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An ICT-Integrated Framework for Battery Monitoring and GIS-Based Distributed Energy Systems: A Review and Design Concept

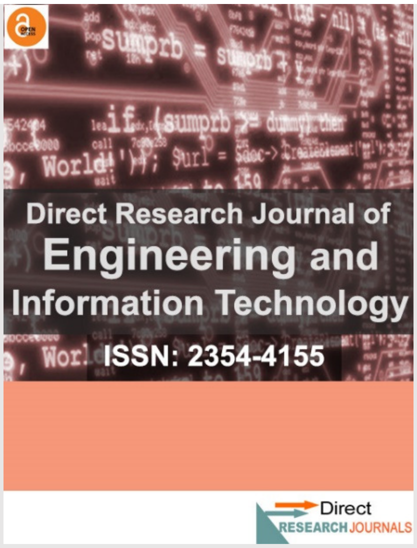
**Adebayo Dosa[1]*, Jemina Wodike[2], Thomas Oke[3], Babatunde Damilare[4],
Adisa Kolawole[5], and Alamoh Olalekan[6]**

[1]Department of Industrial Engineering, Durban University of Technology, Durban, South Africa
[2]Energy Systems Engineering from Memorial University of Newfoundland, Canada
[3]Operations Department, Lumos Nigeria (Tx light Power Solutions Ltd.), Lagos, Nigeria.
[4]Department of Meteorology and Climate Science, Federal University of Technology, Akure, Nigeria
[5]Department of Electrical Electronic Engineering, University of Lagos, Nigeria
[6]Department of Geosciences, Georgia State University, Atlanta, United States.
*Corresponding author email: dosbel@yahoo.com

ABSTRACT

As distributed energy systems (DES) expand across remote and urban landscapes; the integration of intelligent battery monitoring and spatial planning has become essential for optimizing system reliability and performance. This paper presents a comprehensive review and conceptual framework combining Information and Communication Technologies (ICT), Geographic Information Systems (GIS), and battery monitoring solutions for distributed renewable energy systems. Drawing from peer-reviewed studies, we synthesize current practices, identify technological gaps, and propose an ICT-integrated framework that supports real-time monitoring, geospatial visualization, and decision-making. The framework aims to inform future designs of decentralized energy systems by addressing limitations in battery health tracking, energy dispatch optimization, and site-specific planning. We also explore challenges related to interoperability, communication protocols, and infrastructure scalability. This review contributes to the advancement of resilient and intelligent energy systems in both grid-connected and off-grid environments.

Keywords: *Distributed Energy Systems (DES), Geographic Information Systems (GIS), Internet of Things (IoT), Renewable Energy, Energy Storage*



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INTRODUCTION

The global push toward decarbonization and sustainability has catalyzed the evolution of energy systems from centralized, fossil-fuel-driven grids to decentralized, renewable-powered networks. Distributed Energy Systems (DES) which often include solar panels, wind turbines, and micro-hydropower have emerged as viable solutions to meet local energy demands, particularly in rural or underserved areas. Central to the reliability of these systems is battery energy storage, which plays a crucial role in balancing supply and demand, storing excess energy, and ensuring power continuity during outages or low generation periods (Emezirinwune et al., 2024a). However, the performance and longevity of battery systems are highly dependent on rigorous monitoring and intelligent management. Traditional battery monitoring methods often operate in isolation, lacking connectivity to broader control systems or contextual awareness of environmental or geographic factors. Such limitations result in reduced efficiency, increased maintenance costs, and potential safety risks due to overheating, overcharging, or unexpected discharge behaviors (Chen et al., 2024). There is a pressing need for an ICT-integrated battery monitoring framework that offers real-time insights, supports remote diagnostics, and enhances decision-making across distributed infrastructures.

Information and Communication Technology (ICT) has transformed the monitoring landscape by enabling embedded sensing, cloud-based analytics, and remote system control (Babatunde et al., 2025). Systems equipped with Internet of Things (IoT) modules and wireless communication technologies-such as GPRS, Bluetooth, and Wi-Fi-can transmit voltage, temperature, and charge cycle data in real time (Majhi & Mohanty, 2024). These innovations allow for the early detection of faults and promote predictive maintenance, thereby increasing the resilience of DES installations (Atassi & Alhosban, 2023). Simultaneously, Geographic Information Systems (GIS) have become powerful tools in renewable energy planning and optimization. GIS platforms allow energy planners to visualize spatial relationships between generation sites, demand centers, and environmental constraints. They also facilitate site selection, route optimization, and risk analysis through the integration of topographic, meteorological, demographic, and infrastructure datasets (Wahba et al., 2024). For example, GIS-based mapping of solar irradiance and wind patterns enables optimal deployment of generation units. Moreover, geospatial data can inform battery placement by identifying sites vulnerable to heat, flooding, or theft factors that directly impact battery health and lifecycle (Ogunniran et al., 2025).

