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Optimizing Battery Ownership Strategies for B3 Waste Management in Off-Grid Solar PV Systems Using Fuzzy-AHP

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Abstract*— This study aims to determine the most appropriate battery ownership strategy for hazardous (B3) waste management in off-grid solar photovoltaic (PV) systems in archipelagic regions. The research employs a multi-criteria decision-making approach using the Fuzzy Analytical Hierarchy Process (Fuzzy-AHP) to accommodate uncertainty in expert judgment. Six evaluation criteria are considered, namely compliance with B3 waste regulations, capital expenditure (CAPEX), operational and maintenance costs (OPEX), availability of B3 temporary storage facilities and inactive asset warehouses (ATTB), availability of technical human resources and occupational safety competence (K3L), and occupational safety and health risks (K3). Three ownership alternatives are analyzed: full ownership, battery leasing (Battery as a Service), and a hybrid scheme combining ownership and service agreement. The results indicate that occupational safety and health risk (0.536) and availability of technical human resources and K3L competence (0.354) are the most influential criteria. Based on the global weighting, the battery leasing scheme achieves the highest priority among the alternatives. This finding suggests that service-based ownership models have the potential to better address operational constraints in remote and archipelagic areas. The study provides insights for decision-makers in selecting appropriate battery management strategies while considering regulatory, technical, economic, and safety aspects.

***Keywords*— Fuzzy-AHP; off-grid solar PV; battery ownership strategy**

I. Introduction

The The global commitment to achieving Net Zero Emissions (NZE) has accelerated the transition toward low-carbon energy systems. The Paris Agreement underscores the urgency of limiting global temperature rise to well below 2°C, while pursuing efforts to restrict it to 1.5°C [1]. In response, many countries, including Indonesia, have developed long-term strategies aimed at achieving carbon neutrality through energy sector transformation and the increased deployment of renewable energy technologies.

Among various renewable energy sources, solar photovoltaic (PV) technology has emerged as a key driver of decarbonization due to its rapid cost reduction and scalability. Over the past decade, the cost of solar PV has declined significantly, making it one of the most competitive electricity generation technologies worldwide [2]. This rapid deployment is further supported by the development of global supply chains that enable large-scale manufacturing and distribution of PV technologies [3].

In archipelagic and remote regions, where grid expansion is often technically challenging and economically unfeasible, off-grid PV systems play a crucial role in providing electricity access. These systems rely heavily on battery energy storage systems (BESS) to ensure a reliable and continuous power supply. Battery storage has therefore become an essential component of modern energy systems, particularly in decentralized and mini-grid applications [4]. However, despite their advantages, battery systems face several technical challenges, including performance degradation, limited operational lifespan, and end-of-life management issues [5].

Lead-acid batteries remain widely used in off-grid PV systems due to their relatively low cost and widespread availability. Nevertheless, these batteries experience performance degradation over time, such as capacity fade and reduced efficiency, and typically require replacement once their capacity falls below a certain threshold. This degradation can significantly affect long-term system performance [6]. Furthermore, at the end of their useful life, these batteries are classified as hazardous waste due to their chemical composition, posing environmental and health risks if not properly managed [7].

Beyond technical considerations, battery management is also influenced by institutional and operational factors. Unclear ownership structures and ambiguous distribution of responsibilities among stakeholders can result in inadequate maintenance, delayed replacement, and improper waste handling. These challenges highlight the importance of selecting an appropriate battery ownership strategy that integrates technical, economic, environmental, and organizational dimensions.

Despite the growing adoption of off-grid PV systems, studies that specifically address battery ownership strategies—particularly in relation to hazardous waste management in archipelagic regions—remain limited. This reveals a gap in the integration of technical and institutional perspectives in battery lifecycle management, thereby necessitating further investigation.

II. Research Methodology

This study adopts a descriptive-quantitative approach within a Multi-Criteria Decision Making (MCDM) framework. The analytical method employed is the Fuzzy Analytical Hierarchy Process (Fuzzy AHP) using the Extent Analysis (EA) approach developed by Chang (1996). This method is selected due to its ability to accommodate decision-making problems involving multiple criteria with inherent uncertainty and subjectivity.

In the context of battery management for off-grid Solar Power Plants (PLTS) in archipelagic regions, decision-making cannot rely solely on technical or economic considerations. Strategic decisions regarding battery ownership must also consider occupational health and safety risks, limitations in human resources, compliance with hazardous waste (B3) regulations, and infrastructure constraints commonly encountered in island areas. Therefore, a multi-criteria approach is necessary to capture this complexity.

Conventional AHP utilizes pairwise comparisons based on single crisp values. However, expert judgments are often expressed in linguistic terms such as "slightly more important" or "much more important," which are inherently vague. To address this limitation, this study applies a fuzzy approach by converting linguistic variables into Triangular Fuzzy Numbers (TFN).

