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Multi-Criteria Decision Making for Microgrid Development in Southern Vietnam Using AHP: A Case of Solar–Wind–Battery Integration

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ABSTRACT

The creation of microgrids that incorporate renewable energy sources has been fueled by the growing need for robust and sustainable energy systems. The Analytic Hierarchy Process (AHP) is used in this study's multi-criteria decision-making (MCDM) approach to assess and rank the best microgrid configurations in Southern Vietnam. Cost, performance, and environmental impact are the three primary parameters used to evaluate the three options: solar, wind, and battery systems. To guarantee judgment reliability, consistency ratios and pairwise comparison matrices were computed. Despite slightly worse performance when compared to hybrid arrangements, the data show that solar energy ranks first, mainly due to its reduced cost and favorable environmental qualities. For stakeholders looking to improve the region's deployment of renewable energy, this analysis offers an organized and transparent decision-support tool.

***Key words*:** Microgrid, Renewable Energy, AHP, MCDM, Solar Energy, Southern Vietnam, Environmental Impact

I. Introduction

The urgent necessity to shift to sustainable and resilient energy systems has increased recently, propelled by growing apprehensions regarding climate change, energy security, and the exhaustion of fossil fuel resources. The advancement of decentralized energy systems, especially microgrids, has attracted considerable interest. Microgrids are localized energy systems that can function autonomously or in tandem with the primary power grid, providing improved energy security, less transmission losses, and the adaptability to integrate various energy sources [1]. Southern Vietnam, noted for its elevated solar irradiance and considerable wind potential, offers a strategic opportunity for the establishment of renewable energy-integrated microgrids. The region's geographical and climatic attributes facilitate the utilization of solar and wind energy, rendering it a viable choice for the implementation of hybrid energy systems that integrate various renewable sources with energy storage methods[2]. The planning and implementation of microgrids entail intricate decision-making procedures that need the assessment of several, frequently conflicting, criteria including cost, performance, and environmental effect. This complexity is exacerbated by the necessity to reconcile technical feasibility with socio-economic and environmental factors. To address these issues, decision-makers need comprehensive analytical tools that can methodically evaluate different options based on established criteria.

Multi-Criteria Decision Making (MCDM) is a domain of operations research that addresses decision-making issues characterized by many conflicting criteria. It offers a systematic framework for assessing and prioritizing diverse choices based on multiple quantitative and qualitative criteria. MCDM approaches have been extensively utilized in domains such as energy planning, environmental management, and infrastructure construction, where decisions are affected by numerous interconnected aspects [3].

The Analytic Hierarchy Process (AHP) is distinguished among MCDM approaches for its capacity to address intricate decision-making situations that encompass both tangible and intangible factors. Formulated by Thomas L. Saaty in the 1970s, the Analytic Hierarchy Process (AHP) is a systematic methodology that disaggregates a decision-making issue into a hierarchy of more manageable sub-problems, each amenable to independent analysis. It entails pairwise evaluations of criteria and alternatives, enabling decision-makers to establish ratio scales and compute weighted scores that represent the relative significance of each component in the hierarchy. The method incorporates a consistency check to verify the trustworthiness of the judgments rendered during the comparison procedure[4].

In the realm of microgrid development in Southern Vietnam, the application of AHP enables a methodical assessment of various energy integration alternatives—specifically solar, wind, battery storage, and their hybrid configurations. By evaluating these alternatives based on essential characteristics such as cost-effectiveness, operational efficiency, and environmental sustainability, stakeholders may make educated decisions that correspond with regional energy objectives and resource availability.

Prior research has established the effectiveness of AHP in energy planning and the selection of renewable energy sources. Robles Algarin et al. (2017) employed AHP to rank renewable energy alternatives in rural Colombia, demonstrating the method's relevance across various geographical settings [5]. Ahmad and Tahar (2014) utilized AHP to assess sustainable electricity generation systems in Malaysia, highlighting its significance in Southeast Asian energy planning [6].

This study intends to utilize the AHP technique to determine the optimal microgrid architecture for Southern Vietnam, taking into account the region's distinct renewable energy potential and the diverse parameters affecting energy infrastructure choices. The results are anticipated to offer significant insights for regulators, energy planners, and investors aiming to enhance microgrid solutions in analogous situations.