Despite the individual advancements in ICT and GIS, there exists a critical gap in integrating these technologies within a unified framework for battery monitoring in distributed energy contexts (Ataguba et al., 2024). A review of contemporary literature reveals that most battery monitoring systems are either hardware-focused emphasizing microcontroller integration and data sensing or software-driven, with little attention to spatial intelligence. Studies by Habiyaremye et al. (Habiyaremye et al., 2020) and Wahab et al. (Abd Wahab et al., 2018) presented IoT-based battery monitoring systems with GPRS or GSM integration, but they did not consider the geospatial distribution of assets or environmental exposure. Conversely, energy planning models that utilize GIS often exclude real-time battery health analytics, resulting in static and potentially outdated deployment recommendations (Coccato et al., 2025). The convergence of these domains is essential, particularly as energy systems grow in complexity and spatial scale. An integrated ICT-GIS framework would allow stakeholders to monitor battery conditions in real time, visualize component locations on dynamic maps, and predict system performance under varying conditions. For instance, operators could remotely identify failing batteries in flood-prone zones and prioritize them for preventive maintenance, or dynamically reroute energy flows based on both technical performance and spatial accessibility (Bouramdane, 2024). Moreover, such a framework supports resilience-building in remote or underserved regions, where manual inspections are impractical or costly. A GPRS-enabled battery system that logs and communicates data to a centralized server, mapped onto a GIS dashboard, could empower utilities, researchers, and policy makers to implement targeted interventions. Examples include the studies by Hui-Ying et al. (Hui-Ying et al., 2025) and Xiong et al. (Xiong et al., 2021), which highlighted the potential of remote GPRS-based systems in improving hybrid energy management. This paper aims to bridge the research gap by reviewing existing battery monitoring and GIS integration techniques, examining their relevance to distributed generation, and proposing a conceptual ICT-integrated framework. The proposed model builds on previous studies that have used fuzzy logic (Sulaiman, 2022), microcontroller designs (Emezirinwune, 2022), and spatial analytics (Bashingi, 2016), while uniquely combining them into a synchronized monitoring ecosystem. The remainder of this paper is organized as follows. Section 2 presents a comprehensive literature review covering battery monitoring technologies, ICT-enabled systems, and GIS applications in renewable energy. Section 3 details the conceptual framework, including system architecture, data flow, and component integration. Section 4 discusses case scenarios and potential applications in different geographic settings. Finally, Section 5 outlines future research directions, technical considerations, and policy implications for scalable deployment.

By synthesizing interdisciplinary research, this paper contributes to the growing body of knowledge on smart energy infrastructure and provides a pathway for researchers and practitioners to develop more robust, context-aware battery monitoring systems.

LITERATURE REVIEW

The shift from centralized to distributed energy systems (DES) has led to increased research on integrated technologies that ensure system reliability, optimize energy flow, and enhance remote monitoring capabilities. Key among these technologies are battery monitoring systems, Geographic Information Systems (GIS), and Information and Communication Technology (ICT) tools, which together support intelligent energy planning, real-time diagnostics, and sustainable operations.

Battery monitoring systems in distributed energy applications

Battery monitoring is essential for energy storage systems, particularly in off-grid or hybrid renewable energy settings [1], [18]. These systems ensure consistent power supply, manage load demands, and protect against overcharging or deep discharge. According to Ahwiadi *et.al.* (Ahwiadi & Wang, 2025), the lack of real-time battery diagnostics can lead to inefficiencies, reduced lifespan, and system downtime. They reviewed various battery health prediction tools and emphasized the value of continuous, condition-based monitoring to maintain energy system resilience. Recent developments have leveraged Internet of Things (IoT) technologies to design intelligent battery monitoring frameworks. For example, Chakraborty *et. al.* (Chakraborty et al., 2025) demonstrated how IoT-enabled sensors could provide real-time data on voltage, temperature, and current flow in solar installations. Similarly, Alshamrani (Alshamrani, 2022) proposed an integrated IoT model for remote diagnostics, reducing human intervention and maintenance costs. These systems have proven especially beneficial for distributed applications in remote areas where physical inspection is logistically challenging.

GIS applications in renewable and distributed energy systems

Geographic Information Systems (GIS) play a crucial role in energy planning by offering spatial decision-support tools for site selection, environmental assessment, and network optimization. As Zambrano-Asanza et.al. (Zambrano-Asanza et al., 2021) highlighted, GIS allows planners to evaluate terrain, proximity to load centers, and environmental constraints in renewable energy projects. GIS-based models support optimal placement of solar PV and wind turbines to maximize energy yield and minimize transmission losses. Coruhlu et al., (2022) emphasized the relevance of GIS in hybrid systems by demonstrating how spatial layers, such as solar irradiance, land use, and road networks, can be combined to inform planning decisions. Panda et al., (2022) also demonstrated GIS's capacity to enhance distributed generation by integrating resource mapping with load demand analytics, paving the way for smarter microgrid expansion. Despite these advances, the integration of GIS with battery storage systems remains underexplored, presenting an opportunity for improved energy resource coordination and reliability forecasting.

Role of ICT in energy monitoring and control

ICT serves as the digital backbone for smart energy infrastructure by facilitating data acquisition, remote control, and real-time communication. In distributed renewable setups, ICT tools such as GPRS, GSM, embedded controllers, and cloud servers have been used to remotely track energy flow, monitor component status, and alert operators in case of faults. Franco, (2020) described an ICT-based smart energy monitoring system that enabled dynamic load balancing and energy scheduling through cloud computing. Similarly, Saleem et. al. (Saleem et al., 2019) demonstrated the use of GPRS technology for real-time battery monitoring in hybrid renewable setups. Their model highlighted how communication protocols could support low-bandwidth, cost-effective deployment in remote microgrids. Martins and Rodrigues, (2025) explored ICT for electric vehicles, showing how vehicle battery monitoring could be adapted for DES applications. Their system utilized embedded microcontrollers to collect performance data, which was then transmitted to a cloud dashboard for analysis and predictive maintenance.

