption structure of rural East Shewa [19, 29], including a mix of residential and productive uses as well as essential services.

To supply this community, we assume a decentralized solar microgrid with PV generation distributed across 10 nodes (households or community buildings) totaling about 50 kW of installed capacity (5 kW per node). This configuration captures the characteristics of a small-scale off-grid solar network and includes moderate redundancy to handle fluctuations in generation and demand. In addition, a lithium-ion battery system providing 50 kWh of storage and 25 kW charge/discharge power is included to buffer short-term supply gaps, enhance reliability, and improve overall system efficiency. This storage is centrally managed in the simulation to mimic a community battery or aggregated individual batteries.

3.2 Simulation Parameters and Assumptions

We implemented the simulation in Python using the SimPy discrete-event simulation framework. The model operates over a one-year horizon, capturing seasonal and intra-day variations. The simulation uses an hourly time step ($\Delta t = 1$ h) for PV/demand updates, battery dispatch, and market clearing; the daily ranges reported below are used to parameterize the corresponding hourly profiles. Key simulation parameters and assumptions were derived from historical data (2020–2022) and documented studies for the region. All annual performance indicators reported in Section 4 are computed by aggregating the hourly time series over the full simulation horizon (formal definitions are provided in Appendix A). SimPy is a process-based discrete-event library in which system operations are represented as scheduled events; here, PV update, demand realization, battery dispatch, and market clearing are executed in sequence at each hourly interval.

At each time step t, the model executes the following sequence: (i) update PV availability based on the seasonal/daylight profile; (ii) realize user-group demand using the corresponding hourly load profiles; (iii) dispatch the battery under state-of-charge and power limits to reduce immediate deficits; and (iv) perform market clearing and ledger updates for any remaining surplus/deficit. This event ordering ensures that all reported annual indicators are obtained by aggregating the full hourly time series over the simulation horizon (definitions are provided in Appendix A).

Photovoltaic Generation: Based on historical meteorological data and actual electricity loads from the past three years (2020–2022) in East Shewa Zone, this study established photovoltaic generation parameters including an average solar irradiance of approximately 5.2 kWh/m²/day [14]. Seasonal variations were also considered, with daily sunlight duration averaging around 8–10 hours during the dry season (October to May) and approximately 5–7 hours during the rainy season (June to September).

Household Demand: Average daily electricity consumption per household is approximately 1–2 kWh, with a morning peak of about 0.3 kW and an evening peak of approximately 0.5 kW [30, 31]. For trading simulations, household demand is represented as a baseline (essential) component and a flexible (non-essential) component that can be partially reduced during scarcity periods under dynamic pricing; this stylized demand-response assumption is used to test the platform's ability to manage shortfalls rather than to predict household welfare.

Agricultural irrigation load: According to the World Bank and the Food and Agriculture Organization (FAO), irrigated agricultural land in Ethiopia accounts for approximately 5% of total farmland, with rural areas primarily relying on small-scale, decentralized irrigation systems. Consequently, the daily irrigation load for a typical community tends to be relatively low [32, 29]. However, the East Shewa Zone has a relatively higher density of irrigation facilities [20]. Prinsloo [31] indicates that agricultural irrigation loads in typical rural African communities (50–200 households) generally range between 80–200 kWh. Based on this data and relevant literature, agricultural irrigation loads in this study are set as follows:

Dry season: Average daily irrigation load is approximately 100–150 kWh, with a peak daytime power demand of about 20–30 kW [20, 29]. Given the data on increased irrigation intensity reported by Taye et al. [20] and FAO [29], we assume that during peak dry season periods, agricultural irrigation loads rise by approximately 80–100% compared to the typical dry-season baseline (100–150 kWh). Therefore, daily irrigation loads during peak periods are set at approximately 180–250 kWh to more accurately simulate actual possible fluctuations in electricity demand.

Rainy season: Average daily irrigation load is about 40–60 kWh, with peak power of approximately 8–12 kW [20], reflecting occasional supplementary irrigation despite frequent rainfall. Additionally, continuous cloudy and rainy weather reduces photovoltaic generation rates to about 40–60% of typical rainy-season levels. Irrigation demand is treated as low-elasticity within the day and is therefore protected relative to non-essential residential consumption under scarcity pricing; however, the allocation rule prioritizes public facilities and essential household demand before irrigation during shortages (Appendix A).

Public facility load: Average daily demand is 8–12 kWh, with peak power around 1–2 kW [33]. Public facility demand is assumed to be largely inflexible and is treated as the highest-priority load during allocation under shortage conditions. Battery sizing follows the baseline design described in Section 3.1 and is intended to buffer short intra-day PV variability and evening demand peaks rather than provide multi-day autonomy; planning implications are discussed in Section 5.

Where dynamic pricing is applied, non-essential consumption is treated as flexible and may be reduced during scarcity periods, whereas essential services are protected through priority-based allocation. These parameters establish a realistic baseline for examining how the blockchain-based platform operates under normal conditions. Next, we outline the design of the trading mechanism and the special scenarios introduced to test the system's robustness.

