



Examining Essential Requirements for a Smart Grid Evaluation Framework Tailored for low Resource Settings

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ARTICLE INFO	ABSTRACT
Published Online: 16 October 2026	Significant research has been done regarding frameworks for evaluation of smart grids in a bid to assess their efficiency, reliability, and impact. However, the frameworks are mainly targeting developed grids, adapting these frameworks to low-resource settings present significant challenges due to limited infrastructure, constrained budgets, inadequate technical expertise, regulatory gaps, and unreliable power supply. Albeit the automation of the said evaluation frameworks has also not been given enough attention. This study employs a combined User-Centered Design (UCD) and Quality Function Deployment (QFD) approach to examine in detail and identify, prioritize, and translate user requirements into technical specifications for designing an automated tailor-made smart evaluation framework tailored for resource-constrained environments. A mixed-method research design, including literature reviews, interviews, and surveys, was used to gather responses from smart grid users in Uganda and Kenya. According to the findings ease of integration scored (15.2%), localization scored (15.0%), and environmental adaptability returned (14.2%) and these turned out to be the most important technical requirements. This meant that there is need for automated smart grid evaluation frameworks that seamlessly integrate into existing grid and at the same time adapt to the local contexts. Additionally, modularity scored 9.2%, offline capabilities returned 8.8%, and resource efficiency scored 8.4%. Users emphasized these requirements to ensure ease of growth and resilience in environments with poor connectivity and power stability. User requirements such as reliable data acquisition, resilience to intermittent internet connectivity, power outage readiness, and big data management were notably preferred. The study further indicated that the users focus was mainly on energy efficiency metrics, resource conservation, and grid infrastructure robustness. On the other hand, regulatory compliance was recognized but rather ranked lower in importance. This study provides a data-driven foundation for developing automated scalable, adaptive, and locally relevant smart grid evaluation frameworks for low-resource settings, ensuring sustainability, accessibility, and operational resilience. Future work in this series will look at development of a prototype, its validation, and real-world implementation to enhance the practical impact of these findings.
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I. INTRODUCTION

The rapid proliferation of smart grids has ushered in a new era of energy management and efficiency [1] [2] [3]. However, the successful implementation of these advanced systems necessitates robust evaluation frameworks to assess their performance and impact [2]. While existing frameworks have proven valuable in high-resource settings, their applicability to low-resource environments, prevalent in developing countries, remains a subject of ongoing debate [3], [4], [5].

This paper identifies the critical user requirements for a tailored evaluation framework that can effectively assess the performance and impact of smart grid initiatives in resource-constrained contexts. By focusing on the unique socioeconomic, technological, and infrastructural challenges faced by developing nations, this study aims to identify and prioritize the essential requirements for such a framework. Through our analysis, we present valuable insights into the key requirements for a smart grid evaluation framework

tailored to low-resource environments, paving the way for more effective and equitable deployment of these advanced and automated energy systems. To achieve this, we employ a comprehensive methodology combining User-Centered Design (UCD) and Quality Function Deployment (QFD). UCD ensures that the framework is aligned with the specific needs and preferences of users in low-resource settings. QFD facilitates the translation of these requirements into technical specifications, ensuring maximum value and satisfaction. The paper is structured as follows: Section I– Introduction, Section II– Background and Literature review, Section III– Methodology, Section IV– Presentation of Results, Section V Discussion of Results, Section VI– Conclusion, Section VII– References.

II. BACKGROUND AND LITERATURE REVIEW

A. SMART GRIDS IN LOW-RESOURCE SETTINGS

Smart grid systems enhance the traditional electricity grid by integrating digital communication, sensors, and automation to optimize energy distribution and management [6]. In low-resource settings, smart grids can help address energy access issues by improving the efficiency and reliability of electricity distribution [7]. Some implementations in these environments include microgrids, smart meters, and renewable energy integration, allowing for better load management and real-time monitoring. [7].

B. Challenges

Infrastructure Limitations: Many low resource settings lack the physical infrastructure necessary to deploy smart grids. Existing grids may be outdated or unable to support modern technologies like smart meters or advanced sensors [8].

High Costs: Smart grid technologies, including sensors, communication systems, and control infrastructure, are often expensive to implement, which poses a significant challenge in low-resource environments with limited funding [9].

Technical Expertise: The successful implementation and maintenance of smart grids requires skilled personnel, which may be in short supply in low-resource settings [10].

Regulatory and Policy Issues: In many cases, there is a lack of clear policies and regulatory frameworks to guide the implementation and scaling of smart grids. This can delay adoption or lead to misaligned development priorities [8].

Unreliable Power Supply: In low-resource regions, power outages and grid instability are common. This complicates the deployment of smart grids, as they are based on continuous electricity and data flows [11].

C. Existing Evaluation Frameworks

A number of researchers have attempted to develop evaluation frameworks, albeit not suitable for low resource settings [4], as demonstrated in the analysis illustrated in Table 1

D. USER-CENTERED DESIGN (UCD)

User-Centered Design (UCD) is an iterative design process focused on placing the needs, preferences, and limitations of end

users at the forefront of every stage of the design and development lifecycle [12]. UCD principles prioritize understanding the users through research, direct engagement, and continuous feedback, ensuring that the final product aligns closely with their expectations and requirements [12]. By involving key low resource smart grid stakeholders early through interviews, and questionnaires—UCD helped to ensure that the collected requirements are the actual requirements needed for the design of a smart grid evaluation framework that is intuitive, accessible, and effective for the targeted low resource environments [13]. This approach not only enhanced prospects for user satisfaction and adoption rates but shall also minimize costly redesigns and errors [4]. In a resource constrained digital landscape, UCD is crucial in creating solutions that are practical, user-friendly, and aligned with the real needs, making targeted evaluation frameworks more effective in addressing the problems they intend to solve [14].

