Available online at https://asric.africa/engineering-sciences
ASRIC Journal on Engineering Sciences Vol.6(1)(2025) 1-9

# A Peer-to-Peer Energy-Sharing System for Smart Electricity Utility Meters

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Received 10 July 2025; revised 29 August 2025; accepted 23 October 2025

## Abstract

Uganda's power sector transition from a postpaid to a prepaid electricity metering system resulted in improved revenue for utilities and significantly lowered administration costs. Whereas this system is functionally operational, it lacks a mechanism for direct transfer of purchased electricity units between customers, leading to inefficiencies and limited consumer flexibility. This paper presents the development, implementation, and testing of an IoT-enabled peer-to-peer (P2P) energy-sharing model that allows for direct transfer of energy units. Developed using a mixed-methods approach, the prototype utilizes an ESP32 microcontroller, a secure token-based vending platform via a centralized server, and bidirectional data exchange between meters. Experimental evaluation demonstrated ±5% metering accuracy, reliable credit transfer, and automatic load reconnection. The approach addresses a key service gap by enabling surplus unit sharing without utility intervention, promoting collaborative consumption, and enhancing energy equity. Beyond technical performance, the system supports Sustainable Development Goals (SDGs) 7, 8, 9, 10, and 12 by improving access, economic inclusivity, and resource efficiency. This work provides a scalable framework adaptable to other sub-Saharan African contexts and offers utilities an opportunity to enhance customer satisfaction while fostering innovation in decentralized energy distribution models.

**Keywords:** Energy sharing; Pre-paid metering; Electricity billing; Peer-to-Peer; IoT-based electricity metering; Energy token transfer.

## 1. Introduction

Uganda's power sector has experienced significant transformation over the last two decades, with reforms focused on improving efficiency, expanding access, and ensuring long-term sustainability. Before 1999, the Uganda Electricity Board (UEB), a vertically integrated state monopoly, was characterized by severe inefficiencies, including system losses exceeding 40 percent, unreliable electricity supply, and extremely limited national grid access, which stood at only 9 percent (Catrina Godinho, 2019). In response to these challenges, the 1999 electricity sector reforms led to the unbundling of UEB into separate entities for generation, transmission, and distribution, under the oversight of the Electricity Regulatory Authority (ERA, 2025). To attract private investment and improve service delivery, a 20-year concession for electricity distribution was granted to Umeme Limited (Mawejje et al., 2013).

To strengthen revenue collection and operational efficiency, the sector transitioned from a post-paid to a prepaid metering system. This model allows customers to purchase electricity tokens in advance through digital payment platforms and input them into their energy meters. The prepaid system has significantly improved cash flow for utilities, lowered administrative costs, and curtailed electricity theft. As a result, the customer base has grown at an average annual rate of 9.6 percent, expanding from approximately 200,000 grid-connected users in 1999 to over 2 million by 2025 (ERA, 2025).

Despite these improvements, the current prepaid system presents a critical limitation as it does not support the transfer or sharing of purchased electricity units across meters. This becomes particularly problematic for tenants who relocate and cannot transfer their unused energy credits to their new premises, leading to financial loss and user dissatisfaction. In contrast to the telecommunications sector, where users can easily share airtime or mobile data, electricity consumers remain bound to a rigid, non-transferable system. These restrictions not only hinder customer convenience but also highlight a broader gap in the adaptability and user-centric design of existing utility infrastructure (Andoni et al., 2019). Similar gaps in prepaid metering systems have been noted in developing contexts, where they fail to support sustainable revenue recovery and equitable access (Qazi et al., 2020). More importantly, they pose a barrier to the realization of Sustainable Development Goal (SDG) 7, which advocates for universal access to affordable, reliable, sustainable, and modern energy (United Nations, 2015).

To address these limitations, this paper presents the design and implementation of a smart peer-to-peer (P2P) energy sharing system tailored for Uganda's electricity distribution context. The proposed digital architecture enables customers to directly transfer energy units from one meter to another without utility provider intervention (Tushar et al., 2020). By integrating remote token transfers, peer-to-peer energy sharing, and real-time consumption monitoring, the system enhances user autonomy, equity, and flexibility.