Toward integration: bridging GIS, battery monitoring, and ICT

Although significant literature exists in each domain independently, integration across GIS, ICT, and battery systems is still nascent. Baldo et. al. (Baldo et al., 2021) called for a unified approach that links spatial and technical diagnostics for smarter energy planning. They proposed integrating GSM-based battery monitoring with GIS platforms for predictive analytics a concept that remains largely theoretical. Ibrahim et al. (2023) contributed to this effort by proposing a fuzzy logic-based energy management system that used both ICT and spatial modeling to balance load and optimize resource allocation in microgrids. While their study marks a critical step forward, it stops short of proposing a modular framework that can be adopted across diverse DES setups. From a system design perspective, Akinyele and Rayudu (2014) recommended that future battery storage systems be embedded within broader ICT-GIS architectures to leverage real-time diagnostics, location-specific forecasting, and automated control. However, they also noted challenges such as data interoperability, power consumption of monitoring devices, and initial capital costs.

Identified gaps and motivation for a framework

A comprehensive review of existing literature reveals that while significant progress has been made in the development of individual components battery monitoring systems, GIS-based energy planning tools, and ICT-enabled energy infrastructure their integration into a unified and functional design framework remains significantly underexplored. Studies such as those by Adebayo et al. (2025) and Adeyinka et al. (2024) have highlighted the importance of real-time battery monitoring systems in maintaining the efficiency and longevity of energy storage devices, particularly in off-grid and hybrid renewable energy systems. Similarly, GIS has been extensively applied in distributed energy resource (DER) planning to support spatial analysis, optimize system siting, and assess resource availability, as demonstrated by (Alhamwi et al., 2019; Fournier et al., 2023). These tools provide invaluable geospatial intelligence for system deployment and load forecasting. ICT, including GPRS, GSM, and cloud-based communication systems, has been used to support remote monitoring, data acquisition, and system control (Iliev et al., 2022; Patra et al., 2021), making it an indispensable backbone for smart energy systems. Despite these advancements, there remains a lack of research addressing the joint optimization of spatial and technical parameters for battery placement. For instance, while Akram et al., (2021) proposed integrated models that incorporate fuzzy logic and GSM technologies with GIS, these remain theoretical or limited to specific scenarios. Furthermore, few studies propose real-time control and diagnostics systems that fully leverage cloud-integrated ICT tools in conjunction with geospatial insights. Most importantly, modular, scalable frameworks designed to support deployment in rural and underserved communities are rarely addressed, despite their critical importance for equitable energy access (Emezirinwune et al., 2025). These gaps underscore a pressing need for a holistic ICT-integrated design framework that synergizes battery monitoring, GIS, and ICT. Such a framework would enhance energy planning, reduce operational downtime, and enable intelligent, scalable deployments. This paper seeks to address this need by proposing a conceptual model informed by current research and emergent best practices in distributed energy systems.

METHODOLOGY

The development of an ICT-integrated framework for battery monitoring and GIS-based distributed energy systems requires a robust methodological foundation. This study adopts a narrative review methodology complemented by a comparative content analysis of selected peer-reviewed articles. The aim is to synthesize research findings across interdisciplinary domains of electrical engineering, renewable energy, geographic information science, and information and communication technology (ICT) in order to propose a cohesive, modular, and scalable design framework. The review draws from scholarly publications, including those focused on lithium-ion battery monitoring Islam et al., (2022), Luo et al., (2013), Ayodele et al. (2019) and Hong & Lee, (2018). The methodology is organized into three core phases:

Phase one: thematic literature classification

The first step involved categorizing the selected literature into three thematic domains:

1. Battery Monitoring Systems (BMS): This category includes research on hardware sensors, microcontrollers, and algorithms for state-of-charge (SOC) and state-of-health (SOH) monitoring. Battery monitoring is a foundational element for efficient distributed energy systems. For instance, Uzair et al. (2022) proposed a BMS using Arduino and GSM modules for real-time diagnostics, while Cai et al. (2016) examined IoT-based integration with cloud storage to enable remote access and continuous analysis. These studies provided insights into telemetry data structure, diagnostic indicators, and system calibration for long-term performance and fault prediction.

2. GIS in Distributed Energy Systems (DES): The second thematic group included studies that applied GIS for site selection, resource mapping, and spatial load forecasting. Ayodele et al. (2019) and Tafula et. al. (Tafula et al., 2023) emphasized how GIS tools enhance planning for off-grid solar PV and wind installations by integrating terrain, weather, and demographic data. These insights are essential for the proposed framework, particularly in identifying optimal battery and DER placement based on geospatial factors such as solar irradiance, terrain elevation, and population density.

3. ICT and Communication Protocols: The final category focused on ICT infrastructures such as GPRS, GSM, and cloud computing, which enable data communication between the monitoring system and control centers. Habiyaremye et al., (2020) developed a GPRS-based battery monitoring system for remote microgrids, while Liu et al. (2020) used fuzzy logic for adaptive voltage control across distributed systems. These technologies were assessed for their reliability, latency, and ability to support real-time alerts and feedback mechanisms.

Phase two: comparative analysis and synthesis

Following classification, each domain was analyzed for integration potential. A comparative matrix was developed to evaluate the overlap between functional requirements e.g., battery diagnostics, geographic intelligence, and real-time communication and proposed solutions in the literature. For example, while many BMS studies prioritized local data acquisition (Colombo et al., 2016; Hu et al., 2015) few addressed geospatial variability in system performance. Conversely, GIS-centric works excelled in spatial optimization but lacked real-time telemetry or system feedback mechanisms. The comparative analysis revealed that while each component is technically mature in isolation, their combined deployment remains underdeveloped in terms of modular integration, interoperability, and scalability.

Phase three: framework development

The final phase of the methodology involved conceptualizing an ICT-integrated architecture that could combine the strengths of the reviewed domains. The framework design follows a modular systems approach and consists of five key layers (Figure 1). ICT-integrated framework architecture for battery monitoring and GIS-enabled distributed energy systems. The system is composed of five interconnected layers: Sensor Layer, Communication Layer, Data Analytics Layer, Geospatial Intelligence Layer, and Control and Visualization Layer. Each layer performs a distinct function that supports real-time diagnostics, spatial energy planning, and decision-making in distributed energy applications.

