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Evaluating Technology Attributes of Grid-Size Electricity Energy Storage for Palawan: A Multi-Criteria Analysis Study

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Abstract. This study evaluates key technological factors for grid-scale energy storage in Palawan, Philippines, to support renewable energy integration and enhance grid stability. Using the Analytic Hierarchy Process (AHP) and input from various stakeholder groups, we assessed technology attributes such as cost-effectiveness, safety, reliability, and storage capacity. Hydrogen Energy Storage (HES) emerged as the highest-rated technology, with a score of 0.28, followed by lithium-ion batteries at 0.24. This reflects broad support from both scientific communities and the general public. The initial stakeholder evaluation highlighted three key attributes: maintainability (0.094), energy efficiency (0.092), and geographic and climatic suitability (0.085), indicating a focus on practical, localized concerns. The study emphasizes that by combining technical viability with community values, we can develop practical and inclusive off-grid energy solutions. Insights from this comprehensive evaluation provide targeted pathways for policy design, including incentives, public outreach, and equitable financing schemes. Ultimately, aligning technological solutions with social preferences and technical standards can facilitate a just and sustainable energy transition in Palawan.

1 Introduction

1.1 Background and Objectives

Interest in grid-scale energy storage has grown significantly in recent years due to the increasing contributions of variable energy sources, such as wind and solar, to global electricity production [1]. This trend highlights the need for effective and reliable energy storage solutions to balance supply and demand, ensure grid stability, and optimize renewable energy sources [3]. However, the design and optimization of grid-size electricity energy storage systems require careful consideration of various technology attributes. These attributes, such as cost-effectiveness, operational reliability, safety, storage time, and capacity, play a crucial role in determining the suitability of energy storage technologies for grid-scale applications [4]. Given the large scale of stored energy,

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it is essential to prioritize cost-effectiveness, operational reliability, and safety in grid storage technologies [5].

According to research, electrochemical energy storage, specifically rechargeable batteries, has gained significant momentum recently as a promising grid-scale energy storage technology [6]. This is evidenced by the substantial increase in worldwide electrochemical storage projects, with an approximately tenfold growth from 58 to 692 projects between the beginning of this decade and 2016 [7]. This increase reflects the growing social awareness of the importance of electrochemical storage in meeting the evolving energy landscape and integrating renewable energy sources into the grid [8]. Electrochemical energy storage, such as Hydrogen Energy Storage (HES), offers several advantages that make it suitable for large-scale grid applications. Firstly, hydrogen energy storage provides flexibility regarding storage time and capacity, allowing it to meet the diverse requirements of different grid applications [9]. Additionally, it offers high energy conversion efficiency and simple maintenance, making it an attractive option for grid-scale electricity storage [10][11]. Given the significance of grid-scale electricity energy storage and the suitability of electrochemical energy storage for this purpose, it is crucial to understand how different technology attributes are perceived in terms of their importance [4]. This understanding guides the design and optimization of energy storage systems to ensure they are effective and reliable. To evaluate the importance of technology attributes for grid-size electricity energy storage, a multi-criteria analysis was conducted in this research. The multi-criteria analysis aimed to assess how respondents rate the importance of different technology attributes for grid-size electricity energy storage. This research aims to assess how respondents rate the importance of different technology attributes for grid-size electricity energy storage. By understanding the perceived importance of these attributes, this study can provide insights into designing and optimizing energy storage systems, leading to more effective and reliable solutions in integrating HES into the existing off-grid system of Palawan, Philippines. This study is significant as it addresses the need to evaluate the importance of technology attributes for grid-size electricity energy storage.

This evaluation is crucial because it will help identify the key factors to consider when designing and optimizing energy storage systems. Understanding the importance of different technology attributes will allow researchers and policymakers to make informed decisions regarding the implementation of electrochemical energy storage systems, such as HES, in the off-grid system of Palawan.

1.2 Literature Review

Existing literature highlights several criteria for adopting new energy technologies, particularly grid-scale energy storage. One consistently mentioned criterion is cost-effectiveness. For large-scale grid storage, cost is crucial because the technology must be affordable and provide a financially viable solution for storing electrical energy. Several studies have emphasized the importance of cost-effectiveness in grid-scale energy storage technologies [12]. For instance, a study by the United States Department of Energy found that reducing the cost of energy storage systems is critical for their widespread adoption and integration into the grid [13]. However, while cost-effectiveness is widely recognized as essential, there is a need for more nuanced region-specific analyses that consider local economic conditions and consumer willingness to pay—factors that can vary significantly across different geographic and socio-economic contexts.