II. Literature Review

The increasing demand for sustainable energy solutions has driven the investigation and incorporation of renewable energy sources into microgrid systems. Microgrids are localized energy systems that can function autonomously or in tandem with the primary power grid, providing improved energy security, less transmission losses, and the adaptability to integrate various energy sources. In areas such as Southern Vietnam, marked by elevated solar irradiation and considerable wind potential, the establishment of microgrids that incorporate renewable sources offers a strategic opportunity for the improvement of sustainable energy. The decision-making process in the planning and execution of microgrids necessitates the assessment of several, frequently contradictory, criteria including cost, performance, and environmental effect. Multi-Criteria Decision Making (MCDM) approaches have been widely utilized to address these challenges.

The Analytic Hierarchy Process (AHP), created by Thomas L. Saaty in the 1970s, is a prominent and utilized method for managing both quantitative and qualitative data within a systematic decision-making framework.

In recent years, the Analytic Hierarchy Process (AHP) has been extensively utilized in renewable energy planning. Robles Algarín et al. employed AHP to assess and rank different renewable energy sources in Colombia, revealing that solar power emerged as the most viable choice owing to its technical feasibility and environmental advantages [5]. Ahmad and Tahar employed AHP in Malaysia to evaluate sustainable electricity generation alternatives, identifying solar as the optimal option owing to its cost-effectiveness and scalability [6]. In Vietnam, few studies have utilized AHP to assess microgrid or renewable energy development. Nonetheless, the approach has demonstrated significant potential. A recent study conducted by Nguyen et al. utilized the Analytic Hierarchy Process (AHP) to identify the most effective solar panel recycling methods in Vietnam. They evaluated environmental risk, cost, and recovery potential as factors and determined that thermal treatment procedures, although associated with greater initial expenses, provided substantial long-term environmental advantages [7].

This study illustrated the adaptability of AHP in environmental decision-making and established a benchmark for its use in comprehensive energy system design.

Additional regional studies have corroborated the effectiveness of AHP in assessing off-grid systems. Miah et al. employed the Analytic Hierarchy Process (AHP) to identify hybrid renewable energy systems suitable for coastal Bangladesh, taking into account various variables such as environmental sustainability, cost, and social acceptability [8]. Their findings underscore the flexibility of AHP in environments with analogous geographic and socioeconomic characteristics to Southern Vietnam.

The integration of AHP with GIS has become an effective instrument for site selection and energy resource distribution. Ruiz et al. introduced a GIS-AHP methodology to determine suitable sites for solar plant installations in Indonesia, including terrain, solar irradiance, and proximity to infrastructure [9]. This integrative approach may be especially beneficial in Southern Vietnam, where space limitations and land-use planning are essential. AHP has been employed to reconcile trade-offs between environmental and economic considerations, in addition to technical assessment. In microgrid planning, it is imperative that systems achieve performance objectives while ensuring cost-effectiveness and environmental sustainability. Research indicates that when performance indicators are given greater weight, hybrid systems frequently surpass single-source systems [10]. Conversely, when cost prevails in the hierarchy, solar energy becomes the most viable choice, particularly in areas with elevated irradiance.

The research highlights the appropriateness of AHP for organizing intricate decision-making challenges in energy system design. Although numerous international and regional studies illustrate its efficacy in assessing renewable alternatives, there exists a significant deficiency in research specifically addressing microgrid development in Southern Vietnam. This study fills the gap by employing the Analytic Hierarchy Process (AHP) to assess and prioritize integrated microgrid options utilizing solar, wind, and battery resources, while considering local meteorological, environmental, and economic factors.

III. Research Method

This study utilizes the Analytical Hierarchy Process (AHP) as the primary decision-making instrument to assess ideal microgrid topologies that integrate solar, wind, and battery systems in Southern Vietnam. The Analytic Hierarchy Process (AHP) is a prevalent multi-criteria decision-making (MCDM) methodology that enables systematic evaluation of alternatives through expert assessment and pairwise comparisons. The technique comprises four primary stages:

Step 1: Formation of the Decision Hierarchy

A three-tiered hierarchical framework was established to tackle the microgrid planning issue. The objective (Level 1) is to determine the optimal microgrid configuration for the area. The requirements (Level 2) encompass technological, economic, environmental, and social factors. The alternatives (Level 3) encompass various combinations of solar, wind, and battery integration strategies.