This innovation not only supports the goals of SDG 7 but also aligns with Uganda's Vision 2040 and the National Development Plan IV, which prioritize the role of digital technologies in driving inclusive and sustainable growth. By enabling localized, user-driven energy solutions, the proposed system offers a timely and practical approach to leveraging digital innovation in addressing persistent challenges in Uganda's energy sector.

## Literature Review

This section reviews the status of energy metering technologies in Uganda, identifies existing gaps, and presents the proposed solution to mitigate the identified gaps.

### A. Current Technologies

The Uganda Electricity Distribution Company Limited's (UEDCL) prepaid electricity system operates on the Standard Transfer Specification (STS**)** model, where customers pay for electricity before consumption. This system aligns with broader smart grid technologies that integrate renewable energy and demand-side management to enhance sustainability (Kabeyi & Olanrewaju, 2023). In this setup, the major system components are;

i. *Prepaid Meter:* Installed at the customer's premises to measure electricity consumption in real-time and deduct units as they are consumed.

ii. *Customer Interface Unit (CIU*)**:** This indoor device allows customers to enter their 20-digit STS token and view balance information. It features a keypad for entering tokens and an LCD to display the remaining units, error codes, and alerts.

iii. *Vending System:* The central database and transaction platform where customer accounts are managed. It generates unique STS tokens corresponding to the amount purchased.

iv. *Point of Sale (POS) Terminals***:** This is where customers buy electricity credits, either through vendors, banks, or mobile money services.

v. *Utility Management System:* UEDCL's backend platform for monitoring meter performance, managing accounts, detecting tampering, and producing reports.

Figure 1 represents the existing UEDCL prepaid electricity system model, which requires customers to purchase electricity from a UEDCL-authorized outlet or mobile platform, receive a 20-digit STS token, and input it into the meter or CIU. The meter validates the token, loads the purchased kWh, and deducts units as electricity is consumed.

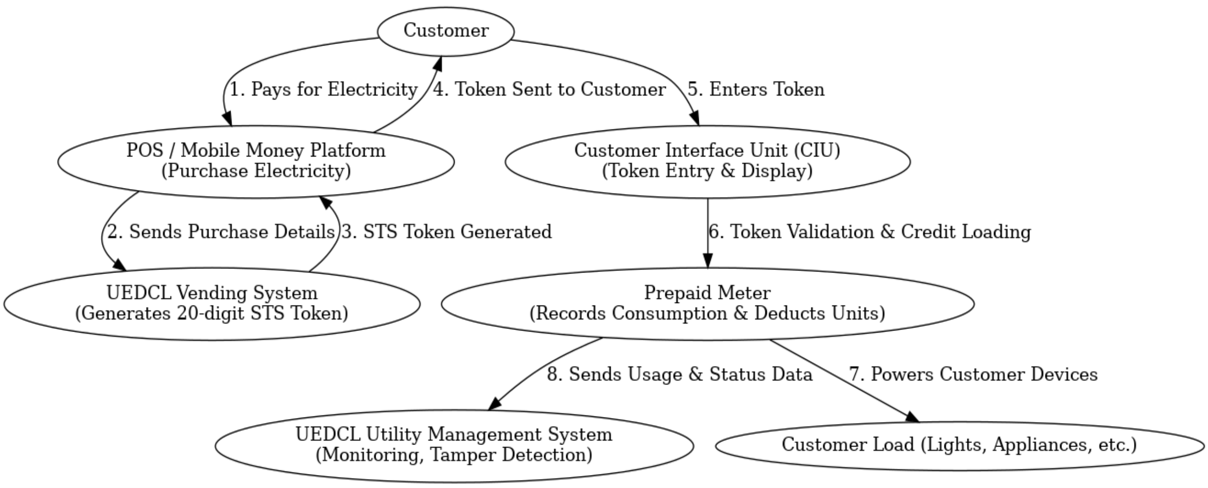


**Fig. 1:** UEDCL Prepaid Electricity System Model

Several meter types have adopted this model, including the hexing, conlog, inhemeter, and split-type meters. These prepaid meters use a secure, one-way STS system where a customer gets a unique, encrypted 20-digit token tied specifically to their meter, awaiting manual input to load the units.

