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A Quality-Driven Framework for Prioritizing Customer and Technical Requirements in Microgrid Battery Integration

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Abstract: ***This manuscript aims to evaluate key challenges related to customer expectations and technical competencies for the successful integration of batteries into microgrid systems. To perform that, there are Six distinct customer expectations and technical requirements were identified through a comprehensive literature review. The criteria weights were determined using the sine trigonometric Pythagorean fuzzy (STPYF) decision making Trial and Evaluation Laboratory (DEMATEL) approach. Additionally, the technical requirements were ranked using a novel method developed in this study, called the "Ranking Technique by Geometric Mean of Similarity Ratio to Optimal Solution" (RATGOS) , which was integrated with the STPYF framework. The study's main contribution lies in simplifying the prioritization process to enhance battery integration efficiency in microgrid systems. Moreover, the introduction of the RATGOS methodology adds a unique element to the decision-making landscape. The analysis revealed that energy storage efficiency is the most critical customer expectation, while the development of smart battery control systems was found to be top technical requirement for optimizing microgrid performance. Based on these findings, strategies must be implemented to improve energy storage efficiency in microgrid systems, emphasizing the selection of appropriate batteries and robust technological infrastructure. Ensuring cybersecurity is equally crucial for safeguarding energy storage processes against external threats, enabling safer battery operation.***

Key Word*: Optimal Battery Integration; Microgrid Systems; Customer Comfort level; Fuzzy Decision-making*

I. Introduction

Microgrids are localized systems aimed at improving the efficiency and performance of energy production, consumption, and distribution. In these systems, surplus energy is stored for future use, and participants who cannot produce sufficient energy have the option to purchase the excess. Furthermore, excess energy generated can be supplied to the main grid, while energy deficits in the microgrid can be supplemented from the main grid. This setup offers numerous advantages. Since renewable energy sources are often prioritized within the grid, microgrids significantly promote the use of clean energy. Additionally, they enhance the efficiency of energy production and consumption processes. Participants can generate their own energy, which helps reduce reliance on external energy sources. Lastly, microgrids enable more effective management of energy demand (Mbungu et al., 2023).

Batteries play a crucial role in enhancing the efficiency of microgrid systems by expanding their energy storage capacity, which contributes to more effective system operation. Batteries store excess energy and release it based on consumption needs. Since climate conditions influence the amount of electricity generated, any surplus can be stored in batteries and easily accessed during periods of high demand. Batteries also provide a reliable backup in the event of power outages, ensuring a continuous energy supply from renewable sources (Memon and Kauhaniemi, 2023). However, for batteries to be successfully integrated into microgrid systems, several factors must be addressed. First, determining the appropriate battery capacity is essential, as it should align with the system's energy storage needs. Additionally, the system requires advanced technological infrastructure to optimize energy management. Proper safety measures must also be in place for batteries to function effectively. Lastly, ensuring spare battery capacity is available for unexpected demand spikes is critical for maintaining system reliability (Seger et al., 2023).

In summary, the successful integration of batteries into microgrid systems relies heavily on an accurate analysis of customer expectations, alongside the technical competencies required to meet them. Given the wide range of both expectations and technical demands, it may not be financially feasible to address every issue. Thus, focusing on the most critical factors is a more practical approach. While existing studies emphasize the importance of batteries, there is a lack of research on determining which factors should be prioritized (Neri et al., 2023). To bridge this gap, conducting a fresh analysis to identify key issues is essential. This will help develop strategies that improve the overall efficiency and effectiveness of the system.

This manuscript aims to evaluate key aspects of customer expectations and technical competencies for the successful integration of batteries into microgrid systems. The central research question focuses on determining which factors should be prioritized to develop investment strategies for the optimal integration of batteries. The proposed methodology combines the House of Quality (HoQ) approach with Multi-Criteria Decision Making (MCDM) models. In this study, six distinct customer expectations and technical requirements are identified based on a thorough literature review. These criteria are weighted using the sine trigonometric STPYF DEMATEL method, while technical requirements are ranked with a newly developed technique, RATGOS, which is also integrated with STPYF sets.

The motivation behind this research is the need for a comprehensive evaluation to ensure the effective integration of batteries in microgrid systems. Decision-making models are critical in this context, but existing models need to address key criticisms for success. Specifically, uncertainty should be reduced effectively during this process. While triangular fuzzy numbers are commonly used to handle uncertainty, they only offer a lower bound, upper bound, and mode value, which may be insufficient in some cases. Moreover, current models often rely on VIKOR and TOPSIS techniques to rank alternatives, but several stages of their analysis processes have been subject to criticism. Therefore, the new model should either enhance these techniques or introduce a new one altogether to improve the decision-making process.