3.3 Blockchain-Based Energy Trading Simulation Design

The simulation incorporates a blockchain-based transaction platform to manage energy trading among the community's participants (households, the farm irrigation system, and public facilities). Producers (households or nodes with excess PV generation) and consumers (nodes with demand exceeding their own generation) automatically trade energy through the platform. The pricing mechanism is set as follows: When electricity supply is sufficient (the net energy balance is non-negative), the price is fixed at 0.08 USD/kWh; under conditions of electricity shortages, prices dynamically fluctuate between 0.08–0.20 USD/kWh, updated each simulation interval (hourly) based on the magnitude of net energy deficit (e.g., prolonged cloudy weather or equipment failures). The price bounds can be interpreted as regulated tariff limits chosen to prevent unrealistic price excursions; because site-specific willingness-to-pay data are unavailable, this range is treated as a modeling assumption and highlighted as a priority for empirical calibration. This dynamic adjustment aims to curtail non-essential consumption and prioritize the supply for basic services. If the network goes down (meaning transactions cannot be cleared in the same interval), the system holds the last stable price constant, logs transactions locally, and reconciles them once connectivity is restored while physical energy delivery follows the predefined priority rule.

At each clearing interval, each participant reports a metered net position (generation minus demand). Participants with positive net positions are treated as sellers and those with negative net positions as buyers. Available surplus is allocated to deficits using a priority rule (public facilities first, then irrigation, then residential), and any remaining deficit is recorded as unmet demand for that interval. We model the blockchain platform abstractly, focusing on its functional roles in matching supply and demand, setting prices, and handling transactions. At each clearing interval, the smart-contract logic receives metered net positions, allocates available surplus energy to deficits according to the priority rule, and records cleared transactions as tuples (seller, buyer, energy in kWh, unit price in USD/kWh, timestamp). Participant balances are updated deterministically from these recorded transactions; the full accounting basis is provided in Appendix A. Key functionalities of the model include:

1. Simulating seasonal and intra-day (hourly) photovoltaic power generation and load fluctuations;
2. Constructing a blockchain-based platform for transaction matching, using smart contracts to automate settlements;
3. Implementing a dynamic pricing strategy that adjusts energy prices at each simulation interval (hourly) based on local supply–demand conditions;
4. Designing multiple scenarios for abnormal conditions (such as prolonged cloudy weather, equipment failure, and communication outages) to evaluate system stability and recovery capabilities.

To thoroughly evaluate performance, we simulate the system under six distinct scenarios (S1–S6), summarized below in Table 1:

Through these simulations, we evaluate the operational performance and boundary conditions of the proposed trading mechanism under normal and stress scenarios in East Shewa. Section 4 reports the resulting performance indicators, including generation–demand balance, pricing dynamics, user-group supply shares, and resilience under network outage.

4. Findings

This section reports the main simulation results in a structured sequence. It begins with overall platform efficiency, then examines seasonal supply-demand matching and dynamic pricing, and finally discusses user-group supply outcomes and resilience under abnormal events.

4.1 Platform Operational Efficiency

Over the one-year simulation, the trading mechanism coordinated local PV generation, battery dispatch, and community electricity demand under the assumed operating rules. Approximately 94% of the community's annual electricity demand was met through local PV generation, indicating a high degree of local self-sufficiency. This indicator is computed by summing served demand and total demand over all hourly intervals across the simulation year (Appendix A). Correspondingly, about 96% of total PV generation was delivered to loads or stored locally over the year, implying an approximate curtailment rate of ~4% due to oversupply. Both ratios are obtained from the same hourly accounting of PV generation, battery charging/discharging, and load served. These results indicate that, under the hourly clearing and dispatch rules and the assumed PV–battery sizing, most demand is served and PV curtailment

Table 1: Six simulation scenarios design.

Scenario ID	Scenario Description	Generation (kWh/day)	Load Demand (kWh/day)	Pricing Mechanism
S1	Normal working day (Dry season: Oct–May)	320–400	208–362	0.08 USD/kWh
S2	Agricultural irrigation peak (Dry season: March)	320–400	288–462	Dynamic Pricing
S3	Normal working day (Rainy season: June–Sep)	200–280	148–272	0.08 USD/kWh
S4	Prolonged Rainy Days (Aug 1–15)	100–160	148–272	Dynamic Pricing
S5	PV equipment failure (Nov 1–10, 20% capacity reduction)	256–320	208–362	Dynamic Pricing
S6	Communication network interruption (random occurrences)	320-400	148-362	Delayed Settlement

Note: The generation and load ranges shown in Table 1 are approximate values derived from installed PV capacity, seasonal daylight duration, and the aggregated user-group demand parameters described in Section 3.2; the corresponding accounting equations are provided in Appendix A.

remains limited outside the stress-test windows. Outside the designed stress-test scenarios, the simulation does not include additional component faults beyond resource variability; service continuity therefore reflects the operating rules rather than exogenous failures.