E. Quality Function Deployment (QFD)

Quality Function Deployment (QFD) is a structured methodology that helps software developers translate user needs and desires into specific, measurable design requirements [15]. This study employed QFD because of its capabilities to help systematically capture user requirements and prioritize them to guide the creation of a smart grid framework that meets or exceed user expectations in low resource settings. The core tool of QFD is the House of Quality, a matrix that links customer requirements to technical design characteristics, ensuring that design decisions are directly aligned with what the intended framework users’ value most [16] QFD was also adopted in the study to help reduce the gap between what users expect and what shall be delivered by fostering clear communication between different stakeholders—such as engineers, electricity consumers, and the team from the electricity regulatory authority. Ultimately, QFD proved to be an essential tool in ensuring that requirements for a user-centric smart grid framework are collected with the right ingredients for the low resource settings and also optimized for performance, quality, and usability [17].

III. METHODOLOGY

The study utilized a variety of data collection methods to capture comprehensive user requirements for a smart grid framework. Key methods included surveys, discussions with subject matter experts, observational studies, document analysis, behavioral studies, task-based studies, and in-depth interviews. The survey questionnaire featured both open- and closed-ended questions, divided into four sections addressing technological, regulatory, environmental, and stakeholder considerations—central to the study’s conceptual framework. Pre-tested by ERA field experts, the survey was refined for clarity, structure, and relevance, ensuring it addressed all critical indicators. Observational studies and document analysis (including operational reports and maintenance logs) validated self-reported data, enabling cross-referencing with objective data for deeper insights. Behavioral and task-based studies provided an objective view of user needs

by observing interactions with smart grid technology, capturing pain points that may not emerge in survey responses. Additionally, in-depth interviews with subsets of users at ERA, KPLC, and UETCL

Butambala districts of Uganda while the power utility providers included UETCL, KPLC and KETRACO. The policy makers were represented by ERA of Uganda. The choice of the two East African countries was justified by the

Table 1: Existing Evaluation Frameworks

No.	Framework	Description – Function	Limitation
1.	Smart Grid Maturity Model (SGMM) [18] , [19] [20], [21] [22]	Helps utilities understand their current	- Assumes a base level of infrastructure and financial resources. - Assumes technological readiness - It is complex
2.	European Smart Grid Architecture Model (SGAM) [22], [23], [24]	Used for standardization and interoperability assessment	- Assumes that grid operators have access to advanced communication networks and power systems - Emphasizes interoperability and standardization, presupposes a sophisticated technology
3.	Analytical Hierarchy Process (AHP)-Based Framework [25] [26] [27] [28] [29]	It is widely used for resource allocation in smart grid projects.	- AHP relies on extensive data to compare different criteria. - The framework heavily depends on expert judgment to assign weights to criteria. - The methodology can be resource-intensive in terms of time and expertise.
4.	Multi-Criteria Decision-Making (MCDM) Framework [30] [28] [5]	It is designed to help utilities prioritize projects based on a balanced consideration of these factors	- MCDM requires access to extensive data and expertise to weigh different criteria. - The framework may struggle to adapt to smaller, decentralized energy systems such as micro grids. in low resource settings. - MCDM frameworks often prioritize projects that require significant initial investments.

offered nuanced insights and allowed for discussion of personal topics, further reducing social desirability bias in responses. This multifaceted approach yielded a robust dataset covering both explicit and latent user needs.

A. STUDY SITES

The study was conducted in Uganda and Kenya, from January 2023 to March 2024 with 200 respondents categorized as electricity consumers, power utility providers and policy makers. The consumers were sampled from Wakiso and

practical, economic, and technological realities in both countries, making them representative of the broader category of low-resource settings in the context of smart grid requirements. In terms of Energy Access and Electrification Rates, both Uganda (42%) and Kenya (75%) have significant populations lacking access to reliable electricity according to the International Energy Agency (IEA) and World Bank reports. Uganda generates around 98% of its electricity from renewable resources. With about 90% of its energy from renewables—geothermal, wind, and solar—Kenya serves as a model for how renewable energy integration can support

resilience in low-resource settings. Both nations have initiated policies to support energy transitions and access. Kenya has one of the most progressive renewable energy policies in Sub-Saharan Africa, with programs fostering private investment in geothermal, solar, and wind energy. Uganda, while less diversified, is actively exploring the use of solar PV systems, particularly for rural electrification. These ongoing initiatives highlight the necessity of a smart grid evaluation framework that can optimize renewable resources, balance supply-demand issues, and potentially offer scalable solutions adaptable across similar low-resource settings.

Wakiso district was selected for its unique mix of Urban (1,681,449) and rural (315,969) population distributions with an overall 22.5% access to electricity. The research also needed a significant blend in of typical rural representation hence the incorporation of Butambala district in the study with 15,553 urban population and 85,287 rural population recording 18.9% access to electricity in the 2014 national census. Selection of this category of respondents was done on the basis of Socio-economic status, access to technology, geographical location, and energy needs in a bid to address the smart grid evaluation requirements of low resource settings.

The choice of UETCL, KPLC and KETRACO was particularly made to enhance the study by grounding it in practical experience, addressing real-world constraints, and ensuring that the requirements gathered for the intended smart grid evaluation framework are viable, sustainable, and transferable to other low-resource settings. These utilities play a core role in national grid operations and transmission, have experience with renewable Integration and Infrastructure Limitations, are significantly involved in the national and regional Smart Grid Initiatives, exhibit Policy Alignment and Regional Relevance. The trio possess deep expertise in the regulatory and technical standards required for safe and efficient grid operation.