The main contribution of this study lies in identifying the most critical strategies for battery integration in microgrid systems through the development of a novel model. The proposed model offers several key advantages, as outlined below:

- One of the key methodological innovations of this study is the creation of a new ranking-based decision-making technique, RATGOS. Existing ranking methods, such as TOPSIS, have been criticized for their reliance on Euclidean distance to calculate optimal values. Scholars have argued that this approach may not provide effective results, especially when determining the distance to the negative ideal solution (Nandi et al, 2024; Ali et al, 2024). Similarly, the VIKOR method only considers the distance to the positive ideal solution, ignoring the negative ideal, which has drawn criticism in many studies (Mahmudah et al., 2024; Yu et al., 2024). To address these shortcomings, RATGOS incorporates the geometric mean to improve the ranking process (Arman et al., 2022; Çelikbilek and Tüysüz, 2020).
- The inclusion of a sine trigonometric structure provides additional advantages. This approach accounts for periodicity and, because of its symmetry with respect to the origin, produces more accurate results compared to previous models. The ST operator also enhances the defuzzification process, making it more precise, which is a significant benefit for minimizing uncertainty when applying fuzzy decision-making techniques (Ashraf et al., 2021). These characteristics make the ST operator a preferred choice in this study (Moslem, 2024; Yuan, 2024).
- Incorporating the House of Quality (HoQ) approach in defining criteria and alternative sets contributes to the development of more effective strategies. By aligning customer expectations with the necessary technical competencies, and factoring in feedback, customer satisfaction is more achievable. This, in turn, leads to more accurate policies that can improve the efficiency of microgrid systems (Dinçer et al., 2021). The second section gives the literature review results. The methodology is explained in the third section. Analysis results are provided in the fourth section. The last section consists of discussion and conclusion. The flow of the article is summarized in Figure 1.

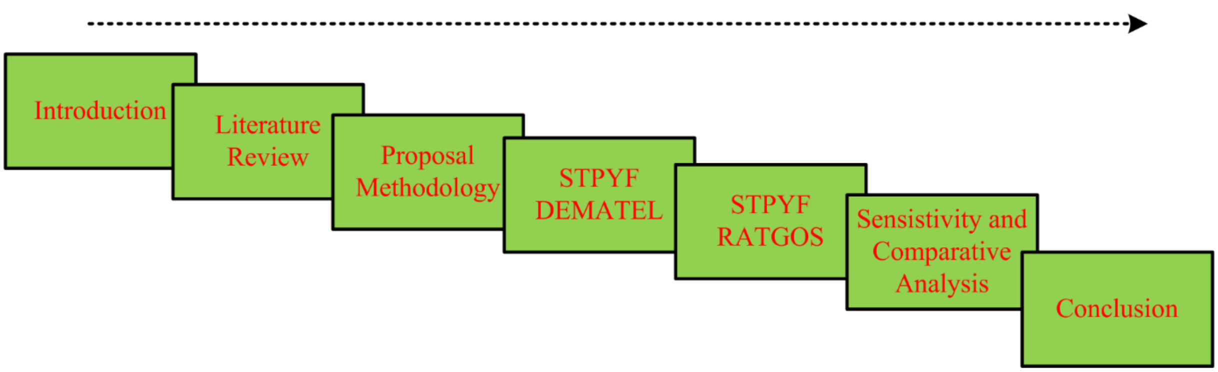

Figure 1: The block diagram summarizing the article

II Literature Review

Advanced technological infrastructure plays a critical role in ensuring effective battery integration within microgrids, which encompass energy production, storage, and consumption (Zarate-Perez et al., 2022). Due to the inherent complexity of microgrids, advanced technology becomes indispensable (Shufian and Mohammad, 2022). With sufficient technological infrastructure, not only is higher-quality energy storage achievable, but faster solutions can also be developed for any system issues. Bovo et al. (2023) explored hydrogen energy storage in microgrids, concluding that advanced technology is crucial for their efficient operation. Lei et al. (2023) reviewed microgrid reliability, further highlighting the importance of technology. Youssef et al. (2023) also emphasized the need for technological infrastructure to enhance microgrid networks. Balaji et al. (2023) argued that technology is a key factor in boosting microgrid efficiency.