4.2 Supply–Demand Matching and Seasonal Variability

The platform coordinated PV generation, storage dispatch, and the allocation of available energy to community loads, while clear seasonal patterns emerged (Figure 2). Figure 2 reports daily aggregates derived from the hourly simulation outputs to make seasonal trends easier to interpret. During the dry season months (approximately October–May), local generation often exceeded or closely matched demand on most days, resulting in regular but manageable energy surpluses. In these periods, the battery storage would capture midday excess and discharge in the evenings, and cleared trades allocated surplus energy to deficit participants subject to the predefined priority rule. We observed a brief exception in late March: a simulated peak irrigation period (Scenario S2) caused a short-term power deficit despite ample sunshine. During this irrigation peak, community demand spiked unusually high (nearly 460 kWh one day), temporarily exceeding PV supply. The platform responded with increased trading activity and drew down the battery; as a result, even though not all demand could be met, unmet demand was largely concentrated in lower-priority loads, while the allocation rule preserved supply to public facilities and other priority uses as far as the available energy allowed.

In contrast, the rainy season (June–September) presented significant challenges due to reduced solar availability. Frequent periods of generation shortfall occurred, with PV generation falling short of demand by roughly

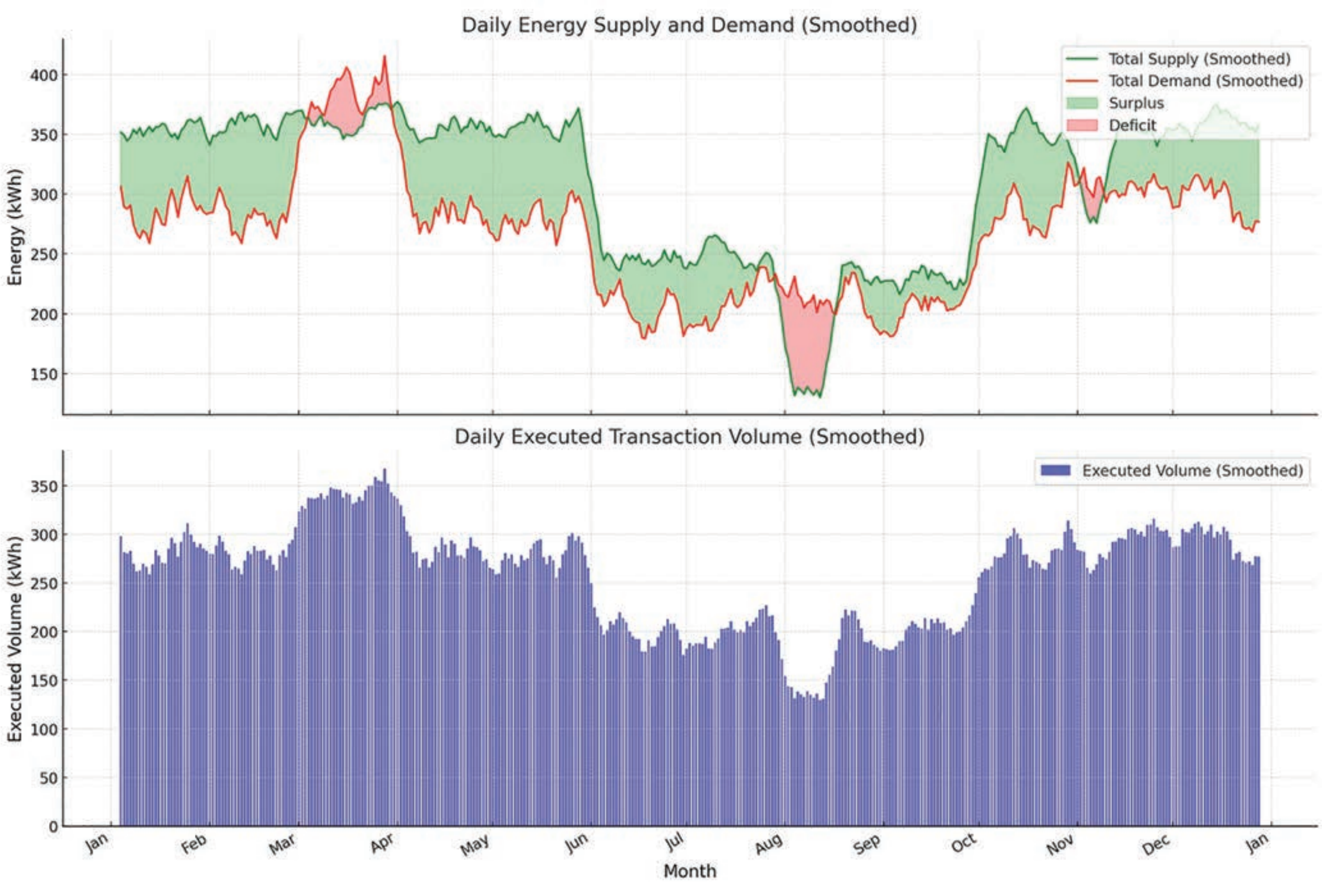

Figure 2: Daily PV generation (green line) and total electricity demand (red line) throughout the year. The plot highlights the seasonal trends: a surplus of generation over demand on most dry-season days, versus frequent deficits on rainy-season days. Shortfall periods (demand line above generation line) are evident in August (extended clouds) and during occasional peak demand events.