## B. Gaps in the Existing Technologies

This operational model presents a practical knowledge application gap with significant limitations for the remote transfer of electricity units from one meter to another. The primary barrier is the lack of a bidirectional, user-initiated communication channel between individual meters and the central vending system for unit transfers. The system is fundamentally designed for a one-way transaction, i.e., purchase of a token from the utility, followed by manual input into a specific meter. The meter itself does not possess the capability to send units to another account. This raises energy justice concerns, as smart grid designs may aggravate inequalities in access and control without addressing privacy, equity, and procedural fairness (Milchram et al., 2018).

To facilitate sharing, the system would require a feature where a customer could remotely instruct the vending system to deduct units from their account and generate a new token for a different meter, a functionality that is not currently part of the standard prepaid metering infrastructure. This limitation means that even if a customer has a surplus of units, they cannot digitally transfer them to a friend or family member, or to a new location when they move, resulting in financial loss. The absence of the units transfer feature in Uganda's electricity metering system represents a missed opportunity to improve customer empowerment, optimize energy use, and advance Sustainable Development Goal 7, which calls for affordable, reliable, and modern energy for all (United Nations, 2015).

## C. Proposed Solution

The proposed energy-sharing system introduces peer-to-peer unit transfers between smart meters. Customers could send surplus units to friends, relatives, or community members, or transfer them when relocating. Such architecture enables decentralized trading, as evidenced in swarm electrification models for rural PV communities (Taouil et al., 2024), and surveys of P2P enabling technologies (Nadeem, 2022). This consumer-centric feature strengthens community energy resilience and encourages collaborative consumption.

The proposed solution uses the components in Table 1 and comprises the following layers;

i. *User Interface Layer:* This has a keypad for input and an LCD for real-time display of balances, instructions, and confirmations.

ii. *Microcontroller Unit (MCU) Layer*: Processes user inputs, communicates with the server, and controls the relay for power supply management. Each meter has a unique identifier for secure verification.

iii. *Communication Layer*: Has a Wi-Fi module that connects the MCU to a centralized server and can communicate with another meter installation.

iv. *Server Layer*: This also has a data analytics module, which stores account balances, tracks consumption patterns, processes transfers, and supports integration of new users.

v. *Relay Control Layer*: To switch load supply based on energy balance status.

**Table 1**: Components used in implementing the proposed solution

| S/No | Component Name | Function |
|---|---|---|
| 1 | 16x2 Liquid Crystal Display | Display user commands and system feedback |
| 2 | Alphanumeric Keypad | Allow users to enter system commands |
| 3 | ESP32 development board | Process all system instructions |
| 4 | ACS172-20A current sensor | Measure the current consumed by the load |
| 5 | ZMPT101B voltage sensor | Measure the system voltage |
| 6 | Relay module | For automatic load control |
| 7 | Loads (Bulbs) | Act as system loads |
| 8 | Battery | Power the user interface system peripherals |

By embedding P2P functionality directly into existing smart meters without disrupting operational workflows, this approach extends the scope of smart metering beyond billing efficiency, towards user empowerment, equitable access, and community-based resilience in energy distribution.

## 2. Methodology

This research employs a pragmatist approach with a mixed-methods design to develop and validate the energy-sharing system. The methodology integrates quantitative measurements such as voltage, current, and power, and qualitative elements such as user interface design and user experience, to create a robust and user-centric solution. The overall research design is experimental, focusing on observing the cause-and-effect relationships within the proposed system. Throughout the process, strict ethical considerations were maintained, prioritizing secure data handling and compliance with open-source licenses. The methodology comprised the following sub-sections;

### 2.1 System Design and Architecture

The system utilizes a modular, three-tier architecture to ensure scalability and maintainability.

a) *Client-Side***:** At the core of the client-side are ESP32 microcontrollers. These were chosen for their integrated Wi-Fi capabilities, low power consumption, and processing power. The microcontrollers are programmed to perform real-time energy monitoring and manage user interactions through a keypad and an LCD.

b) *Server-Side:* The backend is built using the Django REST Framework, leveraging its robust features for rapid API development. A PostgreSQL database was used for its reliability and transactional integrity, handling critical data such as token validation, transaction logs, and the core energy-sharing logic.

c) *Frontend Interface***:** A Next.js web application serves as the user-facing interface, providing a responsive and dynamic experience. This interface enables users to manage their accounts, view their energy consumption, and initiate peer-to-peer energy transfers.