The Ugandan Electricity regulatory authority (ERA) was included so as to offer invaluable insights into regulatory, economic, and policy considerations, enhancing the practical relevance and sustainability of the requirements of the smart grid evaluation framework within Uganda and other similar low-resource settings. ERA's qualities of; regulatory oversight and policy influence, experience with renewable and distributed energy policies, alignment with National Electrification and Access Goals, knowledge of consumer Protection and Pricing Models and above all its regional impact and Policy transferability Therefore, the findings from Uganda and Kenya shall be potentially generalized to other low resource settings, making this study applicable for broader smart grid development efforts in Sub Saharan Africa and similar low resource settings regions globally.

B. SAMPLING

Purposive sampling ensured diverse regional representation for the study [31], gathering insights from electricity sector practitioners and consumers in Uganda and Kenya to

determine key requirements for a smart grid evaluation framework in low resource settings.

C. CASE STUDY

Case study methods were chosen to explore stakeholders' perspectives, employing a mixed methods approach to comprehensively examine the topic [32], [33].

D. QUALITATIVE AND QUANTITATIVE TECHNIQUES

Quantitative aspects adhered to a predefined theoretical framework, while qualitative components delved into expert perspectives, providing deeper insights. Integrating both methodologies offered a holistic examination of smart grid evaluation phenomena.

E. THE USER CENTERED DESIGN APPROACH

This study employed the principles of User Centered Design (UCD) to ensure that the developed smart grid evaluation framework meets the specific needs of users in low-resource settings. UCD is an iterative design process that involves end users throughout the development lifecycle. This approach is particularly appropriate for environments like Uganda and Kenya, where local socio-economic and infrastructural conditions can significantly impact the feasibility of smart grid implementations. The design is structured into three primary stages: User Research, Persona Development and Requirements Gathering. These stages, conducted in collaboration with stakeholders in Uganda and Kenya, ensure that the framework is both relevant and actionable for local contexts.

1) USER RESEARCH

The first step in applying UCD was to conduct user research to gain a deep understanding of the needs, challenges, and expectations of users in low-resource settings. The goal was to capture insights that were to inform the framework's design requirements. The following techniques were used.

- **Interviews**

Semi-structured interviews were conducted with various stakeholders, including local energy consumers, utility providers, policymakers, and community leaders in Uganda and Kenya. These discussions were aimed at identifying the specific energy challenges these groups face, including affordability, reliability, and sustainability of power sources.

- **Field Observations:**

Fieldwork was conducted in rural and urban communities to observe existing power consumption patterns and assess infrastructure limitations. This data provided insights into the environmental and technical constraints influencing smart grid deployment.

- **Surveys:**

A comprehensive survey was administered to a broader group of users across both countries to quantify their expectations and priorities regarding smart grid solutions.

2) DATA COLLECTION:

Data from the user research activities were systematically recorded and analyzed to identify recurring themes and critical issues. These findings informed the next stage, where personas and user needs were developed.

3) PERSONA DEVELOPMENT:

Based on the insights gained from user research, personas were developed to represent the key user groups. Personas are fictional yet data-driven representations of typical users, helping to keep collection of the real user needs in focus.

4) PROCESS OF PERSONA CREATION:

Personas were created by clustering users into segments based on factors including socio-economic status, access to technology, geographical location, and energy needs. The personas used in this study included:

- **Rural Energy Consumer:**
Typically, reliant on non-renewable sources like firewood or kerosene, with irregular access to electricity. Key challenges include affordability and the desire for reliable energy for household and agricultural needs.
- **Urban Business Owner:**
Dependent on electricity for business operations but faces frequent outages. Concerned with cost-efficiency and consistent energy supply to ensure business continuity.
- **Local Utility Provider:**
Focused on maintaining grid stability but constrained by inadequate infrastructure and limited resources

Each persona included detailed descriptions of goals, frustrations, and the technological literacy of the user, providing a foundation for understanding how they would interact with a smart grid system.

5) GATHERING USER REQUIREMENTS:

After developing personas, the next step was translating user needs into requirements for the smart grid evaluation framework. This step involved prioritizing the needs identified during user research using the Quality Function Deployment (QFD) methodology to ensure the final design was rooted in user priorities.

F. Quality Function Deployment

Quality Function Deployment (QFD) was used to translate smart grid user needs and requirements into specific technical solutions. By prioritizing features and functionalities. The following steps were followed.

i. Gathering User Requirements (What's)

The first step involved collecting detailed user needs from stakeholders in Uganda and Kenya, these included local utility companies, government agencies, and end-users. This process was conducted through surveys and interviews, leveraging the principles of User-Centered Design (UCD). The key user requirements included:

- **Affordability:** Keeping costs low to ensure accessibility for consumers.
- **Reliability:** Ensuring consistent energy supply, especially in rural areas.

- **Scalability:** The ability to expand the grid as demand grows.
- **Adaptability to Renewable Energy:** Integration with solar, wind, or other renewable energy sources.

ii. Prioritizing User Requirements

Each identified user need was then assigned an importance weight based on feedback from stakeholders. This weight represented the relative importance of each need and ensured that the most critical requirements were given priority.