A key factor influencing battery integration in microgrids is the cost of batteries, which directly impacts the financial viability of microgrid projects. Beyond just the cost, factors such as battery performance, lifespan, efficiency, and integration must also be considered (Gamil et al., 2022). Abdelghany et al. (2023) highlighted that battery costs are crucial for the long-term sustainability of microgrids. Rahman et al. (2023) developed a model to evaluate energy storage costs, emphasizing the significance of battery costs in the overall energy storage equation. In their study on optimal microgrid planning to reduce carbon emissions, Masaud and Nwaulu (2023) noted that batteries represent a major cost factor in microgrids. Additionally, Siddique et al. (2023) and Lipu et al. (2022) stressed the importance of considering battery costs for optimal energy planning and risk analysis in microgrids.

The efficiency of energy distribution is another crucial factor for the success of microgrids, as it directly impacts their performance, sustainability, and economic viability (Masrur et al., 2022). Efficient energy distribution helps minimize losses, and it becomes even more essential due to the seasonal variations in renewable energy sources commonly used in microgrids (Choudhury, 2022). As such, energy distribution is a key component of these systems. Behrendt (2023) conducted research on aligning microgrids with European Union regulations, highlighting their potential to significantly contribute to the clean energy transition. Grisales-Noreña et al. (2023) focused on optimizing microgrid energy operating costs, emphasizing the critical role of energy distribution efficiency. Similarly, Deowen et al. (2023) explored the optimal design of microgrids for rural areas, concluding that efficient energy distribution is vital for the success of these systems.

Accurate calculation of energy supply and demand is critical to the success of microgrids. Maintaining a balance between supply and demand helps prevent potential power outages (Roccotelli et al., 2022). Renewable energy production in microgrids can fluctuate with the seasons, making it even more essential to ensure this balance to avoid disruptions in energy consumption (Kama et al., 2022). Consequently, balancing energy supply and demand becomes a key consideration during the battery integration process in microgrids (Adak et al., 2022). Yang et al. (2023) explored ways to improve the supply-demand matching in microgrids, highlighting its importance for system efficiency. Rodrigues and Garcia (2023), in their review of microgrid networks, also emphasized that balancing supply and demand is vital for the sustainability of these systems. Similarly, Van et al. (2023) underscored the importance of this balance, while Shezan et al. (2023) pointed outthat energy demand cannot be met solely through traditional methods, making the balance between supply and demand essential for microgrids.

The literature review yields the following conclusions: (i) Microgrids offer several advantages, including improved energy security, economic benefits, and enhanced efficiency. (ii) Various factors influence the success of microgrids. (iii) It is often not feasible to address all factors affecting microgrid success simultaneously, making it necessary to prioritize these factors based on their importance. (iv) There are, however, relatively few studies in the literature that focus on this aspect. Thegoal ofthis study is to identify the key strategies for enhancing microgrid efficiency, thereby addressing the gap in the existing literature with the proposed model.

III Proposal Methodology

In this section of the study, the models utilized are presented. The DEMATEL method is applied to assess the importance levels of the criteria, while the RATGOS method is employed to rank the alternatives. Both methods incorporate sine trigonometric Pythagorean fuzzy numbers (STPYFs).

STPYF-DEMATEL

The DEMATEL method is a multi-criteria decision-making (MCDM) tool that considers the causal relationships between criteria while determining their relative importance. It assumes that the criteria i fluence each other, and the importance weights are calculated based on these effects, using pairwise comparisons as the foundation of the approach (Sun et al., 2022). Sine trigonometric Pythagorean fuzzy numbers (STPYFs) are a type of fuzzy set that incorporate linguistic uncertainty into the analysis through a nonlinear structure. When integrated with DEMATEL, STPYFs account for uncertainty, allowing for more realistic calculation of the criteria's weights. Initially, expert judgments are gathered and converted into STPYFs using the values provided in Table 1.

Table 1: Linguistic Variables

Linguistic Term	**Score**	**PYFs**		**STPYFs**	
		μ	**v**	***μ***	**v**
[illegible]	1	.16	.84	.2334	.5136
Low (L)	2	.24	.76	.3827	.3716
Moderately Low (ML)	3	.34	.66	.5225	.2651
Medium (M)	4	.4	.46	.7071	.1187
Moderately High (MH)	5	.66	.34	.8526	.0702
High (H)	6	.74	.26	.9239	.0353
Very High (VH)	7	.87	.13	.9724	.0126

With calculating the average of the *k* experts' opinions, sine trigonometric Pythagorean fuzzy initial matrix (*A*) is formed as in Equation (1). In this framework, μ is the membership value while v shows the non-membership value. Equation (2) is used to calculate the arithmetic mean.