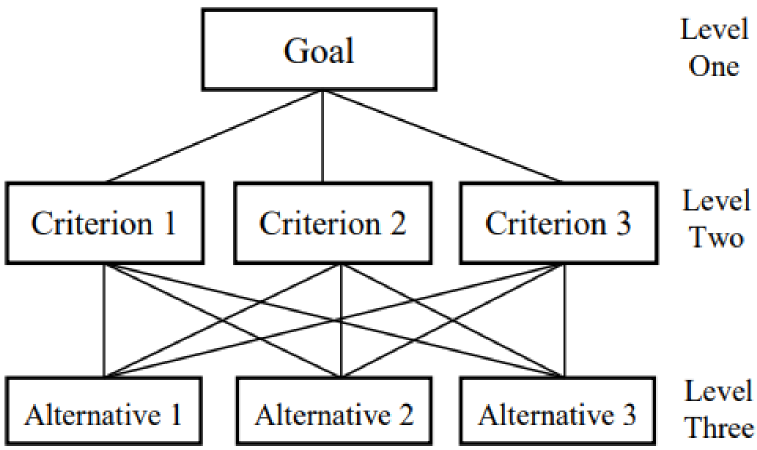

Figure 1: Sample Hierarchical Tree

Step 2: Criteria and Sub-Criteria Identification

A thorough literature review and consultations with subject matter experts led to the establishment of an extensive set of criteria and sub-criteria. These illustrate the operational difficulties and strategic goals pertinent to microgrid implementation in the context of Southern Vietnam. The criteria reflect both technical and socio-economic challenges, such as energy reliability, grid integration, cost-effectiveness, and community engagement. Particular attention was given to the unique climatic conditions and regional energy demands, which influence infrastructure design and resource allocation. his comprehensive framework serves as a foundational tool for stakeholders to evaluate feasibility and prioritize actions tailored to the local context.

Table 1: Ratings for the significance of the variable

Importance Scale	Definition of Importance Scale
1	Equally Important Preferred
2	Equally to Moderately Important Preferred
3	Moderately Important Preferred
4	Moderately to Strongly Important Preferred
5	Strongly Important Preferred
6	Strongly to Very Strongly Important Preferred
7	Very Strongly Important Preferred
8	Very Strongly to Extremely Important Preferred
9	Extremely Important Preferred

Step 3: Pairwise Comparison and Weight Allocation

A survey was administered to a panel of specialists comprising academics, engineers, and policymakers. Participants were instructed to conduct pairwise comparisons among criteria and alternatives utilizing the Saaty scale. The relative weights were determined by eigenvalue calculations, and consistency ratios (CR) were assessed to verify the reliability of the evaluations.

Table 2: Sample questionaire

Factor	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Factor
Privacy	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Reliability
Privacy	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Validation
Privacy	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Verification
Privacy	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Integrity
Privacy	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Confidentiality
Privacy	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Availability

In instances of imperfect consistency and incompatible matrices, the pairwise comparison matrix is unsuitable as a normalized column for deriving Wi.

For a positive and inverted matrix, the Eigenvector approach can be employed, which involves:

$$e^T = (1,1,\dots,1)$$

$$W = \lim_{k\to\infty} \frac{A^k \cdot e}{e^T \cdot A^k \cdot e}$$

To attain convergence among sets in the results of subsequent iterations, the computation must be done numerous times to reach a conclusion when faced with an incompatible matrix. The subsequent formula is utilized to transform raw data into significant absolute values and normalized weights w = (w1, w2, w3… wn).

$$A_w = \lambda\, max\, w\,, \lambda \text{max} \geq n$$

$$\lambda_{max} = \frac{\sum ajwj - n}{w1}$$

$$A = \{a_{ij}\}\, with\; a_{ij} = \frac{1}{a_{ij}}\cdot$$

A: pair wise comparison

w: normalized weight vector

λmax : maximum eigen value of matrix A

aij: numerical comparison between the values i and j.

The consistency ratio (CR) is calculated using the formula, CR = CI/RI in which the consistency index (CI) is:

$$CI = \frac{\lambda\, max - n}{n - 1}$$

Step 4: Integration and Evaluation of Options

The ultimate priority vectors were generated to evaluate the offered configurations. A sensitivity analysis was conducted to evaluate the robustness of the results across different weight distributions. This offered a more refined comprehension of how each factor affects the overall conclusion. This study utilizes AHP in a methodical manner to offer an evidence-based framework for stakeholders to prioritize microgrid options that align with regional characteristics and long-term sustainability objectives.

IV. Results

This study included the perspectives of 15 experts in renewable energy systems, electrical engineering, energy policy, and environmental economics, all of whom are engaged in microgrid development and management in Vietnam. Expert opinions were gathered from February to April 2024 via structured interviews, online consultations, and written surveys. The experts comprised engineers from energy utilities, researchers from solar and wind energy institutes, and policy advisers from governmental organizations. Expert assessments were methodically incorporated into the Analytic Hierarchy Process (AHP) model, recognized as a dependable and transparent decision-support framework extensively utilized across various disciplines, including sustainable infrastructure planning, technology evaluation, and multi-criteria policy analysis.