20–30% on many cloudy days. In a particularly stressful test (Scenario S4: early August), we simulated 15 consecutive days of cloudy/rainy weather. This resulted in very low generation each day and correspondingly lower executed trade volumes (since less energy was available to trade). The community experienced moderate unmet demand during this interval, which underscores that supplemental solutions (such as additional storage capacity or backup generation like diesel or biomass) would be needed to maintain full reliability under such extended adverse conditions. Another targeted stress test in the late dry season (November 1–10) introduced a 20% PV capacity outage (Scenario S5), effectively reducing generation. This caused a temporary deficit but of smaller magnitude; once the PV array was restored, the system quickly returned to equilibrium. These scenarios illustrate that while the platform can handle typical daily and seasonal fluctuations through trading and storage, strategic infrastructure enhancements (e.g. larger batteries or hybrid generation) are essential to ensure year-round reliability, especially to cover prolonged sunless periods or equipment failures.

4.3 Dynamic Pricing Response Mechanism

The blockchain-enabled dynamic pricing mechanism responded to changes in net energy availability at the hourly clearing interval (Figure 3). Throughout the simulation, electricity prices on the platform fluctuated inversely with the net energy balance of the microgrid, as designed. Specifically, during periods of abundant generation (net surplus), the price remained at the baseline 0.08 USD/kWh, ensuring affordable energy for all users. When shortages arose, the price increased to signal scarcity and moderate consumption.

For instance, in the agricultural irrigation peak of March (S2), a sharp net deficit developed on certain days (as noted in 4.2). In response, the price promptly surged toward the upper limit (around 0.18 USD/kWh) during the peak hours of deficit. In the model, higher prices reduce the flexible (non-essential) component of demand during deficit hours, while essential services remain protected by the priority-based allocation. Accordingly, irrigation and critical public loads continue to be served when energy is scarce, whereas discretionary consumption is reduced by design.

During the prolonged rainy period in early August (S4), the platform experienced sustained negative net balances. The pricing mechanism reacted by escalating prices to the cap (~0.20 USD/kWh) for several days in a row, indicating severe scarcity. At these times, the model reduced the served flexible component of demand, while essential services remained protected by priority-based allocation.

In the PV failure scenario (S5, early November), a sudden drop in generation (20% capacity lost) caused immediate deficits. The dynamic pricing rule was applied, raising prices above the base rate for the duration of the failure, and the modeled flexible (non-essential) component of demand was reduced accordingly. Once the PV array was repaired (net balance returned to positive), prices swiftly reverted to the baseline 0.08 USD/kWh rate, and consumption patterns likewise normalized. This rapid return to baseline demonstrated there was no lingering instability or price hysteresis in the system.

Overall, the interval-based pricing rule increased prices during deficit hours and returned to the baseline under surplus conditions. Under the assumed price–demand response function, higher prices reduced the flexible component of demand during deficit hours, helping to limit modeled unmet demand for non-essential uses. However, the magnitude of this effect depends on the elasticity parameters and requires empirical calibration.

4.4 Local Supply Contribution by User Type

A key indicator of energy equity is how reliably different user types (residential, agricultural, and public services) can fulfill their energy needs through local PV generation. Figure 4 illustrates the distribution of the local supply fraction for each user category, revealing notable differences. Here, local supply fraction is defined as the share of a user group's demand that is met by locally generated PV energy (including PV-to-load and PV-to-battery-to-load pathways) aggregated over the simulation horizon.

Residential users achieved a consistently high local supply fraction (close to 1.0) with minimal variation among households. This outcome reflects the platform's prioritization of essential residential consumption and the sufficient sizing of PV generation. Similarly, public facilities (school and health post) maintained a local supply fraction close to 1.0, consistent with their highest priority in the allocation rule.

In contrast, agricultural irrigation loads experienced a lower median local supply fraction (~85%) with considerable variability. Irrigation demands were fully met during sunny periods but frequently curtailed during

