

**Development Of An Intelligent Energy Management System For Smart Homes Using Iot Technology.**

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**Abstract**

The study investigated the design, development, and evaluation of an IoT-based Intelligent Energy Management System (IEMS) aimed at optimizing energy utilization in rural and semi-urban settings in Uganda. The objectives were to design a functional and cost-effective hardware system for real-time energy monitoring, develop robust decision-making algorithms to optimize energy source selection among solar, grid, and battery, and quantitatively evaluate the system's impact on critical energy performance metrics. The hardware prototype demonstrated high accuracy in monitoring key parameters, including voltage, current, power consumption, solar generation, and battery state-of-charge, with measurement accuracy consistently above 95%. The decision-making algorithms significantly enhanced operational efficiency by dynamically selecting the most cost-effective and reliable energy sources. The system reduced daily energy costs by 44–49%, decreased grid dependency by over 50%, and increased renewable energy utilization to 67% while maintaining full load coverage and ensuring stable voltage supply. Overall system reliability improved to 99%, and voltage fluctuations were reduced by 75%, indicating robust performance under real-world operating conditions. These results confirmed that the integration of high-accuracy IoT monitoring with intelligent optimization algorithms could deliver substantial economic and technical benefits. It was concluded that the IEMS was effective, scalable, and contextually appropriate for Uganda, providing a sustainable solution for energy management that maximized renewable energy use, reduced operational costs, and improved load stability and system reliability. The study recommended scaling up deployment across rural and semi-urban areas, building local technical capacity through training, engaging communities to promote acceptance and ownership, integrating the system with supportive policy frameworks, and continuously optimizing algorithms and hardware based on performance data. Further research was advised to assess long-term impacts, scalability, and economic viability in diverse contexts.

**Keywords: IoT-based energy management, intelligent energy optimization, renewable energy, solar-grid-battery integration, system reliability, energy cost savings, Uganda, load stability, smart energy systems.**

**Background of the study**

The global energy landscape is at a critical juncture, characterized by rising electricity demand, volatile fossil fuel prices, and the urgent imperative to mitigate climate change through enhanced energy efficiency and the integration of renewable sources. Globally, buildings are responsible for approximately 30% of final energy consumption and 26% of energy-related emissions (IEA, 2023), with residential buildings accounting for a substantial portion of this footprint. This has catalysed a paradigm shift towards smart homes, which leverage the Internet of Things (IoT) to create interconnected, data-driven, and automated living environments. An Intelligent Energy Management System (IEMS) sits at the core of this transformation, representing a sophisticated cyber-physical framework that utilizes a

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network of sensors, smart meters, actuators, and cloud computing to monitor, analyze, and control energy flows in real-time (Zhao et al., 2023). The global smart home market, valued at USD 99.75 billion in 2023, is projected to grow to USD 380.52 billion by 2030, underscoring the rapid adoption of these technologies (Fortune Business Insights, 2024). The operational intelligence of an IEMS is derived from its ability to collect granular data on appliance-level consumption, environmental conditions, and occupant behaviour, and then use algorithms ranging from simple rule-based logic to advanced machine learning to optimize energy usage (Pawar & Kulkarni, 2024). This optimization can take the form of demand-side management, such as automatically shifting non-essential loads to off-peak hours, or direct control, such as modulating HVAC systems based on occupancy. The tangible benefits are significant; studies indicate that a well-implemented IoT-based IEMS can reduce household energy consumption by 15-30%, thereby lowering utility bills for consumers, reducing peak demand stress on the grid, and contributing directly to global carbon reduction targets (Khan et al., 2023).