- **Affordability** emerged with a weight of 85 percent, reflecting its critical importance in low-resource settings.
- **Reliability** returned a weight of 75 percent, indicating a slightly lower but still significant priority.

iii. Calculating Weighted Scores

To prioritize the technical requirements, the Relative Importance Weight (RIW) of each user requirement was multiplied by the corresponding correlation score in the HoQ matrix. This generated a weighted score for each technical requirement. The formula below was used;

$$C_{ij} = RIW_i \times R_{ij} \quad (1)$$

Where;

- C_{ij} = The weighted score between user requirement i and technical design characteristic j
- RIW_i = The Relative Importance Weight of User Requirement i.
- R_{ij} = The Correlation strength between user need i and technical requirement j

iv. Mapping User Needs to Technical Requirements (HoQ Matrix)

Once the user needs and technical requirements were identified, they were plotted in a House of Quality (HoQ) matrix. In this matrix:

- a) The **User Needs** (affordability, reliability, scalability, etc.) were listed along the rows.
- b) The **Technical Requirements** (energy storage, monitoring, load balancing, etc.) were listed across the columns. For each intersection in the matrix, a correlation score was assigned to quantify how well a particular technical solution satisfied specific user need. For example:

- c) **Cost-Efficient Energy Storage** had a strong correlation (score of 9) with affordability but a weaker correlation (score of 3) with scalability.

v. Summing the Weighted Scores for Prioritization

After calculating the weighted scores for all technical requirements, they were summed to determine the overall priority of each technical solution. The formula was:

$$P_j = \sum_{i=1}^n C_{ij} \dots\dots\dots(2)$$

Where P_j is the total priority score for the jth technical requirement.

This prioritization helped ensure that the technical requirements with the highest scores are the ones most critical to satisfying user needs. That is if the total score for Cost-Efficient Energy Storage is the highest, it becomes the top priority for implementation.

IV. DISCUSSION OF RESULTS

Out of 180 questionnaires sent out to the different categories of respondents (consumers, power utilities and policy makers) in Uganda and Kenya, 162 responses were usable, accounting for 90% response rate. The unused responses missed required parts of information for data analysis. The questionnaire items were measured on a five-point likert-type scale with possible levels of agreement as Strongly Agree (SA) = 5, Agree (A) = 4, Neutral (N) = 3, Disagree (D) = 2, and Strongly Disagree (SD) = 1.

TABLE II: A Summary of the Sites Selected

		Frequency	PCT	Valid	CUM
Valid	Uganda	106	58,9	60.9	60.9
	Kenya	68	37.8	31.9	100
	Total	174	96.7	100	
Missing	System	6	3.3		
Total		180	100		

Focus group interviews followed the survey to gather deeper insights, especially from subject matter experts. Open-ended questions from the questionnaire guided discussions, which involved staff from the regulator (ERA) and Uganda Electricity Transmission Company Ltd (UETCL). Proceedings were recorded with participants' consent, alongside notes taken during discussions. Descriptive statistics (means, standard deviation and frequencies) was used to analyse the questionnaire items using SPSS. The 31 questionnaire items relating to the technological, environmental, regulatory, stakeholder engagement and limited resources requirements presented a high level of reliability with a Cronbach alpha coefficient of 0.849. DeVellis (2016) indicates that a Cronbach alpha coefficient greater than or equal to 0.8 provides a good measure of internal consistency of items in the scale. The results of the study undertaken are presented and discussed in four steps namely; Categorization and Overview of Identified Requirements, Application of the House of Quality (HoQ) in Prioritizing Requirements, Contextual Findings for Low-Resource Settings and Stakeholder Insights and UCD Contributions;

A. Categorization and Overview of Identified Requirements

The study identifies five critical requirement categories for evaluating smart grids in low-resource settings: technological, regulatory, environmental stakeholder engagement, and resource constraints. Using a User-Centered Design (UCD) approach, insights were gathered from 180 stakeholders, including utility companies, regulatory bodies, and end-users in Uganda and Kenya.

a) Technological Infrastructure

Under the Technological Infrastructure category of user requirements, reliable data acquisition emerged with the highest priority as 69% of respondents responding strongly agree, followed by readiness for intermittent internet connectivity with 57%. Provision for big data management and analytics collected a preference of 55%, while the requirement for interoperability had a preference rating of 53%. Readiness for power outages had 51%. Refer to figure 1. These findings indicate that **reliable data acquisition** is the most critical technological and infrastructure related requirement for smart grid evaluation software in low-resource settings, highlighting the need for accurate and continuous data collection despite infrastructure challenges. The strong emphasis on **intermittent connectivity readiness** underscores the importance of systems that remain functional even with unstable networks. Additionally, the demand for **big data management and interoperability** reflects the need for scalable solutions that can integrate diverse data sources. The preference for **power outage resilience** further stresses the necessity for robust systems that can operate despite electricity instability. Overall, smart grid evaluation frameworks for constrained economies must be **adaptive, resilient**, and capable of ensuring **seamless data flow** and **system integration** in insufficient infrastructure provisions.

b) Environmental Requirements Category

A significant number of respondents (38%) emphasized the requirement for including a metrics to assess the energy efficiency. 29% of the respondents demanded for a provision to evaluate the robustness of the grid infrastructure given its key contribution to the environment in which the smart grid implementations operate. Making provision for metrics to assess resource conservation returned 26% of the respondents with a strongly agree response. 24% of the respondents were kin on the inclusion of a requirement to measure the integration of renewable energy resources. On the other hand, 57% of the respondents were not sure on whether it is a key requirement to quantify the reduction in greenhouse gas emissions. The findings suggest that **energy efficiency assessment** is the most critical environmental requirement for smart grid evaluation, reflecting the need for optimizing energy use in resource-constrained settings. The **robustness of grid infrastructure** is also a key concern, emphasizing its role in maintaining system stability and environmental sustainability. Additionally, **resource conservation metrics** and **renewable energy integration measurement** highlight the growing interest in sustainable energy practices. However, the high uncertainty regarding the importance of **quantifying greenhouse gas reductions** suggests a potential gap in awareness or prioritization of direct environmental impact assessments. These insights indicate that while energy efficiency and grid resilience are clear priorities, further awareness and policy emphasis may be needed to highlight the significance of emission reductions in smart grid evaluations in low resource settings.