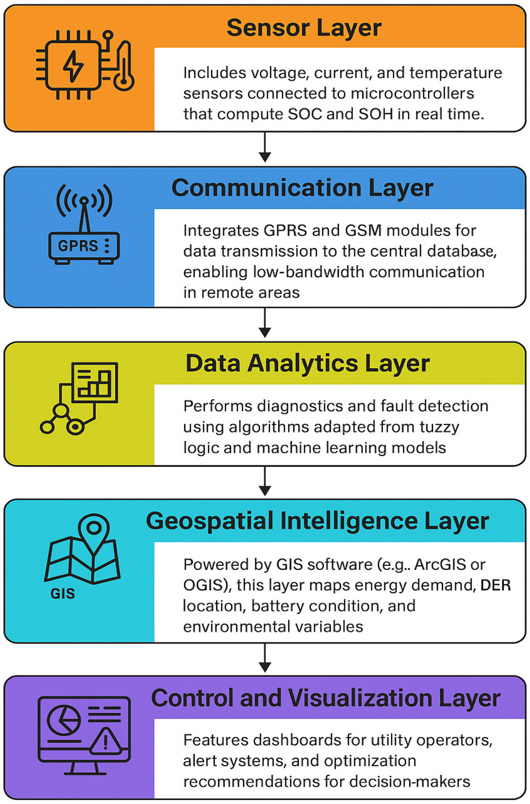

Figure 1: Modular ICT Framework for Battery Monitoring and GIS-Based Energy Management

1. Sensor Layer: Includes voltage, current, and temperature sensors connected to microcontrollers that compute SOC and SOH in real time as outlined in (Gozuoglu, 2025).

2. Communication Layer: Integrates GPRS and GSM modules for data transmission to the central database (Ionel et al., 2012), enabling low-bandwidth communication in remote areas.

3. Data Analytics Layer: Performs diagnostics and fault detection using algorithms adapted from fuzzy logic and machine learning models (Jan et al., 2021).

4. Geospatial Intelligence Layer: Powered by GIS software (e.g., ArcGIS or QGIS), this layer maps energy demand, DER location, battery condition, and environmental variables (McGhee, 2020).

5. Control and Visualization Layer: Features dashboards for utility operators, alert systems, and optimization recommendations for decision-makers (Sethupathy, 2021).

Each layer communicates with adjacent layers via Application Programming Interfaces (APIs) to ensure interoperability and modular scaling. This framework is particularly designed to function effectively in rural and underserved communities, where the combination of GIS and ICT can support location-aware planning, predictive maintenance, and automated alerts. By adopting a narrative synthesis approach and cross-comparing system components, this methodology supports the development of a robust ICT-integrated model. It bridges gaps in prior research by consolidating battery diagnostics, spatial planning, and remote communication into a single adaptive framework. The next section presents this design in full, outlining its components and use-case scenarios in distributed energy environments.

Proposed design concept and framework architecture

Based on the thematic analysis and literature synthesis described in Section 3, this section outlines the proposed ICT-integrated framework for real-time battery monitoring and GIS-supported planning in distributed energy systems (DES). The framework is intended for deployment in microgrids, hybrid renewable energy setups, and off-grid installations, particularly in geographically dispersed or underserved regions.

Overview of the framework

The proposed architecture consists of five functional layers Sensor Layer, Communication Layer, Data Analytics Layer, Geospatial Intelligence Layer, and Control and Visualization Layer each representing a core technical or analytical component necessary for holistic, intelligent energy system monitoring. The framework facilitates seamless interaction between battery data acquisition, spatial intelligence, and system control.

As shown in (Figure 1), the framework starts at the sensor level with voltage, current, and temperature data collection. It then moves through secure communication channels (e.g., GPRS/GSM), into cloud-based analytics platforms, and overlays this information on geospatial dashboards for visualization, fault prediction, and control response.

Sensor layer

This layer includes sensors and embedded microcontrollers that measure real-time parameters such as voltage, current, and temperature. These measurements allow for continuous estimation of the State of Charge (SoC) and State of Health (SoH) of battery systems (Bokstaller et al., 2023). Accurate sensor readings are critical for detecting early signs of battery failure, avoiding thermal runaway, and optimizing charge/discharge cycles.

Communication layer

The communication layer utilizes GPRS, GSM, or LoRaWAN modules to transmit telemetry data from the battery monitoring units to a remote server or cloud environment. GPRS-based models, like the one proposed by (Kantilal, 2022), enable low-bandwidth, cost-effective data transmission suitable for rural and remote applications. Data packets are time stamped, encrypted, and transmitted at intervals optimized for energy consumption and communication reliability.

Data analytics layer

Upon reaching the server, the data is processed by intelligent diagnostic engines that apply machine learning algorithms or fuzzy logic controllers to detect anomalies, estimate SoH, and recommend maintenance actions (El Hadraoui et al., 2024). This layer can also implement battery usage forecasting, charge cycle optimization, and alert classification systems, all of which are valuable in maximizing battery life and reducing downtime. In a more advanced deployment, this layer can incorporate artificial intelligence (AI) techniques for pattern recognition, predictive modeling, and adaptive decision-making.

Geospatial intelligence layer

This layer integrates the processed battery performance data into a Geographic Information System (GIS) environment. Using software like ArcGIS or QGIS, energy system operators can visualize battery conditions across different geographic locations, map energy demand patterns, and identify spatial correlations between environmental factors and battery degradation (McGhee, 2020). The GIS layer also supports spatial asset management, enabling planners to prioritize system maintenance, plan expansions based on load density, and avoid vulnerable areas (e.g., flood zones, high-heat regions). It adds location-specific intelligence that transforms raw sensor data into strategic decision tools.