In Africa, the discourse on energy management is fundamentally shaped by the persistent challenge of energy poverty, where over 600 million people still lack access to reliable electricity (IEA, 2023), and those connected to the grid frequently endure unstable supply and some of the highest electricity tariffs in the world (AfDB, 2022). The continent's power sector is often plagued by technical and commercial losses, ageing infrastructure, and insufficient generation capacity, leading to load-shedding that cripples economic activity and household comfort. However, this challenge is simultaneously creating a unique opportunity for technological leapfrogging. Africa is experiencing one of the world's fastest-growing rates of internet and mobile phone penetration, with smartphone connections expected to reach 1.1 billion by 2025 (GSMA, 2023). This digital foundation provides the perfect springboard for deploying IoT-based energy solutions that bypass traditional, centralized grid management models (Adepetu et al., 2022). The application of an IEMS in the African context, therefore, extends beyond mere convenience and cost savings; it becomes a critical tool for enhancing energy security and resilience. For the emerging middle-class in urban areas, an IEMS can provide stability amidst grid instability by intelligently managing backup power systems like inverters and generators, prioritizing essential loads during outages to extend battery life (Mbuya et al., 2023). Furthermore, as distributed renewable energy systems, particularly solar PV, become increasingly popular, an IEMS is indispensable for managing these hybrid energy systems, optimizing the self-consumption of solar generation, and ensuring the economic viability of these investments (Olabi et al., 2023). The development of cost-effective, robust, and locally adapted IEMS solutions is therefore not a luxury but a necessity for sustainable urban development across the continent.

In Uganda, the energy sector embodies the continental challenges and opportunities in microcosm. While the country has made significant strides in expanding electricity access, now reaching approximately 57% of the urban population,

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the reliability and quality of power remain major concerns (ERA, 2023). The Uganda Electricity Regulatory Authority's 2023 report highlighted issues of voltage fluctuation and occasional load-shedding, which can damage appliances and disrupt daily life. Concurrently, the cost of electricity is a significant burden for households; a typical middle-class home in Kampala can spend a substantial portion of its income on grid electricity and backup generation (UBOS, 2023). This economic pressure, coupled with Uganda's abundant solar resource, has spurred a rapid uptake of residential solar systems and battery inverters. However, the management of these complex energy setups is often manual and inefficient, leading to suboptimal use of solar power, premature battery degradation, and ultimately, higher costs (Tumwesigye et al., 2024). The concept of a smart home, while nascent, is gaining traction among the tech-savvy and affluent urban population. Yet, most available IEMS solutions are imported, expensive, and designed for the stable grid conditions of the Global North, making them ill-suited for the Ugandan reality of hybrid power sources and an unreliable grid (Nakiganda et al., 2023). There is a pronounced gap in the local development of intelligent systems that are context-aware systems that can, for instance, seamlessly switch between grid, solar, and battery power based on availability, cost, and user priority; send real-time alerts during power faults; and provide Ugandan shilling-based cost analytics that are meaningful to the local user (Mbabazi & Byaruhanga, 2024). Therefore, the development of a tailored, affordable, and robust IoT-based Intelligent Energy Management System for Ugandan smart homes is not just an academic exercise but a practical intervention with the potential to deliver significant economic savings, improve energy resilience, and promote the efficient use of both grid and renewable energy, thereby contributing to the nation's broader goals of sustainable energy development as outlined in the Uganda Vision 2040.

### **Problem Statement**

The rising global energy demand, coupled with the instability and high cost of electrical power in Uganda, presents a critical challenge for homeowners, particularly in urban areas. Despite the growing adoption of backup systems like solar panels and inverters, energy management remains highly inefficient. Current practices are predominantly manual, leading to suboptimal use of solar energy, accelerated battery degradation due to poor charging cycles, and excessive reliance on the costly and unreliable national grid (ERA, 2023; Tumwesigye et al., 2024). This inefficiency results in exorbitant electricity bills and inadequate power availability, undermining household financial planning and energy security. While Internet of Things (IoT) technology offers a proven solution through Intelligent Energy Management Systems (IEMS) that can automate and optimize power consumption, these systems are largely designed for stable grid environments in developed nations (Zhao et al., 2023). In Uganda, a significant gap exists: there is a lack of an affordable, locally adapted IEMS that can effectively manage the unique hybrid energy mix of grid, solar, and battery power prevalent in Ugandan homes. Existing commercial solutions are often incompatible with the local power infrastructure, fail to account for frequent grid outages, and are financially inaccessible to the average middle-class household (Nakiganda et al., 2023). Consequently, homeowners are unable to leverage smart technology to reduce their energy costs and enhance system resilience. This study, therefore, seeks to address this gap by developing

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and testing a context-aware IoT-based IEMS specifically designed to automate energy distribution, prioritize loads, and minimize costs within the Ugandan smart home environment.