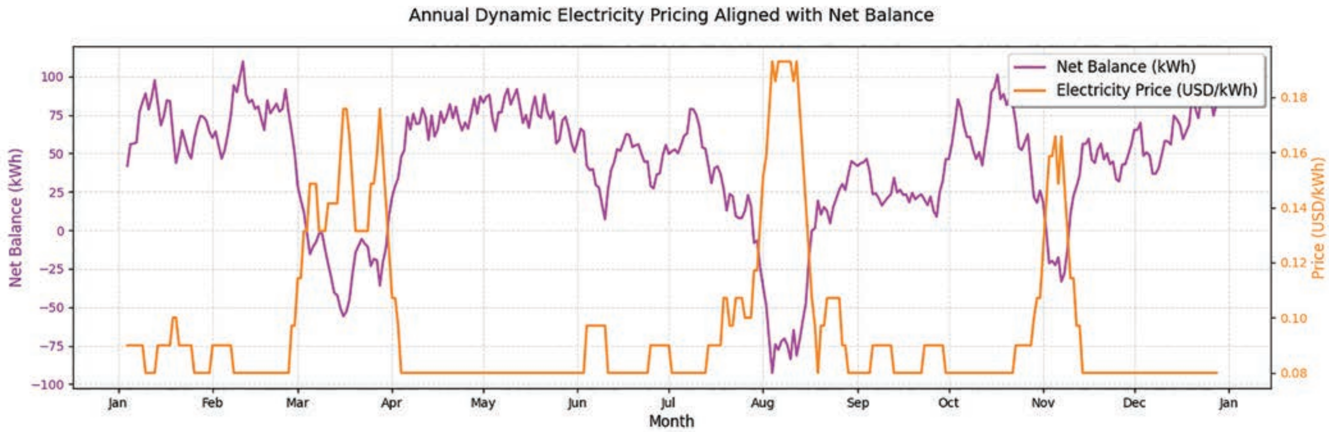

Figure 3: Trends of the platform's net energy balance (purple) and the electricity price (yellow) over time. The figure shows that whenever the net balance dips below zero (shortage), the price (yellow line) rises, and vice versa. Notable peaks in price correspond to the March irrigation peak, the August cloudy spell, and the November PV outage.

extended cloudy periods or peak load events. This disparity highlights a relative disadvantage for agricultural users, indicating that targeted interventions—such as dedicated agricultural PV and storage capacity or demand-side management strategies—are necessary to enhance overall energy equity.

4.5 Resilience to Abnormal Events

Figure 5 illustrates the platform's resilience under simulated communication network outages (Scenario S6). In this scenario, two separate network interruptions (each lasting several hours) occurred, during which the blockchain communication was down and on-chain clearing within the affected hourly intervals was not possible. The platform's built-in delayed settlement mechanism then took effect. Specifically, at the moment each outage began, the electricity price was frozen at the last determined level (one outage happened during normal conditions so price was 0.08 USD/kWh; the other occurred during a slight deficit so price was 0.12 USD/kWh at freeze). During the outages, energy continued to flow based on preset rules – essentially, surplus PV generation was still routed to the battery and to local loads in a pre-programmed priority order (ensuring vital needs are met first). No new price adjustments or trading optimization occurred during these periods; participants continued to exchange energy at the frozen price while metered transactions were cached locally (off-chain) and later reconciled on-chain once connectivity was restored.

Once network connectivity was restored, the platform's settlement module resynchronized the ledger state: the accumulated off-chain transactions were batch-processed at the frozen price, and then normal dynamic pricing resumed. The prices quickly realigned with the updated net energy balance at the next hourly clearing interval (which by then included whatever state the battery and loads were in). In the simulation, the ledger resynchronization completed without manual reconciliation, and service continuity metrics changed only marginally during short outages.

In the simulation, short outages mainly affected settlement timing rather than physical dispatch, because energy allocation continued under the preset priority rules; therefore, served-energy outcomes changed only marginally over outages lasting a few hours. In practice, the robustness of delayed settlement depends on secure metering, signed logs, and dispute-resolution governance.

This resilience result assumes accurate metering and tamper-resistant local logging during outages; practical deployments would require secure signed meter data, auditability, and governance procedures to prevent disputes during delayed settlement.

5. Discussion

This study provides a comprehensive assessment of a blockchain-enabled distributed energy trading platform tailored for a rural off-grid community. The results demonstrate robust performance across critical