c) Regulatory Requirements Category

66% of the respondents gave a “Strongly Agree” response to the requirement to Assess the extent to which smart grid projects comply with regulatory standards while a significant number (62%) had a preference to include a requirement to Assess the effectiveness of regulatory measures in promoting trust in smart grid systems. Assessment of the effectiveness of regulatory measures attracted the attention of 31% of the respondents. Assessing the impact of regulatory policies on electricity market returned mixed feelings with 22% strongly agree, 24% agree and 28% Not sure. The findings indicate that **regulatory compliance** is the top priority, emphasizing the need for smart grid evaluation frameworks to align with established standards. Similarly, **trust in regulatory measures** is a major concern, highlighting the importance of effective governance in fostering confidence in smart grid systems. While the mixed responses on evaluating regulatory policies' impact on the electricity market suggest uncertainty or varying perspectives on how policies influence market dynamics. These insights underscore the need for robust regulatory assessments to ensure compliance, build trust, and clarify policy impacts on the electricity sectors of growing economies.

d) Stakeholders Requirements Category

89% of the respondents indicated emphasis (Strongly Agree) on the provision for a multi lingual feature as a key stakeholder requirement. 83% demanded that the automated smart grid evaluation framework should include a provision for stakeholder feedback. 78% of the respondents needed the system to be simple and easy to use while 70 % emphasized the need for adapting evaluation methodologies to local context. 50% demanded for a provision to carry out stakeholder mapping. On the other hand, the requirement to provide for organizing for online community meetings returned a very low emphasis response of only 9% strongly agree, 13% agree, 38 % not sure and 39% disagree. The findings indicate that the strong demand for a multilingual feature reflects the need to accommodate diverse linguistic backgrounds, ensuring broader usability in communities with varying literacy levels. The emphasis on stakeholder feedback highlights the necessity for participatory decision-making, particularly where regulatory frameworks may be weak or underdeveloped. The preference for simplicity and ease of use and local context adaptation indicates the importance of designing smart grid evaluation tools that are intuitive and adaptable to resource-constrained environments with limited technical expertise. While stakeholder mapping is moderately prioritized, the low interest in online community meetings suggests that internet access and digital literacy barriers may limit virtual engagement, making direct, in-person interactions more effective. These findings emphasize the need for practical, accessible, and locally relevant evaluation frameworks that prioritize direct stakeholder input while minimizing

technological dependencies when it comes to low resource environments. Indeed, in low-resource settings, stakeholder inclusivity and accessibility are critical for effective automated smart grid evaluation frameworks.

B. Quantifying and Prioritizing User Needs

By using QFD, we translated user needs into quantifiable, prioritized technical requirements that align with the unique demands of low-resource settings which in turn shall guide framework development to address the most critical areas. To systematically prioritize the requirements for a smart grid evaluation framework using Quality Function Deployment (QFD), the process was executed in five steps including; Definition of customer requirements and assigning of ratings, Definition of the relationship matrix, calculation of the importance weight, normalization of the importance weights and interpretation of results.

Step1: Definition of User Requirements and Assigning of Ratings

Survey data was collected on the four main categories of requirements namely; technical infrastructure, environmental, regulatory and stakeholder requirement categories. The user centered design (UCD) approach played a central role as demonstrated in section A above. The respondents assigned to each item under those categories an importance rating on a scale of 1 to 5 (5 being the most important). Figure 2 shows the tabulated results. This step kick started the process of translating the user requirements into technical requirements using the QFD approach. The user requirements formed the WHAT's in the QFD language.

Step2: Definition of the Relationship Matrix

The team of experts from ERA, UETCL, KPLC and KETRACO through focus group discussions, zeroed on the key technical design characteristics to be; User friendly, resource efficiency, offline capabilities, a localized product, affordability, accessibility features, modular architecture, customizability, security and ease of integration. Each user requirement was then related to the technical design characteristics with varying degrees of influence which we rated on a scale of; 1= Weak, 3 = moderate and 9=Strong. Figure 3 shows the resulting relationship matrix.