Another essential criterion discussed in the literature is operational reliability. In grid-scale electricity storage, operational reliability ensures that the system operates smoothly and consistently without interruptions, which is particularly important for maintaining power grid stability [14]. Alongside reliability, safety also emerges as a crucial attribute for grid-scale electricity energy storage systems, given the large scale and potential risks associated with these technologies [15]. Despite extensive research on reliability and safety in industrialized regions, there is limited investigation into how these attributes are perceived and prioritized by stakeholders in more remote or island-based communities, where infrastructure limitations and environmental conditions may differ.

A further criterion addressed in existing studies is high-rate performance, which refers to the capability of an energy storage system to charge and discharge electricity at a high rate [16][12]. Additionally, energy density is often highlighted in literature, although it is considered less critical in grid-scale storage compared to portable electronic devices [11]. Nonetheless, current research tends to focus on technical metrics like high-rate performance and energy density without adequately exploring how different stakeholder groups—such as developers, policymakers, and residents—evaluate the trade-offs between performance and other factors like social acceptance, maintainability, and the potential for innovation.

The research article "Evaluating the Importance of Technology Attributes for Grid-Size Electricity Energy Storage: A Multi-Criteria Analysis" specifically examines how respondents rate the importance of these technology attributes for grid-scale electricity energy storage. By understanding the perceived importance of these attributes, the study can provide valuable insights into the design and optimization of energy storage systems for grid-scale applications, ultimately contributing to more effective and reliable energy storage solutions that support the integration of renewable energy sources into the power grid. Moreover, these findings offer guidance for policymakers, electric grid operators, and energy storage system designers in making informed decisions about technology selection and implementation, while highlighting areas for improvement in cost-effectiveness, operational reliability, and safety.

Several studies have investigated how respondents rate and evaluate energy technologies, including grid-scale electricity energy storage. For example, one study explored public attitudes toward different energy technologies, including batteries for grid-scale electricity storage, finding that cost-effectiveness, safety, and reliability were key factors influencing respondents' ratings. Another study examined electric utility professionals' preferences for various energy storage technologies, showing that cost, performance, operational flexibility, and integration with renewable energy sources were prioritized. Similarly, some research focusing on energy experts and policymakers demonstrated that cost, reliability, safety, and environmental impact were primary considerations for grid-scale electricity energy storage.

Despite these valuable contributions, several gaps persist in the literature. First, many existing studies do not adequately address the localized priorities and constraints of regions such as Palawan, where unique environmental conditions and infrastructure challenges can significantly influence technology adoption. Second, there is a lack of research that simultaneously examines both tangible attributes (e.g., cost, performance, safety) and more intangible factors.

2 Methodology

The methodology for this research involves surveying respondents from Puerto Princesa City and the Municipality of Narra in Palawan to gather their opinions and ratings on various technology attributes related to grid-size hydrogen energy storage. Respondents were selected using a random sampling technique to ensure the representativeness of the sample population. Stratified samples were collected to include diverse sectors and backgrounds, such as electric utility professionals, energy experts, policymakers, and residents.

The survey questionnaire included attributes such as Maintainability, Innovation potential, Energy efficiency, Land use, Geographic and climatic suitability, Compatibility with existing infrastructure, Resource availability, social acceptance, Reliability, Job creation, cost-effectiveness, Flexibility, Safety, Scalability, and Environmental Impact. Participants were asked to rate the importance of each attribute on a scale from one (1), as the least important, to five (5), as the most important.

This research utilized four perspectives to better understand the various stakeholder groups involved in the multi-actor decision-making process, based on the work of Elle, Dammann, Lentch, and Hanssen (2010). These perspectives are the Public Relations Frame (PRF), Scientific Frame (SF), Developers Frame (DF), and Layperson-Sensualistic Frame (LSF), as summarized in Table 1.