$$A = \begin{bmatrix} (0,0) & \cdots & \left(\sin\left(\frac{\pi}{2}\mu_{1n}\right), \sqrt{1-\sin^2\left(\frac{\pi}{2}\sqrt{1-v_{1n}^2}\right)}\right) \\ \vdots & \ddots & \vdots \\ \left(\sin\left(\frac{\pi}{2}\mu_{n1}\right), \sqrt{1-\sin^2\left(\frac{\pi}{2}\sqrt{1-v_{n1}^2}\right)}\right) & \cdots & (0,0) \end{bmatrix} \quad (1)$$

$$STPFWA = \left(\sqrt{1-\prod_{i=1}^{n}\left(1-\sin^2\left(\frac{\pi}{2}\mu_i\right)\right)^{1/k}}, \prod_{i=1}^{n}\left(\sqrt{1-\sin^2\left(\frac{\pi}{2}\sqrt{1-v_i^2}\right)}\right)^{1/k}\right) \quad (2)$$

Equation (3) is considered to compute defuzzified values.

$$S(\sin p) = \sin^2\left(\frac{\pi}{2}\mu_p\right) - \left(\sqrt{1-\sin^2\left(\frac{\pi}{2}\sqrt{1-v_p^2}\right)}\right)^2 \quad (3)$$

Then, by Equations (4) and (5), a normalized direct-relation matrix (*X*) is created.

$$X = s.A \quad (4)$$

$$s = \min\left(\frac{1}{\sum_{i=1}^{n} a_{ij}}, \frac{1}{\sum_{j=1}^{n} a_{ij}}\right) \quad (5)$$

In the other step, total relation matrix (*T*) is constructed using Equation (6).

$$T = X * (I - X)^{-1} \quad (6)$$

Then, the row (R) and column (D) sums of this matrix are obtained with Equations (7) and (8).

$$R_j = \sum_{i=1}^{n} t_{ij} \quad (7)$$

$$D_i = \sum_{j=1}^{n} t_{ij} \quad (8)$$

With the help of row and column totals, weights (w) are calculated by Equation (9).

$$w_i = \frac{\sqrt{(R_i + D_i)^2 + (R_i - D_i)^2}}{\sum_{i=1}^{n}\sqrt{(R_i + D_i)^2 + (R_i - D_i)^2}} \quad (9)$$

STPYF-RATGOS

The RATGOS is a multi-criteria decision-making (MCDM) method designed to identify ideal alternative by considering specific criteria. Its foundation lies in the similarity ratio of alternatives to optimal values (Arman et al., 2022; Çelikbilek and Tüysüz, 2020). As traditional ranking methods based on distance metrics have been criticized in the literature, methods that focus on similarity ratios are proposed. RATGOS calculates the similarity ratio of each alternative to the optimal value for each criterion. Given that linguistic terms are used in evaluating alternatives, STPYF numbers are integrated into the method to account for uncertainty in the analysis. The steps of the method enhanced by STPYF numbers begin with gathering expert evaluations, as shown in Table 1. Equation (2) is then used to calculate the average of expert opinions, leading to the construction of the fuzzy decision matrix (B), illustrated by Equation (10).

$$B = \begin{bmatrix} \left(\sin\left(\frac{\pi}{2}\mu_{11}\right), \sqrt{1-\sin^2\left(\frac{\pi}{2}\sqrt{1-v_{11}^2}\right)}\right) & \cdots & \left(\sin\left(\frac{\pi}{2}\mu_{1n}\right), \sqrt{1-\sin^2\left(\frac{\pi}{2}\sqrt{1-v_{1n}^2}\right)}\right) \\ \vdots & \ddots & \vdots \\ \left(\sin\left(\frac{\pi}{2}\mu_{m1}\right), \sqrt{1-\sin^2\left(\frac{\pi}{2}\sqrt{1-v_{m1}^2}\right)}\right) & \cdots & \left(\sin\left(\frac{\pi}{2}\mu_{mn}\right), \sqrt{1-\sin^2\left(\frac{\pi}{2}\sqrt{1-v_{mn}^2}\right)}\right) \end{bmatrix} \quad (10)$$

Equation (3) is used to compute defuzzified all values of B matrix. Equations (11) and (12) denote optimal values for each criterion in matrix B.