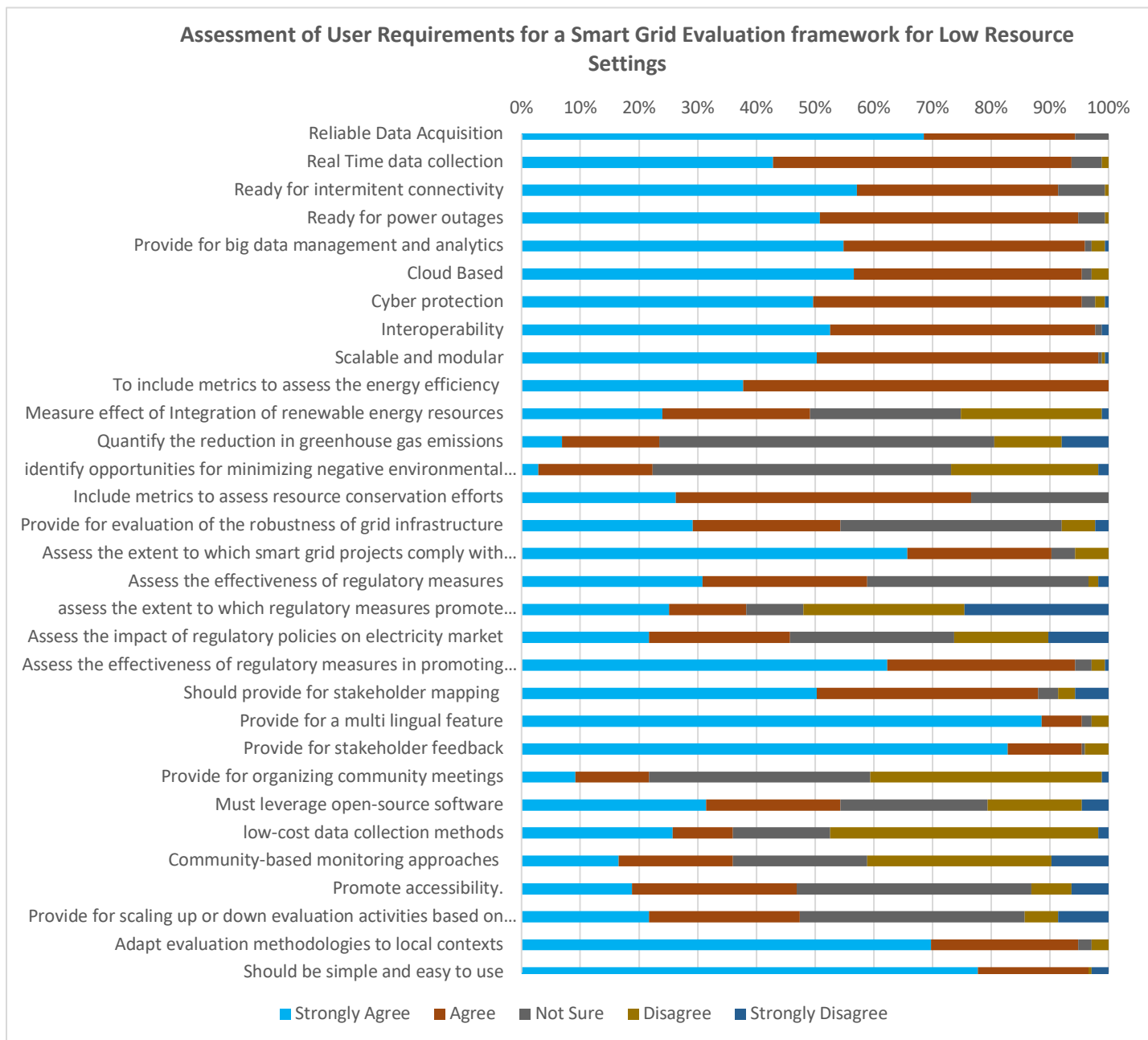


Fig 1: Assessment of User requirements using the UCD

WHAT User Requirements	Category	Importance
Reliable Data Acquisition	Technological Infrastructure	5
Real Time data collection		4
Ready for intermittent connectivity		5
Ready for power outages		5
Provide for big data management and analytics		4
Cloud Based		5
Cyber protection		5
Interoperability		4
Scalable and modular		4
To include metrics to assess the energy efficiency	Environmental	4
Measure effect of integration of renewable energy resources		4
Quantify the reduction in greenhouse gas emissions		5
Identify opportunities for minimizing negative environmental impacts.		4
Include metrics to assess resource conservation efforts		4
Provide for evaluation of the robustness of grid infrastructure	Regulatory	5
Assess the extent to which smart grid projects comply with regulatory standards		5
Assess the effectiveness of regulatory measures		4
Assess the extent to which regulatory measures promote consumer awareness.		5
Assess the impact of regulatory policies on electricity market		5
Assess the effectiveness of regulatory measures in promoting trust in smart grid	Stakeholder	5
Should provide for stakeholder mapping		5
Provide for a multi lingual feature		4
Provide for stakeholder feedback		5
Provide for organizing community meetings		5
Must leverage open-source software		4
Low-cost data collection methods		5
Community-based monitoring approaches		5
Promote accessibility		5
Provide for scaling up or down evaluation activities based on available resources		5
Adapt evaluation methodologies to local contexts		5
Should be simple and easy to use		5
		138

Fig 2: Ratings as assigned to User Requirements

Step 4: Normalizing the Importance Weights

To understand each technical design characteristic relative importance, the weights were normalized by dividing each weight by the total sum of weights. From the calculation of weights above, the summary of the technical design characteristics and their importance weights stands as follows (by applying equation 1) and 2));

Table III: Technical Design Characteristics Importance Weights

No.	Technical Design characteristic	Total Weight
1.	User Friendly	467.39
2.	Resource efficiency	495.65
3.	Offline capabilities	519.56
4.	Localized	886.95
5.	Affordability	360.86
6.	Accessibility Features	591.30
7.	Modular Architecture	543.47
8.	Customizable	839.13
9.	Security	315.21
10.	Ease of integration	900.00
Total Sum of Weights		5919.90