Control and visualization layer

The final layer of the framework offers interactive dashboards that display system status, fault alerts, and performance metrics in real time. These dashboards accessible via web or mobile platforms can assist utility operators in managing daily operations, optimizing load dispatch, and responding to system anomalies. As Moradi et al. (2019) emphasized, visual analytics play a critical role in facilitating timely, data-driven decision-making in distributed energy systems. The layer also supports historical data review, energy consumption reporting, and scenario simulations for future planning.

System interoperability and scalability

All five layers are connected via Application Programming Interfaces (APIs), allowing modular upgrades and interoperability across platforms. This modularity ensures that the framework can be tailored to specific use cases from solar microgrids in Sub-Saharan Africa to urban energy storage units in smart cities while maintaining a consistent architectural backbone. Furthermore, the system is designed to support scalability by integrating new sensor nodes, communication modules, or GIS datasets without overhauling the entire infrastructure. This makes it well-suited for pilot projects, phased deployments, or donor-funded electrification initiatives.

DISCUSSION

The proposed ICT-integrated framework for battery monitoring and GIS-based distributed energy systems addresses a major gap in current energy management strategies: the lack of cohesion between real-time battery diagnostics, spatial intelligence, and control systems. This section discusses the operational implications, advantages, and potential limitations of the design, while highlighting its significance for energy access in underserved and remote communities.

Bridging technical silos

One of the most significant contributions of the proposed framework is its capacity to bridge traditionally siloed domains electrical monitoring, geospatial planning, and information communication technologies. While each of these fields has matured independently, their integration into a layered, interoperable architecture enhances system responsiveness, reliability, and intelligence. As seen in studies by Luo et al. (2013) and Hong et al. (2018), battery monitoring has typically focused on electrical performance. However, such data gains greater meaning when contextualized with location-based variables like temperature gradients, user load patterns, and topographical vulnerability insights enabled by GIS integration. This convergence of sensor telemetry and geospatial analysis allows for smarter deployment decisions and more nuanced performance evaluations. For example, a sudden decline in SoH in a particular region could prompt both a technical inspection and an environmental assessment, potentially identifying spatial drivers such as ambient heat or humidity that accelerate battery degradation.

Enhancing resilience and remote operability

The layered architecture significantly improves operational resilience, particularly in decentralized or off-grid energy systems. Many rural electrification projects struggle with delayed fault detection, inefficient maintenance scheduling, and data blackouts caused by communication breakdowns (Fred et al., 2024). By incorporating low-power, GPRS-enabled communication modules, the framework ensures that data collection and diagnostics are not reliant on broadband or fiber optic infrastructure making it feasible in remote areas with limited connectivity. Moreover, the ability to visualize spatially distributed battery banks and overlay performance metrics with GIS software allows decision-makers to allocate resources more efficiently. Rather than adopting a reactive, site-visit-based strategy for battery maintenance, this system supports predictive maintenance, remote diagnostics, and automated alerts enhancing both sustainability and cost-efficiency.

Scalable and modular design

Another major advantage is the modularity and scalability of the framework. Each layer can function semi-independently while still contributing to an integrated whole. For instance, the data analytics layer could be upgraded to a more advanced AI model without requiring changes in the sensor hardware. Similarly, the GIS component can integrate newer datasets or improved remote sensing tools (e.g., drones or satellite imagery) without altering the data acquisition or communication protocols. This design flexibility makes the framework highly adaptable across contexts, whether in small-scale solar home systems or larger community-level microgrids. Such modularity aligns with the approach of (Manic et al., 2016), who emphasized adaptive energy control systems that evolve with expanding user bases and changing environmental conditions.

Decision support and policy applications

The visualization and control layer also plays a critical role in transforming technical data into actionable intelligence. By delivering fault alerts, energy consumption trends, and location-specific diagnostics in real time, the framework offers utility managers, donor agencies, and public sector stakeholders a transparent view into system performance. This can support not only operational decisions but also policy and investment planning. For instance, ministries of energy or rural development could use spatial performance data to identify areas requiring battery system upgrades or to assess the long-term viability of renewable deployments in climatically challenging zones. NGOs and funding bodies can prioritize intervention in regions where system downtimes correlate with public health or education risks due to power loss.

Limitations and future considerations

While the framework presents a robust design concept, several limitations warrant attention. First, the success of the system depends on the accuracy and durability of field-deployed sensors. Environmental factors like dust, humidity, and physical tampering can compromise sensor reliability, especially in remote regions. Second, while GPRS provides sufficient bandwidth for low-frequency monitoring, it may not support high-resolution, real-time video or thermal data, which could be needed in advanced grid scenarios. Data privacy and cybersecurity also pose challenges. Transmitting energy performance data and location information over mobile networks introduces vulnerabilities that need to be mitigated through encryption and secure protocols. Additionally, the GIS component may face limitations in regions where spatial data is either unavailable or outdated. Finally, effective implementation will depend on local capacity and stakeholder training. The framework assumes a baseline familiarity with GIS tools and digital dashboards, which may not exist uniformly across all project sites. Capacity-building and training programs will therefore be critical to unlocking the full potential of this architecture.