The object of this study is the battery ownership and management strategy for off-grid PLTS systems, with a focus on archipelagic regions characterized by limited accessibility, constrained technical resources, and higher operational risks. This study emphasizes strategic decision-making rather than detailed technical system design.

The respondents consist of ten (10) experts with relevant experience in PLTS management, battery systems, occupational safety and health (K3), and hazardous waste (LB3) management. The expert judgment approach is employed because the problem requires in-depth practical knowledge and contextual understanding. Each respondent provides independent assessments through pairwise comparison questionnaires, and all responses are treated equally and aggregated mathematically.

The decision model is structured into three hierarchical levels:

- Goal: Determining the most optimal battery ownership and management strategy for off-grid PLTS.
- Criteria (C1–C6):
  - C1: Compliance with Hazardous Waste (B3) Regulations
  - C2: Capital Expenditure (CAPEX)
  - C3: Operational and Maintenance Costs (OPEX)
  - C4: Availability of Temporary Hazardous Waste Storage (TPS B3) and Idle Asset Storage Facilities
  - C5: Availability of Technical and HSE Human Resources
  - C6: Occupational Health and Safety Risk
- **Alternatives (A1–A3):**
  - A1: Battery Purchase (Full Ownership)
  - A2: Battery Leasing (Battery as a Service)
  - A3: Hybrid Scheme (Ownership combined with Service Agreement/EPR)

Primary data are collected using pairwise comparison questionnaires based on this hierarchical structure.

Respondents evaluate criteria and alternatives using linguistic scales, which are then converted into triangular fuzzy numbers.

The data analysis procedure consists of several stages. First, respondent judgments are aggregated using the **geometric mean**. Second, fuzzy pairwise comparison matrices are constructed in the form of (l, m, u). Third, **synthetic extent values** and **degree of possibility** are calculated using Chang's EA method. Finally, criteria weights and alternative weights are normalized to obtain global weights, which are used to determine the final ranking of alternatives.

The research methodology is illustrated using diagrams to provide a clear and systematic representation of the analytical process.

Figure 1 presents the research workflow, which describes the sequential stages of the study. The process begins with problem identification related to the sustainability of battery management in off-grid PLTS systems in archipelagic regions, followed by defining the research objective. Subsequently, criteria and alternatives are identified based on literature review, regulatory considerations, and field conditions.

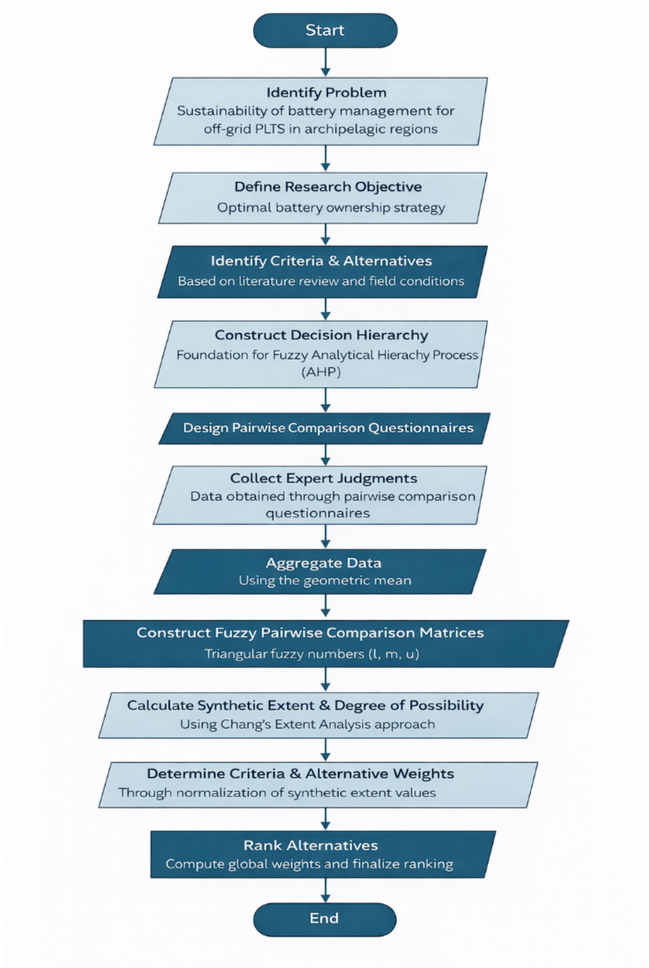

Figure 1. Research Methodology Flowchart

A hierarchical decision structure is then constructed as the foundation for the Fuzzy AHP method. Pairwise comparison questionnaires are developed and distributed to expert respondents. The collected data are aggregated using the geometric mean method and transformed into fuzzy pairwise comparison matrices.

The analysis continues with the calculation of synthetic extent values and degree of possibility using Chang's Extent Analysis approach. Based on these results, the weights of criteria and alternatives are determined through normalization. Finally, global weights are calculated to produce the final ranking of alternatives.