WHAT User Requirements	Category	Technical Design Characteristics											
		Importance	PCT	User friendly	Resource efficiency	Offline Capabilities	Localized	Affordable	accessibility features	Modular Architecture	Customizable	Secure	Ease of integration
Reliable Data Acquisition	Technological Infrastructure	5	3.62319	9	9	9	9	5	5	5	5	3	9
Real Time data collection		4	2.89855	9	3	9	9	5	5	5	5	3	9
Ready for intermittent connectivity		5	3.62319	3	9	9	9	5	5	5	5	5	9
Ready for power outages		5	3.62319	9	3	9	9	9	5	5	5	5	9
Provide for big data management and analytics		4	2.89855	3	9	9	9	5	5	5	5	9	9
Cloud Based		3	2.17391	9	9	3	3	3	5	5	5	9	9
Cyber protection		5	3.62319	3	3	5	9	5	5	5	5	5	9
Interoperability		4	2.89855	3	9	9	9	5	5	5	5	9	9
Scalable and modular		4	2.89855	3	9	3	9	3	5	5	5	9	9
To include metrics to assess the energy efficiency	Environmental	4	2.89855	3	3	5	9	0	5	5	5	0	9
Measure effect of integration of renewable energy resources		4	2.89855	3	3	5	9	0	5	5	5	0	9
Quantify the reduction in greenhouse gas emissions		5	3.62319	0	3	0	9	0	3	3	5	0	9
Identify opportunities for minimizing negative environmental impacts.		4	2.89855	0	0	0	9	0	3	3	5	0	9
Include metrics to assess resource conservation efforts		4	2.89855	0	3	0	9	0	3	3	5	0	9
Provide for evaluation of the robustness of grid infrastructure	Regulatory	5	3.62319	3	3	3	9	0	3	3	5	0	9
Assess the extent to which smart grid projects comply with regulatory standards		5	3.62319	3	0	3	9	0	3	3	5	0	9
Assess the effectiveness of regulatory measures		5	3.62319	3	0	5	9	0	3	3	5	0	9
Assess the extent to which regulatory measures promote consumer awareness.		4	2.89855	3	3	5	9	0	3	3	5	0	9
Assess the impact of regulatory policies on electricity market		5	3.62319	0	0	3	9	0	3	3	5	3	9
Assess the effectiveness of regulatory measures in promoting trust in smart grid systems	Stakeholder	5	3.62319	3	0	5	9	0	3	3	5	3	9
Should provide for stakeholder mapping		3	2.17391	0	3	3	9	3	3	3	5	0	9
Provide for a multi lingual feature		5	3.62319	9	9	3	9	3	9	9	9	3	9
Provide for stakeholder feedback		4	2.89855	3	3	3	9	3	5	5	5	3	9
Provide for organizing community meetings		3	2.17391	9	9	3	9	3	5	5	5	3	9
Must leverage open-source software		4	2.89855	9	9	3	9	9	9	9	9	3	9
Low-cost data collection methods		5	3.62319	3	9	9	9	9	9	9	9	3	9
Community-based monitoring approaches		5	3.62319	3	9	9	9	9	9	9	9	3	9
Promote accessibility		5	3.62319	9	9	9	9	9	9	9	9	3	9
Provide for scaling up or down evaluation activities based on available resources		5	3.62319	9	3	9	9	9	9	9	9	3	9
Adapt evaluation methodologies to local contexts		5	3.62319	9	3	9	9	9	9	9	9	3	9
Should be simple and easy to use		5	3.62319	9	9	9	9	9	9	9	9	3	9
		138	100	467.391	495.652	519.565	886.957	360.87	591.304	543.478	839.13	315.217	900

Fig 3: The Relationship Matrix

Normalized Importance Weights

The formula below calculates the relationship between each technical design characteristic based on their weighted priorities, correlations, and importance ratings [11]. It was used to normalize the importance weights.

$$R_{ij} = \frac{\sum_{k=1}^n WP_k \times C_{ki} \times IR_{kj}}{\sum_{k=1}^n WP_k} \times 100 \quad (3)$$

a) **User Friendliness**

$$\frac{467.39}{5919.5} \times 100 \\ = 7.9\%$$

b) **Resource Efficiency**

$$\frac{495.65}{5919.5} \times 100 \\ = 8.4\%$$

c) **Offline capabilities**

$$\frac{519.57}{5919.5} \times 100 \\ = 8.8\%$$

d) **Localized**

$$\frac{886.96}{5919.5} \times 100 \\ = 15.0\%$$

e) **Affordability**

$$\frac{360.87}{5919.5} \times 100 \\ = 6.1\%$$

f) **Modular**

$$\frac{543.48}{5919.5} \times 100 \\ = 9.2\%$$

g) **Environmental adaptability**

$$\frac{839.13}{5919.5} \times 100 \\ = 14.2\%$$

h) **Security**

$$\frac{315.22}{5919.5} \times 100 \\ = 5.3\%$$

i) **Ease of Integration**

$$\frac{900.0}{5919.5} \times 100 \\ = 15.2\%$$

j) **Accessibility Features**

$$\frac{591.3}{5919.5} \times 100 \\ = 10.0\%$$

Step 5: Analysis of Results

By combining UCD and QFD, the study ensured that the Smart Grid Evaluation Framework Software user requirements are not only user-driven but also technically sound, scalable, and optimized for low-resource settings. This structured approach results in a highly usable, efficient, and impactful automated evaluation framework that aligns with both user expectations and the software engineering constraints.

The end results attained after critically examining the essential requirements for a smart grid evaluation framework tailored for low resource settings are discussed below;

1. Ease of Integration (15.2%) – Top Priority

The final results indicate a top priority score of 15.2%. This is attributed to the fact that in low-resource settings, existing infrastructure is often outdated, fragmented, or relies on multiple disconnected systems. Smart grid evaluation software must integrate seamlessly with legacy energy monitoring tools, diverse hardware, and government-mandated reporting systems [35]. On the other hand, developed countries often

have standardized grid infrastructure with well-established APIs and interfaces, reducing the burden of integration [36].