Table 1. The Four Technology Frames to be Adopted in Identifying the Stakeholders

	PRF	SF	DF	LSF
View of Environmental and Technical indicators for Hydrogen Production	A means to document government and industry users' environmental commitment	Quantitative scientific information	General information on what is the status of the current existing technology	An Incomprehensible expert tool but useful to identify what the general public knows about the technology
Typical Actors	Industry Users, Politicians, and Government Regulating Body	Researchers, Consultants, and Academe with Engineering Background	Developers and Suppliers of HES systems	Non-professional End-Users: Residential and Commercial
Goal	To obtain a favorable public image of the technology	(a) To sell scientific and technical experience. (b) To evaluate hydrogen production infrastructures scientifically and precisely (c) To ensure that efforts made lead to environmental and technical improvements	To avoid infrastructure design restrictions	To create a green identity and social coherence among the non-professional end-users and recognize critical view of mainstream society about the technology

After data collection, a unified Multi-Criteria Decision Analysis (MCDA) approach was implemented to analyze the responses obtained through four separate Excel questionnaires extracted from the Google form questionnaire. Specifically, Question (Q)1 instructs respondents to "Rate the importance of the following criteria in your decision-making process for adopting new energy technology for electricity generation and distribution, with one (1) as the least important and five (5) as the most important." Q2 asks them to "Please rate each of the following energy technologies based on their suitability for electricity generation and distribution in the Philippines, starting from one (1) as the least suitable to five (5) as the

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most suitable." Q3 prompts respondents to "Rate each of the following grid-size electricity storage technologies available in the Philippines in terms of their viability for integrating with new and existing energy sources, with one (1) as the least viable and five (5) as the most viable." Finally, Q4 states, "For each grid-size electricity storage option—Lithium-ion batteries, Hydrogen Energy Storage, Flow batteries, and Pumped Hydro Storage (PHS)—rate the importance of the following attributes in your decision-making process, with one (1) as the least important and five (5) as the most important."

Once the raw data were imported into Excel, they were standardized and converted from qualitative judgments into quantitative scores to ensure consistency across all responses. Descriptive statistics were computed to capture central tendency and dispersion measures, thereby providing quantitative and qualitative insights into the underlying data patterns. Normality tests, such as the Shapiro-Wilk test, were conducted to determine whether the data follow a normal distribution, guiding the selection of appropriate parametric or non-parametric analyses. Outlier detection using boxplots and reliability analysis via Cronbach's alpha were used to further confirm data integrity and internal consistency.

Subsequently, key criteria were identified by analyzing recurring themes across responses through Minitab's frequency analysis, cross-tabulation, and exploratory factor analysis. Normalization methods, such as min-max normalization or z-score transformation, were then used to align all scores on a standard scale, allowing for meaningful aggregation of the normalized weights from each questionnaire. These weights were combined, typically by averaging or weighted averaging, to produce a unified set of criteria weights. Advanced inferential analyses in Minitab, including correlation tests to evaluate relationships among criteria and regression tests to assess their influence on composite scores, were used to validate the weighting schemes. The normalized scores were then visualized using spider graphs, where each criterion was plotted on an individual axis to depict expert preferences and emphasize strengths across the four frames. Finally, sensitivity and robustness tests were carried out to ensure that the decision framework remains stable even under criteria-weight variations.

This comprehensive methodology effectively utilized Excel's data manipulation capabilities, the Analytic Hierarchy Process for prioritization, and Minitab's statistical rigor, providing a transparent and robust MCDA process that supports the study's findings on grid-size hydrogen energy storage in Palawan.

3 Data Discussion

3.1 Data Result Discussion for Q1 on Four Frame Actors

This study aimed to identify the most important criteria for assessing grid-scale electricity energy storage technologies in Palawan. Using a spider graph (Fig. 1), four stakeholder frames—PRF, SF, DF, and LSF—rated five attributes: reliability, safety, environmental impact, cost-effectiveness, and high-rate performance.