#### **Specific Objectives**

1. To design and prototype a functional, cost-effective IoT-based hardware system capable of autonomously monitoring key energy parameters
2. To develop and implement robust decision-making algorithms for the system that automatically optimize energy source selection (solar/grid/battery) and load control based on real-time data, predefined user priorities, and cost-saving logic.
3. To quantitatively evaluate the performance of the deployed Intelligent Energy Management System by measuring its impact on critical metrics

#### **Methodology**

This study employed a design science research framework, which was chosen to facilitate the iterative creation and evaluation of a novel artifact the Intelligent Energy Management System (IEMS) within a real-world context. The methodology was executed in three distinct phases over a twelve-month period: system design and development, laboratory testing and calibration, and field deployment and performance evaluation. The research was conducted in collaboration with the Department of Electrical Engineering at Makerere University, utilizing their embedded systems laboratory for the initial prototyping and testing phases. The system architecture was fundamentally based on the Internet of Things (IoT) paradigm, integrating a network of sensors, a central processing unit, and actuator controllers, all communicating via a hybrid Wi-Fi and LoRaWAN protocol stack to ensure reliable data transmission even during intermittent internet connectivity, a common occurrence in the local context.

#### **Data Collection and System Development**

The hardware development involved the design and assembly of a central control unit based on an ESP32 microcontroller, which served as the brain of the IEMS. This unit was interfaced with a suite of sensors to measure key input variables: energy generation was measured using a current transformer (CT) sensor clamped onto the solar PV inverter's output, providing data in watts; grid status was determined using a voltage sensor connected to a grid outlet, registering a binary variable (ON/OFF) and detecting voltage sags or surges; battery state of charge (SoC) was estimated by measuring the terminal voltage of the lead-acid battery bank using a voltage divider circuit, with the voltage (in volts) calibrated against a known discharge curve; and load consumption was measured by individual CT sensors on critical appliance circuits (e.g., refrigerator, lighting, sockets), with power consumption calculated in watt-hours. The output variables for system control were operationalized as three discrete states for a solid-state relay (SSR) array: Source Selection (prioritizing solar, then battery, then grid), Load Prioritization (shedding non-essential loads based on a predefined hierarchy when battery SoC fell below 40%), and Load Scheduling (delaying the activation of

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high-wattage appliances like water heaters until periods of peak solar generation). The software was developed in C++ within the Arduino IDE, implementing rule-based algorithms for real-time decision-making, and a companion mobile application was developed using MIT App Inventor to provide users with a dashboard for monitoring real-time data and receiving system alerts.

**Data Analysis and Performance Evaluation**

The analysis of the system's efficacy was conducted in two stages. First, a laboratory-based calibration and stress test was performed, where the IEMS was subjected to simulated grid failures and varying solar inputs using a programmable DC power supply and a variable AC source. During this phase, the response time of the system (the delay between a simulated grid failure and the successful switch to battery power) was measured in milliseconds, and the accuracy of the sensor readings (voltage, current) was validated against calibrated bench-top multimeters, with percentage error calculated for each sensor. Subsequently, a field deployment and evaluation was conducted in five selected households in Kampala for a continuous period of three months. The performance was analyzed by comparing pre- and post-installation data. Key performance indicators (KPIs) were quantitatively analyzed: Energy Cost Savings were calculated by comparing monthly electricity bills from the utility provider before and after IEMS installation, with the data tested for statistical significance using a paired-sample t-test; Grid Dependency was measured as the percentage reduction in total energy drawn from the national grid, calculated from the daily energy log data extracted from the system's SD card; and Battery Health was inferred by analyzing the frequency of deep discharge cycles (instances where SoC fell below 20%), with a lower frequency indicating improved battery management.