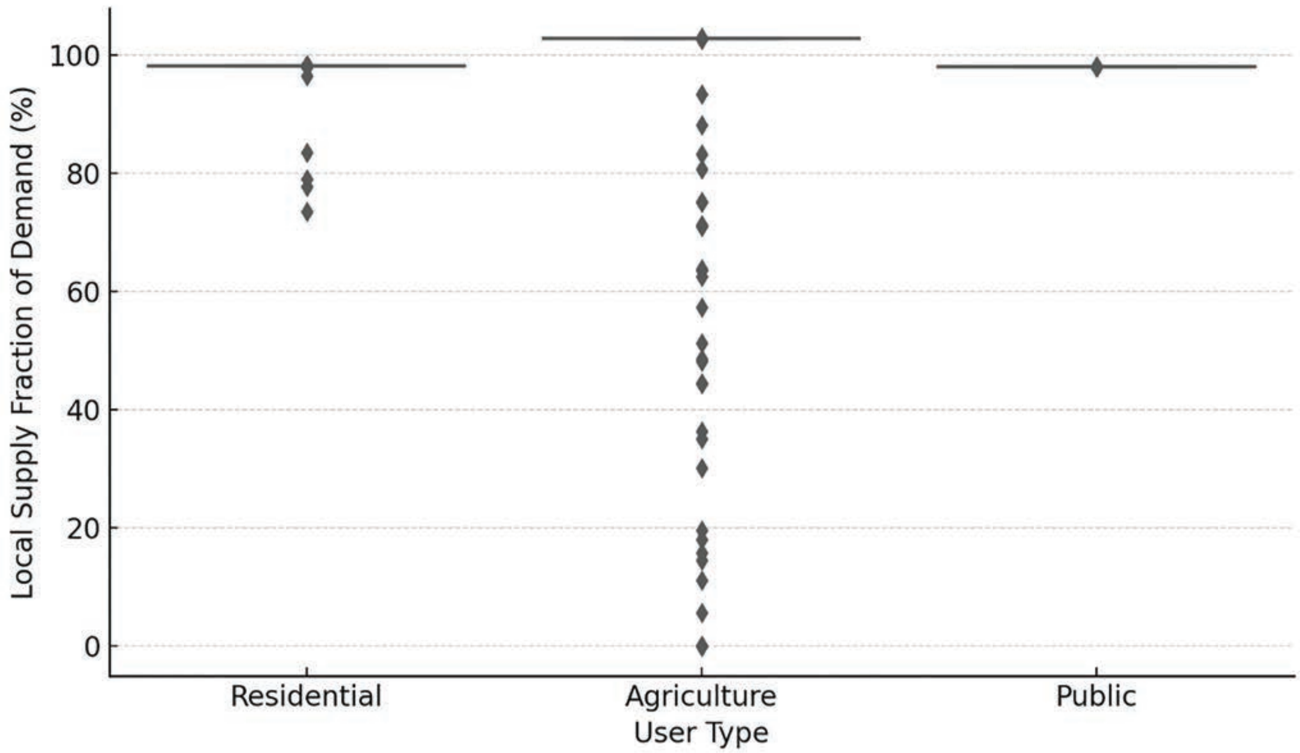

Figure 4: Distribution of local PV supply fractions for residential, agricultural, and public facility users, showing near-100% consistent supply for residential and public facilities, and a lower, more variable fulfillment for agriculture, highlighting a potential equity gap.

operational metrics --- including efficiency of local energy use, ability to handle seasonal variability, responsive pricing for demand management, and resilience to abnormal events. Here we discuss these findings in the context of existing literature and highlight the originality and implications of this work.

5.1 Interpretation of Main Findings

First, the platform achieved high operational efficiency in utilizing local renewable energy. Approximately 94% of the community's electricity demand was supplied by local PV generation, with only ~6% unmet and ~4% of generation curtailed. This suggests that the blockchain-based coordination effectively maximized the self-consumption of solar energy. Comparable levels of renewable utilization have been reported in other P2P energy sharing studies; for instance, a recent microgrid trial found that P2P trading helped prosumers achieve very high renewable usage and reduced reliance on external grid power [34]. Our results align with these findings, but notably, we demonstrate such efficiency in a remote rural context with limited infrastructure. This indicates that, under the modeled assumptions, off-grid communities may approach the technical performance reported in more infrastructure-rich settings when supported by appropriate metering, pricing, and settlement mechanisms.

Importantly, the simulation assumes that users can and will participate in metered trading (e.g., via smart meters and payment arrangements); actual uptake will depend on affordability, trust, governance, and institutional support, which are not modeled here.

Second, the system adeptly managed seasonal variations in supply and demand, though not without limitations. During the long dry season, the community enjoyed surplus generation most of the time (except brief deficits during peak irrigation). In the rainy season, significant deficits emerged that could not be fully mitigated by trading or storage alone. This highlights the inherent limitations of a solar-only microgrid in a monomodal climate – an issue well-documented in rural electrification literature. Many studies emphasize the need for complementary solutions like energy storage or hybrid generation to handle seasonal gaps [30].