III. Results and Discussion

This study applies the Fuzzy Analytical Hierarchy Process (Fuzzy AHP) using Chang's Extent Analysis (EA) method to determine the optimal battery ownership strategy for off-grid solar PV systems in archipelagic regions. This method is selected to accommodate uncertainty and subjective expert judgment in multi-criteria decision-making. The analysis involves six criteria, namely regulatory compliance (C1), CAPEX (C2), OPEX (C3), infrastructure availability (C4), technical human resources (C5), and occupational safety risk (C6), along with three alternatives: ownership (A1), leasing/Battery as a Service (A2), and hybrid scheme (A3). The results are presented in the form of tables and analytical explanations to highlight the dominance of specific criteria and their implications.

The fuzzy pairwise comparison matrix was constructed using triangular fuzzy numbers (l, m, u), resulting in total values of 35.769 (l), 42.377 (m), and 47.167 (u). These values represent the aggregated uncertainty of expert judgments. Based on the row sum analysis, criterion C6 (occupational safety risk) consistently shows the highest dominance compared to other criteria. This indicates that safety considerations are perceived as the most critical factor in battery management for off-grid PV systems, especially in remote areas with limited infrastructure and supervision.

The synthetic extent (Si) values were calculated and followed by the degree of possibility analysis to obtain normalized criteria weights. The results show that C6 has the highest weight (0.536430), followed by C5 (0.354093) and C2 (0.109477), while C1, C3, and C4 have weights of zero. This outcome is a known characteristic of the Chang EA method, where criteria that do not dominate others in pairwise comparison may result in zero weights. This does not indicate irrelevance, but rather reflects lower relative importance compared to dominant criteria. The findings suggest that occupational safety and human resource readiness are the primary determinants in decision-making.

The evaluation of alternatives for each criterion shows consistent dominance of A2 (leasing/BaaS). In terms of regulatory compliance, A2 is preferred due to its ability to transfer regulatory responsibilities to service providers. For CAPEX and OPEX, A2 is also dominant because it reduces upfront investment and stabilizes operational costs through service-based contracts. In the case of human resources and occupational safety, A2 again becomes the preferred option as it minimizes dependency on local technical capacity and ensures standardized safety procedures handled by experienced providers.

A different pattern appears in the infrastructure criterion (C4), where A3 (hybrid scheme) shows the highest local weight (0.873989), followed by A2 (0.126011), while A1 remains zero. This indicates that hybrid schemes provide greater flexibility in managing temporary storage facilities and extended producer responsibility (EPR). However, since C4 has a global weight of zero, its influence on the final decision is negligible.

The global weight calculation confirms that A2 achieves a value of 1.000000, while A1 and A3 both result in zero. This extreme result occurs because only three criteria (C2, C5, and C6) have non-zero weights, and A2 dominates all of them. Therefore, the final ranking places A2 as the first priority, followed by A3 and A1. Although the results appear extreme, they reflect a strong consensus among respondents rather than a methodological error.

From a practical perspective, the dominance of A2 indicates that battery leasing (BaaS) is the most suitable strategy for off-grid PV systems in archipelagic regions. This is mainly driven by its ability to reduce safety risks, address limitations in technical human resources, and shift capital expenditure into more manageable operational costs. Although infrastructure aspects do not significantly influence the final ranking, they remain important for regulatory compliance and implementation planning. Overall, the results highlight that safety and human resource readiness are the key factors determining the sustainability of battery management in off-grid solar PV systems.

IV. Conclusion

1. This study applies the Fuzzy Analytical Hierarchy Process (Fuzzy AHP) with the Extent Analysis approach to determine the optimal battery ownership strategy for off-grid solar photovoltaic (PV) systems in archipelagic regions under multi-criteria decision uncertainty.

2. The results indicate that only three out of six evaluated criteria have significant weights, namely occupational health and safety risk (C6 = 0.536430), availability of technical and HSE human resources (C5 = 0.354093), and initial investment cost (CAPEX) (C2 = 0.109477). Among these, safety risk is identified as the most dominant factor influencing decision-making.
3. The remaining criteria, including regulatory compliance (C1), operational cost (C3), and waste storage availability (C4), obtain weights of 0.000000, reflecting their lower relative importance within the aggregated expert judgments based on the Extent Analysis method.
4. The alternative evaluation shows that the battery leasing scheme or Battery as a Service (A2) achieves the highest global priority with a normalized weight of 1.000000, while full ownership (A1) and hybrid/EPR schemes (A3) yield 0.000000, indicating no significant contribution.
5. These findings confirm that the Battery as a Service (BaaS) model is the most optimal and robust strategy for battery management in off-grid PV systems, particularly in archipelagic areas, due to its effectiveness in reducing safety risks, addressing technical workforce limitations, and minimizing upfront capital investment.

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