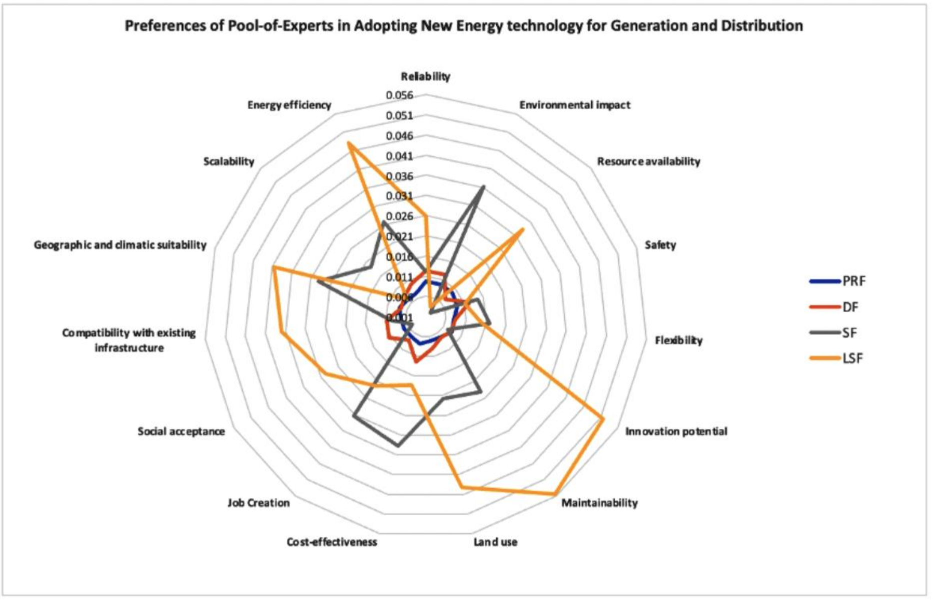

Fig 1. Spider diagram visualizes how four stakeholder frames rate the importance (from 1 as least important to 5 as most important) of various criteria—such as reliability, cost-effectiveness, and environmental impact—for adopting new energy technology for electricity generation and distribution

The results indicated that maintainability was the highest priority, scoring 0.094, followed by energy efficiency at 0.092 and Geographic and climatic suitability at 0.085. Safety scored 0.047, while scalability received the lowest score of 0.042, indicating that these two attributes were considered less critical. Among the stakeholder frames, the Layperson Sensualistic Frame (LSF) emphasized maintainability, innovation, and ease of use, reflecting community-level values. The Scientific Frame (SF) emphasizes environmental impact, cost-effectiveness, and job creation. It highlights the importance of addressing climate change, recovering costs, and contributing to economic and social development.

There was a significant agreement among the different perspectives about the importance of clearly communicating intentional design choices that are rooted in community values and cost-effectiveness. This common understanding emphasizes the practical needs that resonate with both experts and community members. These insights have been vital in shaping subsequent evaluations of energy storage technologies and their relevant attributes, guiding us toward solutions that align with community values as well as scientific requirements.

3.2 Data Result Discussion for Q2 on Four Frame Actors

The Q2 spider diagram (see Figure 2) illustrates how four stakeholder frames— PRF, SF, DF, and LSF —rate the suitability of various energy technologies (e.g., Solar, Wind, Geothermal, Hydroelectric, Biomass, Waste to Energy, Liquefied Natural Gas, Coal, Diesel, Bunker Fuel, Nuclear) for electricity generation and distribution in the Philippines. The ratings range from one (least suitable) to five (most suitable). These results directly inform the study.

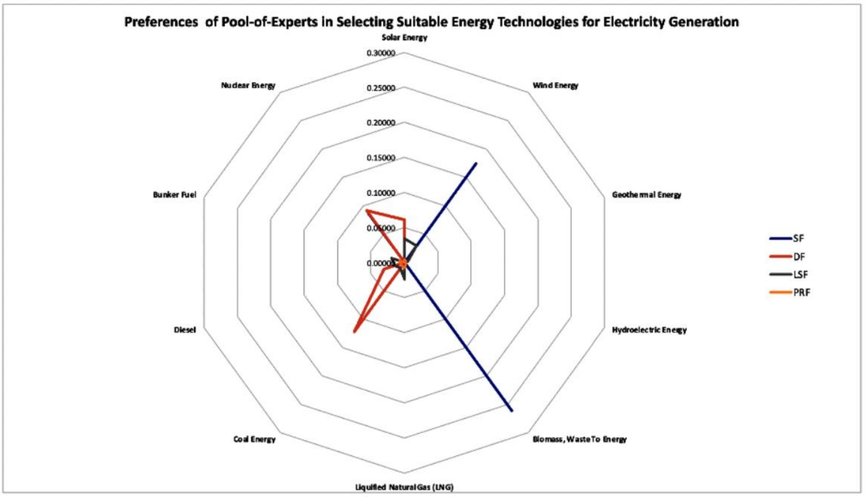

Fig 2. The spider diagram illustrates how the four stakeholder frames— PRF, SF, DF, and LSF —rate each energy technology's suitability for electricity generation and distribution in the Philippines on a scale of 1 (least suitable) to 5 (most suitable), allowing a clear visual comparison of their varying preferences.