$$optimal = \max b_i \quad for\ benefit\ criteria \quad (11)$$

$$optimal = \max \frac{1}{b_i} \quad for\ cost\ criteria \quad (12)$$

Equations (13) and (14) are used to defined the similarity ratio (N).

$$N = \frac{B}{optimal} \quad for\ benefit\ criteria \quad (13)$$

$$N = \frac{optimal}{B} \quad for\ cost\ criteria \quad (14)$$

Equation (15) is considered to construct weighted normalization matrix (Z).

$$Z = wN \quad (15)$$

Geometric mean (G) is used to calculate average similarity ratio as in Equation (16).

$$G_i = \sqrt{\prod_{i=1}^{n}(1 + z_{ij})} - 1 \quad (16)$$

IV Analysis Results

In this section, the results of the proposed model are provided in the following subtitles.

Defining the Customer Expectations and Technical Requirements for Battery Integration to Microgrids

Based on the results of the literature review, six main customer expectations are selected for battery integration to microgrids as shown in Table 2.

Table 2: Customer Requirements for Battery Integration to Microgrids

[illegible]	[illegible]
[illegible]	(Zarate-Perez et al., 2022)
Efficiency of storing energy (STGY)	(Shufian and Mohammad, 2022)
[illegible]	(Gamil et al., 2022)
Low-cost battery solutions (LWTT)	(Lipu et al., 2022)
[illegible]	(Masrur et al., 2022)
Flexibility in microgrid investments (FBXT)	(Choudhury, 2022)

To enhance the performance of battery integration into microgrids, thorough analysis of the energy supply and demand balance is essential. Additionally, efficient implementation of energy storage is crucial to achieving this goal. Effective energy distribution also plays a pivotal role in this process. Battery costs should be considered a flexible factor, and minimizing carbon emissions is critical. Moreover, microgrids need to be adaptable to accommodate technological advancements. Table 3 further outlines five key technical improvements for integrating batteries into microgrids.

Table 3: Technical Requirements for Battery Integration to Microgrids

[illegible]	[illegible]
[illegible]	(Lipu et al., 2022)
Long-lasting battery selection (LLBT)	Roccotelli et al., 2022)
Smart battery control systems (STBC)	(Masrur et al., 2022)
Compatibility with safety constructions (CSCR)	(Kama et al, 2022)
Modular system designing (MDGG)	(Masaud and Nwaulu, 2023)
[illegible]	(Youssef et al., 2023)

Microgrids must have adequate storage capacity to enhance the performance of battery integration. Additionally, the batteries should be durable to ensure cost-effectiveness. Smart battery control systems can further improve the efficiency of energy production and distribution. Moreover, necessary safety measures must be in place to support performance improvements in the system. The design should also be modular, with stable grid loads and a reliable response to maintain system stability.

Weighting Customer Expectations for Battery Integration to Microgrids

Evaluations are based on seven different scales provided by three decision-makers. The first expert is a general manager at an international renewable energy company. The other two experts are academicians who conduct significant research on microgrid systems, battery types, energy storage effectiveness, and carbon emissions. Table 4 shows the evaluations concerning customer expectations for integrating batteries into microgrids.

Table 4: Expert Evaluations related to the Customer Expectations

Expert opinions are averaged using Equation (2). Next, the matrix is defuzzified according to Equation (3). The normalized direct-relation matrix is then derived using Equations (4) and (5). Following this, the T matrix is computed with Equation (6). Weights are determined using Equations (7) through (9). The results are presented in Table 5.

Table 5: Weights

	D	R			
	.3228	.8415	1.1643	.5187	.1449
STGY	1.5065	.5108	2.0173	-.9957	.2557
PTMS	1.1604	.5262	1.6866	-.6342	.2048
LWTT	.3249	.7211	1.0460	.3962	.1271
FTPG	.2808	.7306	1.0115	.4498	.1258
FBXT	.4758	.7411	1.2169	.2652	.1416

The efficiency of energy storage is identified as the key issue, given its highest weight of 0.2557. Additionally, optimizing the energy distribution process is also crucial, with a weight of 0.2048. In comparison, low-cost battery solutions and footprint reduction in energy management are less significant than the other factors.

Ranking Technical Requirements for Battery Integration to Microgrids

The evaluations for the technical requirements are also provided from the experts. The evaluations are generated based on 7 different scales. Table 6 explains the details of these evaluations.

Table 6: Expert Evaluations related to the Technical Requirements

Expert opinions are converted into STPYFs and the average value is computed by Equation (2). Then, the matrix is defuzzified by Equation (3). Equation (11) is considered to determine the optimal values. Then, N matrix is obtained with Equation (13). Using the weights in Table 5, the Z matrix is obtained with the help of Equation (15). The result is denoted in Table 7.