### 2.2 Hardware and Software Implementation

The hardware design integrates several key components to ensure accurate and reliable operation. ESP32 microcontrollers serve as the central processing unit. Energy measurements are performed using an ACS712 current sensor and a ZMPT101B voltage sensor for high-precision data acquisition. An LCD provides real-time feedback to the user, while a keypad facilitates user input. Relays are used for load control. These components are interconnected according to the system layout shown in Fig. 2. The firmware, written in C++ using the Arduino IDE, manages the sensor readings and communication with the server.

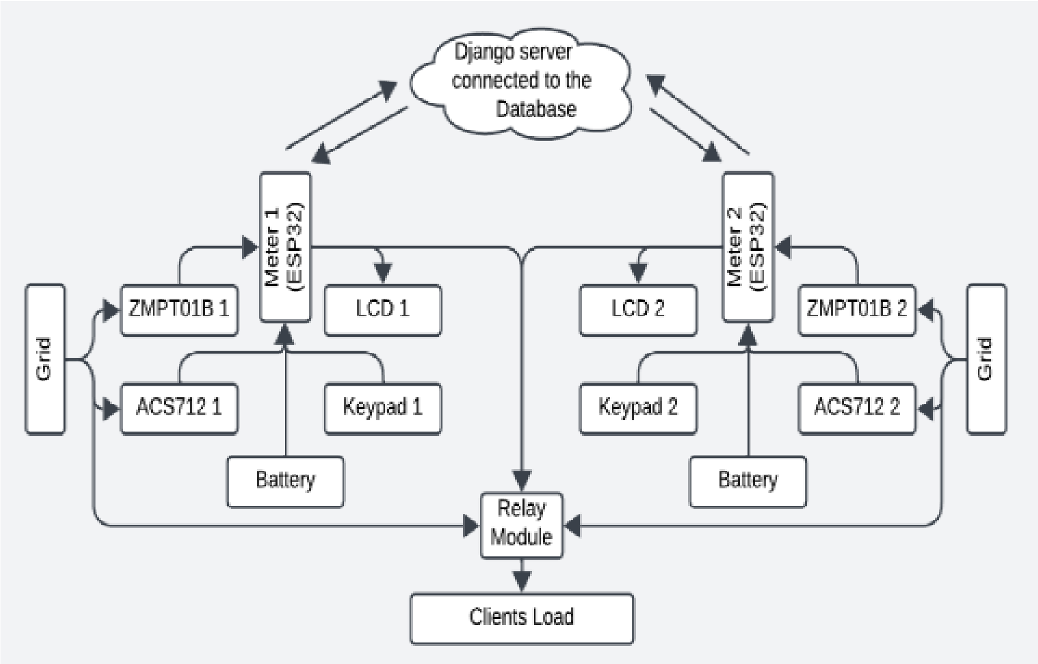


**Fig. 2:** Proposed system layout

The software development focused on creating a secure and efficient communication protocol. The backend logic, developed in Python, handles all transaction and sharing requests. To ensure data integrity and security, communication between the client and server is secured using JSON Web Tokens (JWT) authentication and HMAC-SHA256 encryption.

### 2.3 System Validation and Testing

The system underwent a rigorous validation process. Data was collected from sensor readings, keypad inputs, and server communication logs. Postman API was instrumental in simulating and testing the backends' HTTP requests. Hardware simulations were conducted using the Proteus design suite to verify circuit functionality in a virtual environment before physical implementation. The validation process concluded with a series of comprehensive tests, including unit integration tests and end-to-end configuration of the peer-to-peer transfer functionality. This iterative testing approach ensured the system's reliability and effectiveness prior to deployment.