Factor analysis from Q2 indicates that the Layperson-Sensualistic Frame (LSF) was the most consistent stakeholder group, consistently valuing ease of use, local relevance, and daily practicality. The Scientific Frame (SF) ranked second, highlighting the importance of environmental compliance, cost recovery, and socio-economic contribution. If preferences for the LSF prevail, future policies will likely favor user-friendly and inclusive technologies while still adhering to scientific standards.

The spider graph results also revealed higher suitability scores for renewable energy sources such as solar (0.30), wind (0.27), and geothermal (0.24) compared to traditional sources like coal and diesel. This aligns with the global shift towards low-emission systems but also emphasizes the importance of local acceptability.

Palawan could implement inclusive policies, such as tiered subsidies or community-based financing, to facilitate this transition and ensure that benefits reach lower-income groups. Providing clear technical guidelines and conducting public campaigns, particularly for hydrogen storage, can help ease adoption.

Overall, the alignment between the LSF and SF suggests that hydrogen energy storage has strong adoption potential in Palawan if it is framed as both socially accessible and scientifically sound. This balanced approach supports both equity and system reliability.

3.3 Data Result Discussion for Q3 on Four Frame Actors

Question (Q3) asks respondents to evaluate the viability of four grid-size electricity storage technologies, Hydrogen Energy Storage, Lithium-ion batteries, Flow batteries, and Pumped Hydro Storage (PHS), regarding their integration with new and existing energy sources in the Philippines. Each of the four stakeholder perspectives— PRF, SF, DF, and LSF —assigns a score from one (least viable) to five (most viable). This scoring reveals how each group perceives the practical integration of these storage options. The resulting spider diagram offers valuable insights into which technologies are viewed as more adaptable and acceptable in the context of Palawan, informing the study titled "Evaluating Technology Attributes of Grid-Size Electricity Energy Storage for Palawan: A Multi-Criteria Analysis."

According to the Q3 diagram (Fig. 3), Hydrogen Energy Storage received the highest viability score of 0.28, followed by lithium-ion batteries with a score of 0.24. This demonstrates strong support among stakeholders. In contrast, flow batteries and pumped hydro storage (PHS) scored lower, raising concerns about technical constraints, costs, or geographic suitability—particularly for systems like PHS that depend on specific terrain. These results emphasize a clear preference for scalable, flexible storage solutions that align with global clean energy trends.

For Palawan, this indicates that policymakers can develop targeted incentives such as subsidies, tax breaks, or public-private partnerships to support the deployment of hydrogen and lithium-ion technologies. Implementing appropriate safety regulations, performance standards, and robust community outreach is crucial, mainly focusing on the environmental and economic benefits. This approach can foster local trust and boost investor confidence.

These technologies must benefit wealthier individuals and middle—and lower-income groups. Without inclusive policies such as tiered tariffs and community-level financing, their implementation could inadvertently reinforce energy inequality. By promoting equitable access, Palawan can facilitate a just energy transition.

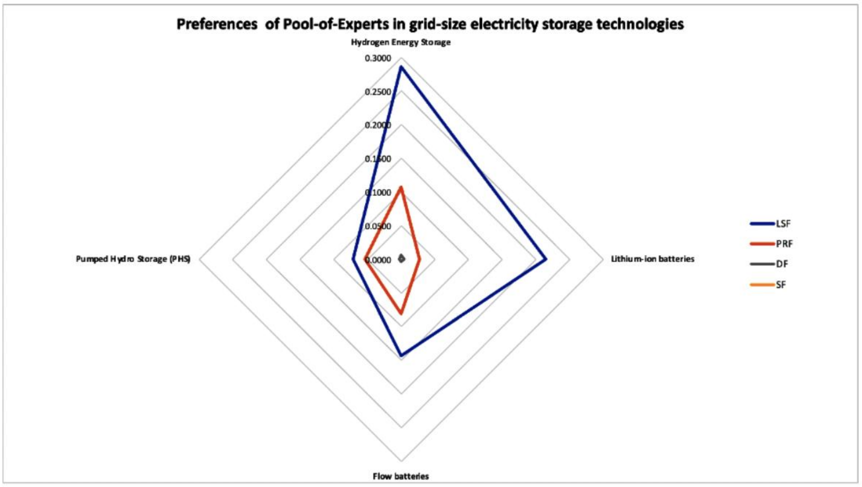

Fig 3. This spider diagram illustrates how the four stakeholder frames— PRF, SF, DF, and LSF— rate the viability of Hydrogen Energy Storage, Lithium-ion batteries, Flow batteries, and Pumped Hydro Storage (PHS) for integration with new and existing energy sources in the Philippines, on a scale from one (1) as the least viable to five (5) as the most viable, offering a clear visual comparison of each group's preferences.