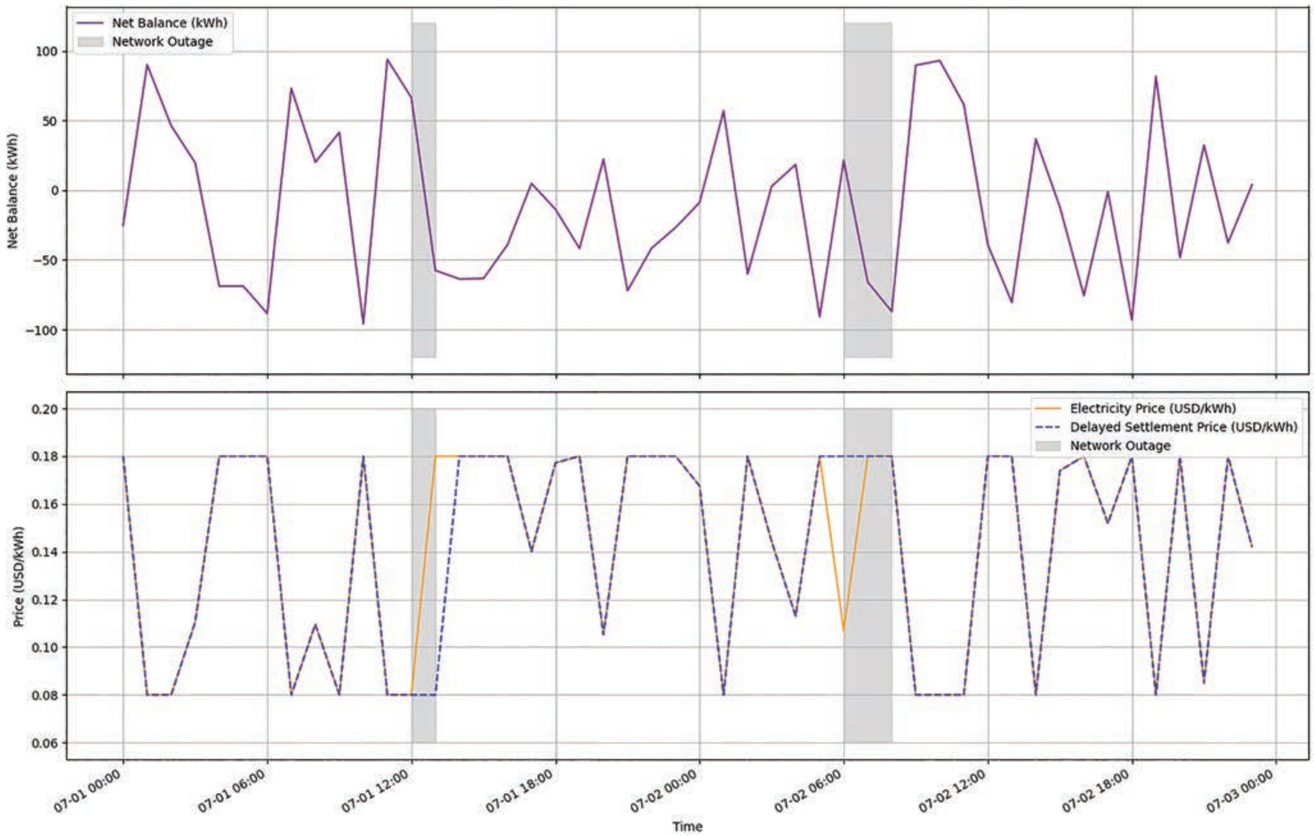

Figure 5: Platform performance during two simulated communication outages. The top panel shows the net energy balance fluctuating during outages. The bottom panel shows the electricity price: it remains flat (held constant) during each shaded outage interval, then rapidly updates to the correct dynamic level once communication is restored. This illustrates effective mitigation of market disruption during network failures.

Our simulations reinforce this: even with an advanced trading mechanism, energy shortfalls during extended cloudy periods will occur unless additional resources are available. However, the platform's allocation and settlement logic supported operational robustness in the simulation by allocating limited energy according to explicit priority rules. The findings underscore that strategic infrastructure planning (e.g. adding batteries or a backup generator) should go hand-in-hand with blockchain adoption. From an energy-planning perspective, this reinforces IJSEPM's broader emphasis on flexibility and storage within integrated smart energy systems rather than single-technology fixes [35, 36]. This is consistent with other feasibility analyses in Ethiopia which conclude that PV-based off-grids must be supplemented by storage to ensure reliability through rainy seasons [30].

Third, the blockchain-based dynamic pricing mechanism demonstrated clear benefits for hourly (interval-based) demand response. In scenarios of heightened demand (irrigation peaks), prolonged low generation (rainy spells), and equipment failure, prices on the platform rose to reflect electricity scarcity. This price signal successfully moderated consumption and prioritized critical uses, essentially performing a demand-side management function in the simulation through price signals and the assumed price–demand response. Prior research has highlighted the potential of dynamic pricing in microgrids to balance load and generation [10], and our results provide concrete evidence of this in action within a blockchain framework. Notably, unlike many pilot projects that fix tariffs or require manual demand response, our implementation shows that smart contracts can automate an interval-based (hourly) pricing scheme to which loads respond according to the specified elasticity assumptions. This is an important contribution, as it illustrates a pathway toward self-regulating community energy systems. One implication is that rural communities, often thought to be too under-resourced for sophisticated demand response, could in fact participate in and benefit from such market-based mechanisms if the technology is properly tailored [28]. The success of our dynamic pricing also validates theoretical models which predict that P2P trading with variable pricing may, in some settings, improve economic efficiency relative to static incentive schemes, depending on market design and user behavior [34]. Essentially, price-driven flexibility can act as a useful balancing mechanism in the model for balancing the microgrid under stress. Nevertheless, the magnitude of these effects is sensitive to temporal resolution and behavioral parameters; future work can test sub-hourly dispatch and empirically grounded elasticity to assess robustness.

In our baseline specification, irrigation demand is treated as low-elasticity and is not directly price-curtailed; its lower local supply fraction is primarily driven by the magnitude and seasonality of irrigation demand and by periods of prolonged low irradiance. As a productive-use load, irrigation may require targeted design measures (e.g., dedicated PV/storage capacity, scheduling constraints, or tailored tariffs/priority mechanisms) to improve reliability and distributional outcomes.