## 3. Results and Findings

This section focuses on the key project deliverables and experimental results of the study undertaken. The project successfully delivered on three key objectives, each contributing to a fully functional energy-sharing system.

### 3.1 Deliverable 1: Energy Metering System Development

A functional prototype of an energy metering system was successfully developed and implemented as shown in Fig. 3. It utilized an ESP32 microcontroller with an ACS712 current sensor and a ZMPT101B voltage sensor to accurately measure real-time values for voltage, current, and single-phase active power. The system displayed these readings on a 16x2 LCD screen and captured consumption metrics every 5 seconds. Validation against a calibrated multimeter showed an acceptable degree of accuracy, with a deviation of about ±5%. This confirmed that the system effectively met the requirements for real-time energy measurement and accurate energy monitoring.

**Fig. 3:** Functional energy-sharing system hardware prototype

### 3.2 Deliverable 2: Implementation of the pre-paid billing functionality

Figure 4 shows that the system implemented a secure, token-based prepaid billing mechanism with the server generating encrypted tokens that corresponded to the energy units purchased.

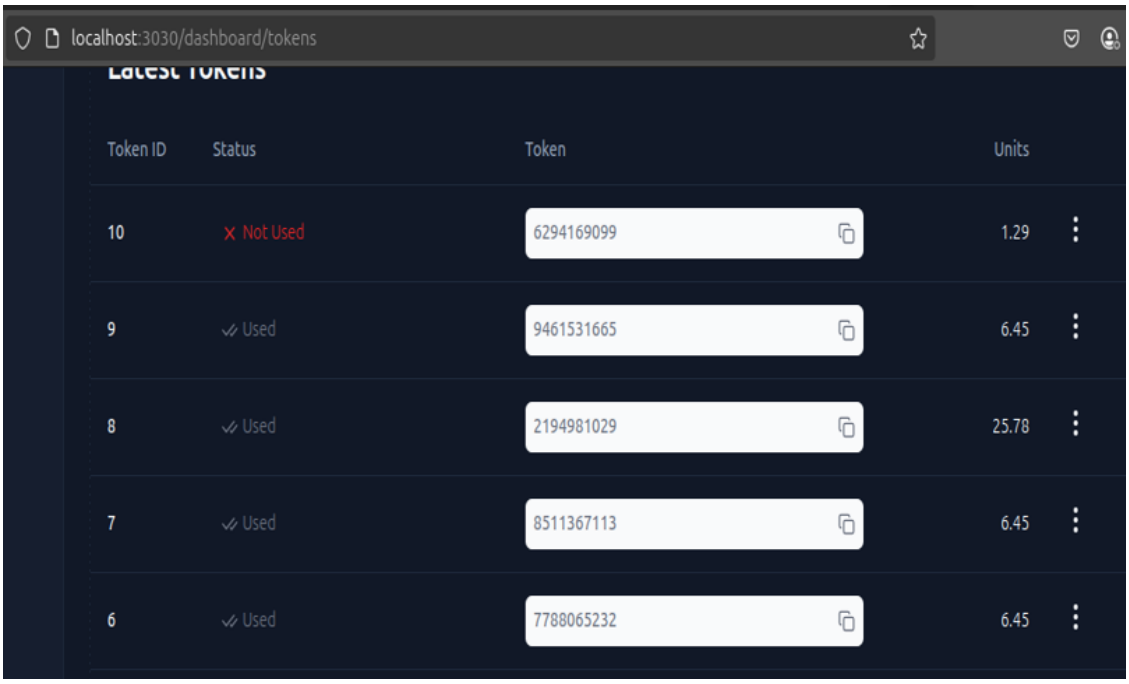


**Fig. 4**: Generated pre-paid billing tokens with their respective energy units in kWh

Upon entry via the keypad, the ESP32 validated these tokens using JWT verification, securely adding units to the meter balance. The system's relay module was configured to automatically disconnect the load when the balance reached zero and reconnect upon a successful recharge. Testing confirmed that transactions completed swiftly (1-2 seconds) and that the robust JWT verification prevented token fraud.