Conclusion

The transition toward decentralized and sustainable energy systems has highlighted the critical need for intelligent monitoring, control, and planning frameworks especially in regions with limited infrastructure. This paper has proposed a multi-layered, ICT-integrated framework that combines real-time battery monitoring, geospatial intelligence, and low-power communication technologies to support the design and operation of distributed energy systems. Drawing on insights from recent literature and technological advancements, the framework addresses a key gap in current energy infrastructure: the disjointed development of monitoring, spatial planning, and system optimization tools. By unifying these components, the proposed architecture enables improved situational awareness, predictive maintenance, and informed decision-making. At the core of this framework is the sensor layer, which continuously captures voltage, temperature, and current data to estimate State of Charge (SoC) and State of Health (SoH). This data is transmitted via GPRS and GSM modules, ensuring operability in bandwidth-constrained environments. The analytics layer processes this information through adaptive algorithms, while the GIS layer spatially contextualizes performance metrics for strategic planning. Visualization dashboards offer end users such as rural energy operators and policymakers' real-time insights that support both technical interventions and broader energy access strategies. Despite its promise, the framework is not without limitations. Sensor durability in remote climates, data security during mobile transmission, and the availability of up-to-date spatial data may present operational challenges. Furthermore, successful deployment hinges on stakeholder training, local engagement, and alignment with regulatory policies.

Recommendations

Pilot implementation in target communities

Before large-scale adoption, the proposed framework should be piloted in a select number of off-grid or underserved areas. This will allow for the testing of system reliability, identification of contextual limitations, and refinement of the interface based on user feedback.

Capacity building and local ownership

Training programs must be designed to equip local technicians, utility staff, and community leaders with the knowledge to operate and maintain the system. Digital literacy and familiarity with GIS tools should be prioritized to promote long-term sustainability

Open-source and modular development

Where possible, open-source software and modular hardware designs should be used to reduce costs and allow for community-driven innovation. The ability to add or swap modules such as sensors or analytics tools will ensure flexibility and scalability.

Policy integration and funding alignment

Development agencies and national governments should be encouraged to adopt the framework as a strategic tool within rural electrification and sustainability plans. Its geospatial outputs can help align energy infrastructure with climate resilience, public health, and economic development objectives.

Cybersecurity and data ethics

Given the reliance on remote data transmission and cloud storage, protocols must be established to protect sensitive information. Encryption, user authentication, and compliance with digital rights standards are essential to safeguard both energy infrastructure and community trust.

Future research directions

Future iterations of this research should explore integration with machine learning-driven control algorithms, remote sensing technologies (e.g., drones), and blockchain for energy transaction tracking. Additionally, greater emphasis should be placed on user-centered design to improve system adoption across diverse cultural and economic settings. This framework contributes to the evolving discourse on smart, sustainable energy infrastructure by presenting a holistic model that is adaptable, scalable, and context-aware. As global demand for clean energy accelerates particularly in underserved regions ICT-integrated solutions that connect batteries, location, and data are not just innovative but essential. By bridging the divide between engineering, geography, and communication technologies, this framework offers a pathway toward more resilient, efficient, and equitable energy systems.

REFERENCES

Abd Wahab, M. H., Anuar, N. I. M., Ambar, R., Baharum, A., Shanta, S., Sulaiman, M. S., & Hanafi, H. F. (2018). IoT-based battery monitoring system for electric vehicle. International Journal of Engineering & Technology, 7(4.31), 505–510.

Adebayo, D. H., Ajiboye, J. A., Okwor, U. D., Muhammad, A. L., Ugwuijem, C. D., Agbo, E. K., & Stephen, V. I. (2025). Optimizing energy storage for electric grids: Advances in hybrid technologies. Management, 10, 11.

Adeyinka, A. M., Esan, O. C., Ijaola, A. O., & Farayibi, P. K. (2024). Advancements in hybrid energy storage systems for enhancing renewable energy-to-grid integration. Sustainable Energy Research, 11(1), 26.

Ahwiadi, M., & Wang, W. (2025). Battery health monitoring and remaining useful life prediction techniques: A review of technologies. Batteries, 11(1), 31.

Akinyele, D. O., & Rayudu, R. K. (2014). Review of energy storage technologies for sustainable power networks. Sustainable Energy Technologies and Assessments, 8, 74–91.

Akram, S. V., Singh, R., Gehlot, A., Rashid, M., AlGhamdi, A. S., Alshamrani, S. S., & Prashar, D. (2021). Role of wireless aided technologies in the solid waste management: A comprehensive review. Sustainability, 13(23), 13104.

Alhamwi, A., Medjroubi, W., Vogt, T., & Agert, C. (2019). Development of a GIS-based platform for the allocation and optimisation of distributed storage in urban energy systems. Applied Energy, 251, 113360.

Alshamrani, M. (2022). IoT and artificial intelligence implementations for remote healthcare monitoring systems: A survey. Journal of King Saud University-Computer and Information Sciences, 34(8), 4687–4701.

Ataguba, H. E., Kokofi, C., Alade, O. O., & Babatunde, E. D. (2024). Integrating cybersecurity and ICT into climate-smart agriculture: a framework for resilient food systems. Information Technologist, 21(2).

Atassi, R., & Alhosban, F. (2023). Predictive Maintenance in IoT: Early Fault Detection and Failure Prediction in Industrial Equipment. Journal of Intelligent Systems & Internet of Things, 9(2).

Ayodele, T. R., Ogunjuyigbe, A. S. O., Amedu, A., & Munda, J. L. (2019). Prediction of global solar irradiation using hybridized k-means and support vector regression algorithms. Renewable Energy Focus, 29, 78–93.

Babatunde, O., Adedoja, O., Oyebode, O., Kareem, U. A., Babatunde, D., Adedoja, T., Akintayo, B., Emezirinwune, M., Ighravwe, D. E., Ogunniran, O., & others. (2025). Techno-Economic Optimization and Assessment of Solar Photovoltaic--Battery--Hydrogen Energy Systems with Solar Tracking for Powering ICT Facility.