2. Localization (15.0%)

The results indicate that it is critical that software be adapted to local languages, regulatory frameworks, energy policies, and cultural expectations in developing economies. This is to ensure usability and compliance. Smart grid evaluation in regions like East Africa or South Asia needs to support multilingual interfaces and align with local power governance structures [8]. Unlike resource constrained economies, with developed regions, energy frameworks are often standardized at a national or continental level (e.g., EU energy policies), reducing the need for extensive localization [3].

3. Environmental Adaptability (14.2%)

This can be attributed to climate-related challenges such as extreme weather, power outages, and variable renewable energy supply that require software that can function effectively under unstable conditions. This includes resilience to high temperatures, humidity, and unreliable connectivity. This is not the case for developed countries which generally have stable environmental conditions and robust infrastructure, meaning environmental adaptability is less of a priority [6] [20].

4. Modular (9.2%)

Technically, modular software architecture allows systems to be customized based on available resources, regulatory changes, or evolving energy needs [37]. It ensures cost-effective upgrades without requiring a complete overhaul. This feature works well for resource constrained environments unlike developed nations which often have fully funded IT systems, allowing for comprehensive, large-scale software deployments without modular constraints.

5. Offline Capabilities (8.8%)

The results indicate that offline capabilities is a critical requirement because Internet access in low-resource settings is intermittent, slow, or expensive [38]. The smart grid evaluation framework must work offline with local data caching and sync when connectivity is available. On the contrary high-income countries have high-speed, stable internet infrastructure, reducing the need for offline functionality.

6. Resource Efficiency (8.4%)

This user requirement is also critical for automated smart grid frameworks destined to operate in struggling nations because the software needs to be lightweight, consume minimal processing power, require low bandwidth, and operate on basic hardware due to older computers or mobile devices [39]. On the other hand high-resource settings typically have abundant computational power and cloud infrastructure, making efficiency less critical.

7. Accessibility Features (10%)

Indeed, the requirement for accessibility in regions like East Africa is key due to diverse literacy levels, physical disabilities, and digital skill gaps. Features such as voice-guided navigation, simple interfaces, and visual enhancements

improve usability. In contrast, with developed regions digital literacy and accessibility compliance (e.g., WCAG standards) are more established in developed regions [14].

8. User-Friendliness (7.9%)

The results indicate a priority weight of 7.9% on this feature because in developing nations, systems should be intuitive and require minimal technical training, as many end-users may not have prior exposure to advanced digital tools [6]. This is not the case for our developed counterparts whose users are generally more tech-savvy, reducing the emphasis on extreme simplicity.

9. Affordability (6.1%)

Limited budgets mean the evaluation framework software should have low licensing costs, leverage open-source tools, and minimize hardware dependencies. This is a critical requirement in low resource settings. On the contrary developed markets have higher budgets for energy projects, making affordability less of a constraint [38].

10. Security (5.3%) – Lowest Priority

While security is an essential technical requirement, in low-resource settings, basic functionality and accessibility often take precedence over advanced cybersecurity measures. However, data protection and compliance should still be considered. Developed countries, on the other hand, place higher emphasis on cybersecurity due to strict regulations (e.g., GDPR, NIST) and increased risk of cyberattacks [28].

V. CONCLUSION

This study underscores the critical role of User-Centered Design (UCD) and Quality Function Deployment (QFD) in examining the essential requirements for a smart grid evaluation framework tailored for low resource settings. By systematically collecting user requirements through UCD and translating them into technical specifications using QFD, this study ensures that the resulting automated smart grid evaluation framework shall be both practical and effective in addressing the unique challenges of energy management in constrained environments. The findings reveal that ease of integration, localization, and environmental adaptability are the top priorities, reflecting the fragmented infrastructure, diverse regulatory landscapes, and unstable operational conditions prevalent in low-resource settings. Additionally, the need for modular design, offline capabilities, and resource efficiency highlights the necessity for a resilient, flexible, and cost-effective evaluation framework. While accessibility, affordability, and user-friendliness remain essential, security ranks lower, indicating that basic functionality and usability take precedence over advanced cybersecurity measures in these contexts. Comparing these priorities with those of developed regions highlights key differences: while high-income economies emphasize cybersecurity, cloud integration, and automation, low-resource settings demand robust, adaptable, and locally relevant solutions that can function with limited connectivity, infrastructure, and funding. This research provides a blueprint for developing a scalable, inclusive, and impact-driven automated smart grid evaluation solution, paving the way

for more effective and sustainable energy governance in emerging economies.

VI. RECOMMENDATIONS FOR FUTURE WORK

This study lays the foundation for adapting smart grid evaluation frameworks to low-resource settings. Future research should focus on real-world pilot testing of the proposed requirements to validate their effectiveness. Additionally, integrating emerging technologies such as AI and IoT could enhance grid reliability and efficiency. Further exploration is needed to optimize ease of integration, localization, environmental adaptability, modularity, offline capabilities, and resource efficiency within these frameworks. The next step is to design and implement a smart grid evaluation framework tailored to low-resource environments based on the identified requirements.

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Appendix I: The Complete House of Quality

No.	Questionnaire Option	QFD Notation	Rating	Symbol	Sign
1.	Strongly Agree	Very Strong	9	●	++
2.	Agree	Strong	3	○	+
3.	Not Sure	Weak	1	△	-
4.	Disagree	Negative impact	0	↓	-
5.	Strongly Disagree	Negative impact	0	↓	-