Finally, the platform's resilience to network outages is a novel finding with practical importance. We showed that even if the blockchain network connectivity fails temporarily, the energy trading can continue with minimal disruption by using a graceful degradation strategy (holding prices constant and settling later). This aspect is less emphasized in much of the literature, which often assumes reliable communication; in many rural settings this assumption is weak. By demonstrating a working approach to handle communication failures, our study contributes a unique insight: blockchain-based energy systems can be designed to tolerate offline periods, which is crucial for real-world viability. Few if any prior works have simulated this; thus, our implementation can be seen as an important step toward making blockchain grids practical in rural settings. The fact that the system self-recovered and synchronized correctly after outages also speaks to the robustness of distributed ledger systems when augmented with appropriate protocols. It is worth noting that in the broader context, resilience isn't just about communications – it also involves physical resilience of the energy supply. While our work focused on communications resilience, it adds to the narrative that blockchain microgrids can be made reliable against various threats. Future projects could build on this by incorporating fault-tolerance for other components (e.g., inverter failures, cyber-attacks) in the blockchain control logic.

5.2 Comparison with Existing Models and Initiatives

The concept and outcomes of our blockchain-driven platform can be compared to existing rural electrification models to understand how it complements or diverges from them. A clear point of comparison is with the Pay-As-You-Go (PAYG) solar home system model widely used in East Africa. The PAYG approach, exemplified in Kenya, tackles the affordability barrier by allowing households to pay for solar kits in small installments [22, 23]. This has been very successful in disseminating basic lighting solutions. However, PAYG systems typically operate in isolation for each household and do not enable energy sharing or community-level optimization. Our blockchain platform, in a sense, builds upon the PAYG foundation by networking households together once they have solar access. It enables peer-to-peer trading of surplus energy, thereby improving overall asset utilization and potentially delivering better economic returns on the solar installations. In other words, while PAYG gets the device into the home, a blockchain market ensures any excess production isn't wasted but rather sold to a neighbor who needs it. This could significantly enhance the impact of PAYG deployments by creating community microgrids from individual systems. It builds on the premise of PAYG that small, frequent payments can lower adoption barriers, while extending the model toward a more integrated community energy approach.

Another relevant comparison is with India's "Lighting a Billion Lives" (LaBL) initiative and similar community microgrid projects that emphasize local involvement and sustainability [24, 25]. Such projects often establish village committees, employ local technicians, and use community financing to operate microgrids, underscoring that governance and local capacity can influence reliability and acceptance. Our blockchain-style settlement layer can be interpreted as a digital accounting and rule-enforcement component that may reduce manual reconciliation and make transactions more auditable, provided that metering, data integrity, and institutional arrangements are in place. We therefore view technical settlement mechanisms and community governance as complementary design dimensions; empirical work is needed to test how specific governance models, tariffs, and participation rules affect adoption and outcomes in practice.

Lastly, when compared to urban or industrial blockchain energy trading pilots (like Lition in Germany or Brooklyn Microgrid), our study confirms some universal benefits of blockchain while breaking new ground in context. Those international cases have shown improved transaction efficiency, transparency, and prosumer engagement in energy markets [10, 11]. We observed similar efficiency in the simulation, in terms of automated settlement, transparent accounting, and price-based allocation outcomes. However, user engagement, willingness to adopt dynamic pricing, and trust in the trading arrangement were not empirically evaluated, and therefore should not be inferred from technical results alone. The key difference is the context: relatively few studies have analyzed blockchain-enabled trading mechanisms in rural Sub-Saharan African off-grid settings. As such, it fills a notable gap in the literature regarding real-world implementation in developing regions. It suggests that some benefits observed in better-resourced contexts (e.g., automated accounting and explicit allocation/pricing rules) could be relevant to off-grid villages under enabling conditions such as governance capacity, maintenance arrangements, and supportive regulation. However, our results also highlight additional considerations (like the communication issues, or the need for balancing equity with market forces) that are less prominent in those developed country pilots.

6. Conclusion

This study developed an hourly, one-year simulation of an off-grid PV microgrid in East Shewa, Ethiopia, augmented with a blockchain-style settlement layer for peer-to-peer trading, interval-based dynamic pricing, and delayed settlement under communication outages. The model evaluates supply–demand coordination, scarcity signaling, allocation priorities across user groups, and operational robustness under seasonal variability and stress scenarios.

Under the modeled assumptions, the platform provides a transparent, rule-based mechanism for coordinating energy exchanges by recording cleared transactions, updating bounded prices as a function of net deficit, and allocating limited supply using explicit priority rules.

These findings should be interpreted as operational potential rather than evidence of user adoption or social acceptance. Key behavioral parameters (e.g., willingness-to-pay and demand flexibility) were assumed rather than empirically calibrated, and institutional, regulatory, and governance constraints were not explicitly modeled. Future work should combine field-based parameterization with pilot-oriented evaluation of metering/payment arrangements, governance readiness, and user response to dynamic pricing to assess feasibility beyond the simulated setting.

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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