**Results**

**Table 1: Performance of IoT-Based Hardware Prototype for Energy Monitoring**

Parameter Monitored	Min Value	Max Value	Average Value	Accuracy (%)	Notes
Voltage (V)	210	242	226	98	Stable measurement under varying load
Current (A)	0.5	15	7.6	97	Accurately captured peak loads
Power Consumption (kW)	0.1	3.5	1.7	96	Minor lag observed at rapid fluctuations
Energy Generation (Solar kWh)	0.0	12.4	6.2	95	Properly tracked PV output over 24 hrs
Battery State of Charge (%)	15	100	68	99	Correctly detected charging/discharging cycles

Source: Primary Data, 2025

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The IoT-based hardware prototype demonstrated excellent accuracy in autonomously monitoring key energy parameters, with an average accuracy above 95% across voltage, current, power, energy generation, and battery state-of-charge readings (Nelson et al., 2022). The system consistently captured fluctuations in grid supply, solar PV output, and battery discharge levels, indicating robustness for real-time monitoring. The high measurement fidelity suggested that the sensors, microcontroller, and communication modules were well-integrated, minimizing data loss or latency. These results indicated that the hardware design successfully met the objective of being functional, reliable, and cost-effective while maintaining high precision, which is crucial for energy optimization algorithms to operate effectively.

**Table 2: Decision-Making Algorithm Performance for Energy Source Optimization**

Metric	Grid Only	Solar Only	Battery Only	IEMS Optimized	Improvement (%)
Average Energy Cost per Day (USD)	7.5	5.2	6.0	3.8	49
Peak Grid Demand (kW)	5.0	0.0	0.0	2.1	58
Load Coverage (%)	100	87	90	100	0
Algorithm Response Time (seconds)	-	-	-	0.8	-
Renewable Energy Utilization (%)	0	100	0	67	-

**Source: Primary Data, 2025**

The IEMS decision-making algorithms significantly improved energy efficiency and cost savings. When compared to single-source operation, the system reduced average daily energy costs by 49%, decreased peak grid demand by 58%, and ensured full load coverage while maximizing renewable energy utilization (67%) (Nelson et al., 2023). The real-time optimization incorporated user priorities, battery availability, and cost-saving logic effectively, switching between solar, grid, and battery in a seamless manner. The algorithm response time of 0.8 seconds confirmed that decisions were executed nearly instantaneously, ensuring minimal disruption to critical loads. These results indicated that the automated decision-making component met the design objective by delivering smart, cost-effective, and dynamic energy management.

**Table 3: Quantitative Evaluation of IEMS Performance Metrics**

Metric	Before IEMS Deployment	After IEMS Deployment	% Improvement	Observation
Daily Energy Cost (USD)	6.8	3.8	44	Significant cost savings

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Grid Dependency (%)	85	42	51	Reduced reliance on grid energy
Renewable Energy Utilization (%)	15	67	347	Maximized solar and battery usage
Load Stability (V fluctuation %)	$\pm 8$	$\pm 2$	75	More stable power supply to appliances
System Reliability (uptime %)	92	99	7	Reduced downtime of energy system

Source: Primary Data, 2025

The quantitative evaluation revealed that the deployed IEMS had a transformative impact on critical energy metrics. Daily energy costs dropped by 44%, demonstrating tangible financial benefits for end-users. Grid dependency was reduced by over half, reflecting successful integration of solar and battery resources and better use of renewable energy (Faith et al., 2023). The system also stabilized voltage fluctuations by 75%, ensuring safer and more reliable energy delivery to connected loads. Overall system reliability increased to 99%, highlighting the robustness of the IoT-based hardware and decision-making algorithms under real-world operating conditions. These improvements underscored the practical feasibility and effectiveness of the IEMS as a sustainable solution for rural or semi-urban energy management.

**Discussion of results**

The study revealed that the IoT-based Intelligent Energy Management System (IEMS) effectively achieved the intended objectives of real-time energy monitoring, automated decision-making, and optimization of energy utilization in a cost-effective manner. The hardware prototype consistently captured key energy parameters including voltage, current, power consumption, solar generation, and battery state-of-charge with high accuracy, exceeding 95% across all metrics. This demonstrated that the sensors, microcontrollers, and communication modules were well-integrated and capable of reliably acquiring precise measurements under dynamic load conditions (Winy et al., 2023). The system accurately detected voltage fluctuations, peak currents, and battery charge/discharge cycles, confirming its robustness and operational reliability. These results indicated that the designed hardware was fully capable of supporting real-time energy monitoring, forming a critical foundation for the subsequent algorithmic decision-making processes.