Resources,14(5), 74.

Baldo, D., Mecocci, A., Parrino, S., Peruzzi, G., & Pozzebon, A. (2021). A multi-layer lorawan infrastructure for smart waste management. Sensors, 21(8), 2600.

Bashingi, N. (2016). Investigating ICT solutions for the public transportation system improvement in the Free State: Opportunities and challenges.

Bokstaller, J., Schneider, J., & vom Brocke, J. (2023). Estimating SoC, SoH, or RuL of rechargeable batteries via IoT: A review. IEEE Internet of Things Journal, 11(5), 7559–7582.

Bouramdane, A.-A. (2024). Natural hazards in electricity grids: from landscape dynamics to optimal mitigation and adaptation approaches. Emergency Management Science and Technology, 4(1).

Cai, H., Xu, B., Jiang, L., & Vasilakos, A. V. (2016). IoT-based big data storage systems in cloud computing: perspectives and challenges. IEEE Internet of Things Journal, 4(1), 75–87.

Chakraborty, P., Sachin, M., Prithvi, S., & Rao, S. (2025). Real-Time Solar Monitoring with Charging and Grid Control Using IoT. 2025 International Conference on Intelligent and Innovative Technologies in Computing, Electrical and Electronics (IITCEE), 1–6.

Chen, S., Fan, G., Wang, Y., Zhou, B., Ye, S., Liu, Y., Guo, B., Zhu, C., & Zhang, X. (2024). The impact of intermittent overcharging on battery capacity and reliability: Electrochemical performance analysis and failure prediction. Journal of Power Sources, 591, 233800.

Coccato, S., Barhmi, K., Lampropoulos, I., Golroodbari, S., & van Sark, W. (2025). A Review of Battery Energy Storage Optimization in the Built Environment. Batteries, 11(5), 179.

Colombo, T., Fröning, H., Garc\`\ia, P. J., & Vandelli, W. (2016). Optimizing the data-collection time of a large-scale data-acquisition system through a simulation framework. The Journal of Supercomputing, 72(12), 4546–4572.

Coruhlu, Y. E., Solgun, N., Baser, V., & Terzi, F. (2022). Revealing the solar energy potential by integration of GIS and AHP in order to compare decisions of the land use on the environmental plans. Land Use Policy, 113, 105899.

El Hadraoui, H., Ouahabi, N., El Bazi, N., Laayati, O., Zegrari, M., & Chebak, A. (2024). Toward an Intelligent diagnosis and prognostic health management system for autonomous electric vehicle powertrains: A novel distributed intelligent digital twin-based architecture. IEEE Access.

Emezirinwune, M. U. (2022). Design and Construction of an Automatic Voltage Regulator for a Synchronous Alternator. The Scientific Bulletin of Electrical Engineering Faculty, 22(1), 1–7.

Emezirinwune, M. U., Adejumobi, I. A., Adebisi, O. I., & Akinboro, F. G. (2024a). Off-grid PV/biomass/DG/battery hybrid renewable energy as a source of electricity for a farm facility. E-Prime-Advances in Electrical Engineering, Electronics and Energy, 10, 100808.

Emezirinwune, M. U., Adejumobi, I. A., Adebisi, O. I., & Akinboro, F. G. (2024b). Synergizing Hybrid Renewable Energy Systems and Sustainable Agriculture for Rural Development in Nigeria. E-Prime-Advances in Electrical Engineering, Electronics and Energy, 100492.

Emezirinwune, M. U., Adejumobi, I. A., Adebisi, O. I., & Akinboro, F. G. (2025). Application of Energy Balance and MCDM approach to the selection of hybrid renewable energy systems for agricultural application. Franklin Open, 100317.

Fournier, E. D., Federico, F., Cudd, R., & Pincetl, S. (2023). Building an interactive web mapping tool to support distributed energy resource planning using public participation GIS. Applied Geography, 152, 102877.

Franco, A. (2020). Balancing user comfort and energy efficiency in public buildings through social interaction by ICT systems. Systems, 8(3), 29.

Fred, O., Ukagwu, K. J., Abdulkarim, A., & Eze, V. H. U. (2024). Reliability and maintainability analysis of Solar Photovoltaic Systems in rural regions: A narrative review of challenges, strategies, and policy implications for sustainable electrification. KIU Journal of Science, Engineering and Technology, 3(2), 103–122.

Gozuoglu, A. (2025). IoT-enhanced battery management system for real-time SoC and SoH monitoring using STM32-based programmable electronic load. Internet of Things, 30, 101509.

Habiyaremye, J., Zennaro, M., Mikeka, C., Masabo, E., Kumaran, S., & Jayavel, K. (2020). GPRS sensor node battery life span prediction based on received signal quality: experimental study. Information, 11(11), 524.

Hong, Y., & Lee, C. W. (2018). Pareto fronts for multiobjective optimal design of the lithium-ion battery cell. Journal of Energy Storage, 17, 507–514.

Hu, S., Yao, S., Jin, H., Zhao, Y., Hu, Y., Liu, X., Naghibolhosseini, N., Li, S., Kapoor, A., Dron, W., & others. (2015). Data acquisition for real-time decision-making under freshness constraints. 2015 IEEE Real-Time Systems Symposium, 185–194.

Hui-Ying, L., Ru-Xin, W., Wen, T., & Wen-Juan, L. (2025). GPRS and Remote Meter Reading are used in the Design and Implementation of a Simultaneous Line Loss Electricity Consumption Information Collection System. International Journal of High-Speed Electronics and Systems, 2540508.