Alternatives are ranked using Equation (16), where the highest G value indicates the most significant alternative. Table 8 reveals that smart battery control systems are the most crucial for improving battery integration into microgrids. Storage capacity is also a key issue, while long-lasting battery selection and safety compatibility rank lower.

Table 7: Z Matrix

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Sensitivity Analysis

A sensitivity analysis is conducted to validate the results for ranking technical requirements for battery integration into microgrids. This analysis involves calculating weights for ten different scenarios obtained through simulation. The findings from the study serve as the input for the simulation modeling, which generates new weights used to rank the alternatives. By considering various weights, the process ensures the coherence of the findings. The alternatives are then re-ranked based on these weights, and the results are compared. The sensitivity analysis is detailed in Table 8, and the results confirm the rankings derived from the SFPFY RATGOS analysis.

Table 8: Results of Sensitivity Analysis with Simulation Modeling

	Sim_1	Sim_2	Sim_3	Sim_4	Sim_5	Sim_6	Sim_7	Sim_8	Sim_9	Sim_10
SCPC	2	2	2	2	2	2	2	2	2	2
LLBT	5	5	5	5	5	5	5	5	5	5
STBC	1	1	1	1	1	1	1	1	1	1
CSCR	6	6	6	6	6	6	6	6	6	6
MDGG	4	4	4	4	4	4	4	4	4	4
SBYL	3	3	3	3	3	3	3	3	3	3

Comparative Analysis using STPYF TOPSIS

The result of ranking of technical requirements for battery integration to microgrids is compared with a second ranking algorithm to demonstrate the robustness of the ranking results. The results of the RATGOS method are compared with the STPYF-TOPSIS method to demonstrate the reliability of the findings. The main results are denoted in Table 9.

Table 9: Result of Two Analysis

	[illegible]	[illegible]
[illegible]	.1305	.852
STGY	.0422	.019
PTMS	.1657	1.00
LWTT	.0273	.004
FTPG	.0445	.046
FBXT	.0467	[illegible]

According to the results of the two methods used to rank the alternatives, the ranking is depicted in Figure 2.

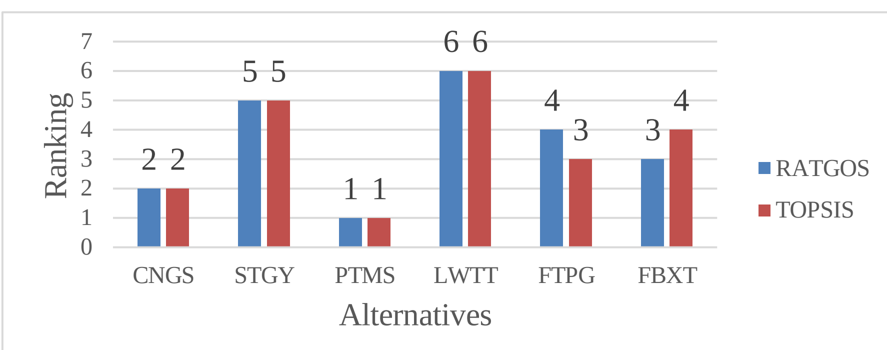

Figure 2: Ranking Results of Alternatives

Figure 2 identifies that the findings are similar for RATGOS and TOPSIS. It is concluded that the proposed model generate coherent solutions.

V Conclusion

This study evaluates the significance of microgrids and the role of battery integration in meeting customer and technical requirements using the House of Quality (HoQ). Six customer expectations and technical requirements were identified through a literature review and weighted using STPYF DEMATEL. Technical requirements were ranked using STPYF RATGOS. The study finds that energy storage efficiency is the top customer expectation, while smart battery control systems are the most critical technical requirement for improving microgrid performance. Smart battery control systems are essential for optimizing energy processes, enabling real-time data analysis, and improving energy storage efficiency. These systems enhance battery management by providing accurate charging and discharging information and detecting issues early. Information security is crucial to protect against cyber-attacks that could disrupt energy production or manipulate system data. The study's main contribution is its prioritization analysis for improving battery integration in microgrids and the introduction of the RATGOS ranking technique, which adds methodological originality. However, the study does not consider country-specific evaluations, which could impact performance due to varying climatic conditions. Future research should explore country-specific performance, improve the model by incorporating varying expert qualifications, and evaluate emerging battery technologies or optimization techniques.

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