The evaluation of the decision-making algorithms showed substantial operational and economic benefits. By dynamically optimizing the selection of energy sources solar, grid, or battery the system reduced average daily energy costs by approximately 49% when compared to single-source operation. Additionally, peak grid demand decreased

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by 58%, demonstrating that the algorithms effectively minimized reliance on grid electricity while maximizing renewable energy utilization, which reached 67% (Deus, 2023). The system achieved full load coverage without interruptions, and the algorithm's rapid response time of less than one second ensured seamless load switching, confirming that the automated control logic was both timely and effective. These findings indicated that the algorithms successfully interpreted real-time data, considered user-defined priorities, and applied cost-saving logic to maintain energy efficiency and operational stability, fulfilling the study's objective of developing robust energy optimization algorithms.

The quantitative evaluation of the deployed system under real-world conditions further highlighted the transformative impact of the IEMS. Daily energy costs decreased from 6.8 USD to 3.8 USD, representing a 44% reduction, while grid dependency fell from 85% to 42%, reflecting a major shift toward renewable energy integration (Ariyo, 2023). Voltage fluctuations were significantly stabilized, with variation reduced by 75%, enhancing the reliability of electricity supplied to connected loads and reducing the risk of damage to sensitive equipment. Overall system reliability increased from 92% to 99%, indicating minimal downtime and confirming the practical feasibility and durability of the system under real-world operating conditions. These results collectively demonstrated that the integration of high-accuracy hardware with intelligent decision-making algorithms yielded measurable improvements in cost savings, renewable energy utilization, load stability, and system reliability.

### **Conclusions**

The study concluded that the IoT-based Intelligent Energy Management System (IEMS) was highly effective in achieving its objectives of monitoring energy parameters, optimizing energy source selection, and improving overall energy efficiency in a cost-effective manner. The hardware prototype was capable of accurately and reliably capturing critical energy metrics including voltage, current, power consumption, solar generation, and battery state-of-charge with accuracy consistently above 95%. This confirmed that the system was technically robust and suitable for real-time energy monitoring in dynamic operational environments.

It was also concluded that the decision-making algorithms significantly enhanced energy management by dynamically switching between solar, grid, and battery sources based on real-time data, user-defined priorities, and cost-saving logic. The system successfully reduced daily energy costs by approximately 44–49%, decreased grid dependency by over 50%, and maximized renewable energy utilization to 67%. Additionally, the algorithms ensured stable power supply, maintained full load coverage, and responded rapidly to changes in energy availability and demand, indicating that the automated optimization effectively balanced reliability, cost, and sustainability.

Furthermore, the study concluded that deploying the IEMS led to measurable improvements in operational performance, including a 75% reduction in voltage fluctuations and an increase in system reliability to 99%, demonstrating its practical feasibility under real-world conditions. Overall, the research established that integrating precise IoT-based monitoring with intelligent energy management algorithms provided a scalable, sustainable, and economically advantageous solution for energy optimization. The system was concluded to be particularly relevant for contexts like Uganda, where intermittent grid access, high energy costs, and abundant solar resources create an urgent need for efficient, renewable-based energy management solutions.

### **Recommendations**

The system should be implemented across multiple rural and semi-urban communities in Uganda to reduce dependence on grid electricity, optimize renewable energy utilization, and achieve cost savings at a broader scale. Pilot programs can be expanded gradually to include schools, healthcare facilities, and small businesses where energy reliability is critical.

Local technicians, engineers, and energy managers should receive comprehensive training on the installation, operation, maintenance, and troubleshooting of the IEMS. This would enhance local technical capacity, ensure proper system upkeep, and reduce the risk of malfunction or underperformance.

End-users and community stakeholders should be educated about the benefits of automated energy management, including cost savings, renewable energy utilization, and load stability. Awareness campaigns can foster acceptance, encourage responsible energy use, and support community ownership of the systems.

Policymakers should develop regulatory frameworks and incentives that support the adoption of IoT-based energy management solutions. Subsidies, tax incentives, or low-interest financing for renewable energy systems combined with smart management tools can accelerate uptake and make the technology accessible to low-income households and institutions.

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