Ibrahim, O., Bakare, M. S., Amosa, T. I., Otuoze, A. O., Owonikoko, W. O., Ali, E. M., Adesina, L. M., & Ogunbiyi, O. (2023). Development of fuzzy logic-based demand-side energy management system for hybrid energy sources. Energy Conversion and Management: X, 18, 100354.

Iliev, I., Kanev, I., & Krasteva, V. (2022). A Survey on the Application of Mobile Communication Devices in Remote Cardiac Monitoring Systems. The International Symposium on Bioinformatics and Biomedicine, 299–311.

Ionel, R., Vasiu, G., & Mischie, S. (2012). GPRS based data acquisition and analysis system with mobile phone control. Measurement, 45(6), 1462–1470.

Islam, M. M., Nooruddin, S., Karray, F., & Muhammad, G. (2022). Internet of things: Device capabilities, architectures, protocols, and smart applications in healthcare domain. IEEE Internet of Things Journal, 10(4), 3611–3641.

Jan, S. U., Lee, Y. D., & Koo, I. S. (2021). A distributed sensor-fault detection and diagnosis framework using machine learning. Information Sciences, 547, 777–796.

Kantilal, B. V. (2022). IoT based air quality monitoring system with power consumption optimization and air quality parameters prediction using deep learning. Maharaja Sayajirao University of Baroda (India).

Liu, W., Xu, Y., Wang, Y., & Feng, X. (2020). Fuzzy-logic based Adaptive Control of Distributed Energy Storage Systems for Simultaneous V/f Regulation. 2020 IEEE Power & Energy Society General Meeting (PESGM), 1–5.

Luo, M., Xiao, Y., Sun, W.-M., & Wang, Z. (2013). Online battery monitoring system based on GPRS for electric vehicles. 2013 5th International Conference on Intelligent Human-Machine Systems and Cybernetics, 1, 122–125.

Majhi, A. A. K., & Mohanty, S. (2024). A comprehensive review on internet of things applications in power systems. IEEE Internet of Things Journal.

Manic, M., Wijayasekara, D., Amarasinghe, K., & Rodriguez-Andina, J. J. (2016). Building energy management systems: The age of intelligent and adaptive buildings. IEEE Industrial Electronics Magazine, 10(1), 25–39.

Martins, J. A., & Rodrigues, J. M. F. (2025). Intelligent Monitoring Systems for Electric Vehicle Charging. Applied Sciences, 15(5), 2741.

McGhee, R. (2020). Utilising GIS mapping to identify areas of opportunity for photovoltaic power station deployment in an urban environment.

Moradi, J., Shahinzadeh, H., Nafisi, H., Marzband, M., & Gharehpetian, G. B. (2019). Attributes of big data analytics for data-driven decision making in cyber-physical power systems. 2020 14th International Conference on Protection and Automation of Power Systems (IPAPS), 83–92.

Ogunniran, O., Babatunde, O., Akintayo, B., Adisa, K., Ighravwe, D., Ogbemhe, J., & Olanrewaju, O. A. (2025). Risk-Based Optimization of Renewable Energy Investment Portfolios: A Multi-Stage Stochastic Approach to Address Uncertainty. Applied Sciences (2076-3417), 15(5).

Panda, S., Mohanty, S., Rout, P. K., Sahu, B. K., Parida, S. M., Kotb, H., Flah, A., Tostado-Véliz, M., Abdul Samad, B., & Shouran, M. (2022). An insight into the integration of distributed energy resources and energy storage systems with smart distribution networks using demand-side management. Applied Sciences, 12(17), 8914.

Patra, D., Chavhan, S., Gupta, D., Khanna, A., & Rodrigues, J. J. P. C. (2021). An efficient method for remote control and cloud-based monitoring of industrial equipment over GSM network. 2021 6th International Conference on Smart and Sustainable Technologies

(SpliTech), 1–6.

Saleem, Y., Crespi, N., Rehmani, M. H., & Copeland, R. (2019). Internet of things-aided smart grid: technologies, architectures, applications, prototypes, and future research directions. Ieee Access, 7, 62962–63003.

Sethupathy, U. K. A. (2021). Empowering Intelligent Decision-Making: Architecting Resilient Real-Time Data Platforms with Actionable Visual Dashboards.

Sulaiman, M. A. M. (2022). UAV-Driven Building Inspection and Integrated Facility Maintenance Management. Western Michigan University.

Tafula, J. E., Justo, C. D., Moura, P., Mendes, J., & Soares, A. (2023). Multicriteria decision-making approach for optimum site selection for off-grid solar photovoltaic microgrids in Mozambique. Energies, 16(6), 2894.

Uzair, M., Yacoub Al-Kafrawi, S., Manaf Al-Janadi, K., & Abdulrahman Al-Bulushi, I. (2022). A low-cost IoT based buildings management system (BMS) using arduino mega 2560 and raspberry pi 4 for smart monitoring and automation. International Journal of Electrical and Computer Engineering Systems, 13(3), 219–236.

Wahba, D., Omran, A. A., Adly, A., Gad, A., Arman, H., & El-Bagoury, H. (2024). Optimizing site selection for construction: integrating GIS modeling, geophysical, geotechnical, and geomorphological data using the analytic hierarchy process. ISPRS International Journal of Geo-Information, 14(1), 3.

Xiong, Y., Liu, Q., Deng, M., & Niu, Z. (2021). Remote monitoring system design of power substation based on GPRS. Journal of Physics: Conference Series, 2108(1), 12031.

Zambrano-Asanza, S., Quiros-Tortos, J., & Franco, J. F. (2021). Optimal site selection for photovoltaic power plants using a GIS-based multi-criteria decision making and spatial overlay with electric load. Renewable and Sustainable Energy Reviews, 143, 110853.