Finally, the results are consistent with Q2's findings, where the Local Stakeholder Framework (LSF) prioritizes usability and public benefit, while the Scientific Framework (SF) emphasizes technical credibility. For hydrogen to be successful, it must meet the expectations of both frameworks: being publicly accessible yet scientifically valid. These insights are instrumental in guiding practical and balanced strategies, transforming hydrogen energy storage from an abstract concept into a locally accepted and viable option for Palawan.

3.4 Data Result Discussion for Q4 on Four Frame Actors

Question (Q)4 asks respondents to rate the importance of various attributes—such as regulatory compliance, operating costs, safety, environmental impact, and maintenance requirements—for each grid-size electricity storage option: Lithium-ion batteries, Hydrogen Energy Storage, Flow batteries, and Pumped Hydro Storage. The four stakeholder perspectives— PRF, SF, DF, and LSF —each assign scores on a scale from one (least important) to five (most important). This approach provides insight into which factors most strongly influence their decision-making. The resulting spider diagram supports the study "Evaluating Technology Attributes of Grid-Size Electricity Energy Storage for Palawan: A Multi-Criteria Analysis" by illustrating where different perspectives converge or diverge on key considerations.

The Q4 data reveals that key attributes such as regulatory compliance (0.1004), energy efficiency (0.08511), and operating cost (0.0885) received the highest ratings, indicating a strong agreement among stakeholder groups. In contrast, attributes like environmental impact (0.033) and Geographic and climatic suitability (0.0345) showed more variation, highlighting differing opinions on environment and location priorities.

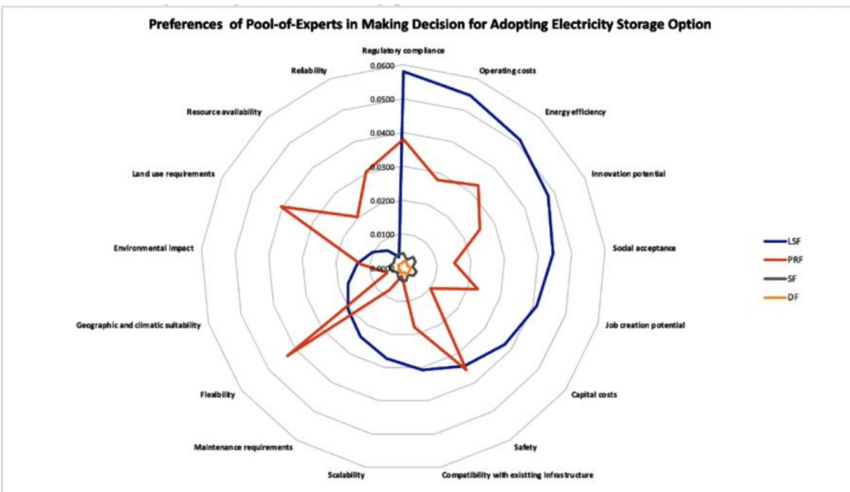

Fig 4. This spider diagram illustrates how four stakeholder frames— PRF, SF, DF, and LSF—rate the importance of various attributes (e.g., safety, operating costs, environmental impact) for each grid-size electricity storage option (Lithium-ion batteries, Hydrogen, Flow batteries, and PHS), on a scale from 1 (least important) to 5 (most important), providing a clear visual of where their priorities converge or diverge.

These results underscore the importance of technical reliability and public trust for the long-term success of energy storage solutions. To facilitate adoption, policymakers in Palawan can implement targeted incentives, establish safety regulations, and promote transparent cost-benefit communication. For instance, hydrogen energy storage could gain public support if it complies with defined performance standards while addressing local concerns about health, the environment, and costs.