### 3.3 Deliverable 3: Energy-sharing scheme

The central innovation of the project, i.e., the energy-sharing feature, was successfully implemented and validated. The system enabled one user to transfer units to another by entering the recipient's meter token, the amount to be shared, and a personal PIN via the keypad. The server securely authenticated the recipient, and upon a successful transaction, the recipient's balance was updated.


**Fig 5:** Meter status before sharing of electricity units


**Fig 6**: Updated meter status after successful transfer of 10kWh

Figure 5 shows the initial status of the sender's CIU with a positive credit of 50kWh and the recipient's CIU with a zero-credit status prior to initiating a transfer. Figure 6 shows the updated meter statuses with the sender's CIU remaining with 40kWh after successful transfer of 10kWh to the recipient's meter.

In Fig. 7, the recipient's power supply that had initially been disconnected due to a zero-credit status was automatically reactivated via a relay upon successful transfer. This is explicitly shown in Fig. 6, where the recipient's meter status was updated, and in Fig. 8, where the recipient's load was reactivated.

**Figure 7:** System status before transfer of electricity units

**Figure 8:** System status after successful transfer of electricity units

## 4. Discussion

The experimental outcomes demonstrate the technical feasibility and practical value of integrating a peer-to-peer (P2P) energy-sharing capability into Uganda's prepaid electricity metering infrastructure. The proposed system directly addresses the key limitation identified in existing STS-based prepaid systems in the form of the inability to transfer unused energy credits between meters. By enabling unit transfers without utility intervention, the system shifts from a purely utility-centric model toward a more consumer-driven and flexible framework.

Compared to conventional prepaid metering, the implemented solution introduces bidirectional data exchange between smart meters and a centralized server, leveraging secure API endpoints and ESP32 microcontroller connectivity. The results confirm that the combined hardware-software integration can be achieved using cost-effective components without compromising measurement accuracy, as deviations remained within ±5% of calibrated instruments. This is consistent with findings from Tushar et al. (2020), who emphasized the potential of low-cost IoT-enabled meters for decentralized energy management. Advances in P2P energy trading further support this, offering scalable frameworks that address market structures, technical challenges, and implementation methodologies (Zedan et al., 2024).

The prepaid billing and load control mechanisms performed reliably during tests, confirming the suitability of the JWT-secured token system for both standard purchases and shared energy credits. The automatic load reconnection upon successful transfer addresses an operational gap in traditional systems and aligns with SDG 7 by reducing downtime for vulnerable households.

The broader implications of this work extend to community-based energy resilience and demand-side management. In settings where affordability and access barriers remain significant, the ability to share surplus units could encourage collaborative consumption, reduce wastage, and foster social energy networks (Gorbatcheva et al., 2024). Furthermore, the approach is adaptable to other developing-country contexts with similar prepaid infrastructure.

Nevertheless, there are practical considerations for large-scale adoption. Integration with existing utility vending systems would require regulatory approval and cybersecurity audits to prevent fraud and maintain grid stability. Additionally, the Wi-Fi-based communication layer, while effective in controlled tests, may require alternative or redundant connectivity options, e.g., cellular networks, for deployment in areas with limited internet coverage (Nabuzale et al., 2024).

## 5. Conclusion

This paper presented the design, implementation, and validation of a smart P2P energy-sharing system adapted to Uganda's prepaid electricity model. The prototype demonstrated accurate real-time monitoring, secure token-based billing, and seamless consumer-to-consumer credit transfer, achieving high reliability and acceptable metering accuracy. By enabling direct sharing of purchased units, the system enhances flexibility, reduces energy waste, and promotes community-level equity, aligning with SDG 7 and national development priorities.

Future improvements should focus on integrating the P2P transfer logic into existing utility vending systems with regulatory oversight, expanding communication options beyond Wi-Fi to improve rural coverage, and conducting longitudinal field trials to evaluate user adoption, behavioral impacts, and effects on revenue collection. If scaled, this architecture could transform prepaid electricity from a static, one-way purchase model into a dynamic, community-driven energy exchange platform. Such innovation has the potential to support more inclusive, sustainable, and equitable access to electricity in Uganda and similar contexts across Africa.

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