Since high upfront costs may exclude lower-income communities, inclusive measures such as tiered subsidies, community-level financing, and equitable allocation of resources are necessary to ensure fair access. These initiatives can promote sustainable adoption without exacerbating energy inequality.

Like Q2, the Local Stakeholder Forum (LSF) remained the most influential group, followed by the Scientific Frame (SF). This dual focus on community acceptance and technical credibility indicates that hydrogen storage solutions must be usable and reliable. Overall, the Q4 findings highlight the necessity of a multidimensional approach compassing social, economic, environmental, and technical aspects—to guide inclusive and resilient energy strategies in Palawan.

4 Conclusion

The findings of this research indicate that we have successfully achieved our objectives, particularly in identifying and evaluating the critical technological factors for grid-sized electricity energy storage in Palawan. The results from Questions (Q1) to (Q4) each addressed different aspects of stakeholder priorities, providing a comprehensive understanding of key attributes—such as reliability, cost-effectiveness, safety, and environmental impact—that influence decision-making processes.

This study quantitatively captured and reconciled these diverse perspectives using an MCDA framework, supplemented by descriptive statistics, normalization techniques, and inferential methods in Excel and Minitab. This structured, data-driven approach effectively fulfilled the objective of evaluating technology attributes.

Q1 (Criteria Importance): The results indicated that maintainability was the top priority, followed by energy efficiency and geographic suitability. Safety was rated lower, while scalability received the lowest score. Stakeholder preferences varied depending on the framework: the Layperson Sensualistic Frame (LSF) prioritized maintainability and ease of use, whereas the Scientific Frame (SF) focused on environmental impact and cost-effectiveness. Despite these differences, there was consensus on the importance of intentional design that aligns with community values and is economically viable. These insights have guided the evaluation of energy storage technologies, highlighting both practical and scientific considerations.

Q2 (Suitability of Energy Technologies): Our findings reinforced the preference for cleaner, more socially accepted technologies and aligned with the global shift toward renewable sources. The LSF and SF emerged as the most influential perspectives, emphasizing that any future storage solution must balance practicality and technical rigor to meet Palawan's needs.

Q3 (Viability of Storage Technologies): We identified highly viable options for hydrogen energy storage and lithium-ion batteries. This supports our objective of exploring which technologies can be integrated into Palawan’s energy mix, guiding policymakers and developers toward specific solutions that balance cost, safety, and environmental considerations.

Q4 (Attribute Priorities for Each Storage Option): The findings underscore that regulatory compliance, energy efficiency, and operating costs are the top priorities for stakeholders, highlighting the importance of technical reliability, cost transparency, and public trust in energy storage adoption. Conversely, attributes like environmental impact and geographic suitability showed varying opinions, indicating differing views on ecological and locational factors. This suggests a need for a comprehensive strategy that balances social, economic, environmental, and technical aspects. The roles of the Local Stakeholder Forum (LSF) and Scientific Frame (SF) highlight the significance of community acceptance and scientific credibility. To promote equitable adoption—particularly in areas like Palawan—policymakers should consider inclusive measures such as tiered subsidies, community financing, and performance standards addressing local health and environmental concerns.

Overall, the results indicate that advanced energy storage solutions, particularly hydrogen energy storage, can be successfully adopted in Palawan if they are both community-friendly (addressing LSF preferences) and technically robust (meeting SF requirements). Middleclass and lower-income communities benefit from these technologies, provided that equitable policy measures—such as tiered subsidies and community-level financing—are introduced to prevent favoritism towards wealthier or well-connected groups. This outcome addresses our objective of understanding how technology attributes and stakeholder perspectives interact to facilitate a just and sustainable energy transition.

Implications for Future Technology Evaluation

This research illustrates how MCDA can be used to weigh multiple, often conflicting, criteria across diverse stakeholder perspectives. By systematically quantifying these preferences, MCDA provides a replicable framework for future evaluations of emerging energy technologies applicable in Palawan and other regions with similar socio-economic and infrastructural contexts. This quantitative grounding ensures that subsequent policy decisions, investment strategies, and community engagement efforts align with local conditions and broader sustainability goals.

Ultimately, the multi-criteria approach validated in this study confirms that deploying grid-sized electricity energy storage in Palawan can be strategically guided by understanding stakeholder values, technical feasibility, and equity considerations. By integrating these insights into planning and policy, Palawan can move toward a more resilient, inclusive, and renewable-based energy system.

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