The Analytic Hierarchy Process (AHP) model was utilized to assess and rank four prospective configurations for microgrid development in Southern Vietnam: Solar, Wind, Battery, and Hybrid Solar–Wind–Battery. The alternatives were evaluated according to three main criteria: Cost, Performance, and Environmental Impact, as outlined in the decision hierarchy depicted in Figure 1.

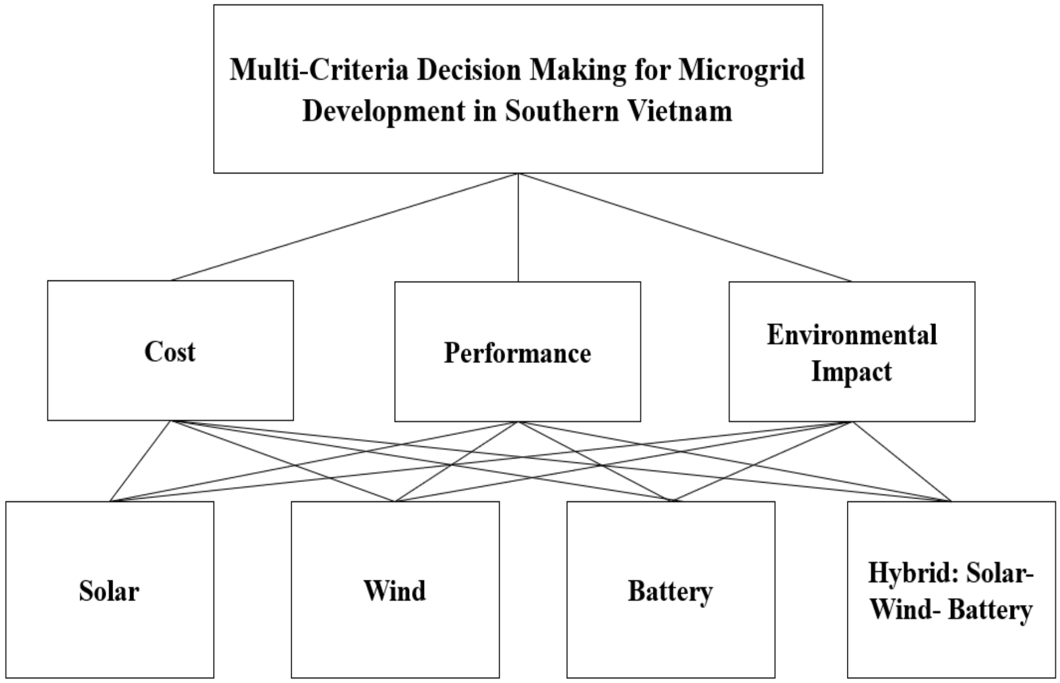

Figure 2: Framework of Analytical Hierachy Process

Upon creating the pairwise comparison matrices and calculating the normalized weights for each criterion and option, the final priority weights were obtained using aggregation. Table 4 presents a thorough assessment of the comparative performance of each choice inside the decision-making framework.

The findings demonstrate that Solar energy is the most favorable option, attaining a final score of 0.403, succeeded by Wind at 0.270, Hybrid at 0.186, and Battery at 0.144.

The weight analysis of the criterion indicates that Environmental Impact is the most significant factor in the decision-making process, followed by Cost, and finally, Performance. This indicates that in the context of microgrid growth in Southern Vietnam, prioritizing the reduction of ecological footprint is paramount, consistent with the region's and the nation's increasing focus on sustainable and ecologically responsible energy solutions. Cost is a crucial component, indicative of the budgetary limitations prevalent in developing regions, while performance, albeit pertinent, is seen less essential than environmental and economic considerations.

Table 3: Evaluation Results of the Alternatives

Alternative	Cost Weight	Performance	Environmental Impact	Final Score
Solar	0.452	0.163	0.501	0.403
Wind	0.283	0.268	0.259	0.270
Hybrid	0.102	0.475	0.092	0.186
Battery	0.163	0.082	0.147	0.144

- Cost proved to be the predominant element in establishing the ideal microgrid configuration. Of the assessed options, solar energy received the highest rating for this category. This is mostly due to the substantial reduction in photovoltaic (PV) system costs over the last ten years, propelled by technology innovations, economies of scale, and global investment in solar production. In the Vietnamese setting, notably in the Southern provinces of Ninh Thuan and Binh Thuan, elevated solar irradiation levels (averaging 4.5 to 5.5

kWh/m²/day) render solar systems both viable and economically beneficial. Furthermore, the comparatively uncomplicated infrastructure necessary for solar implementation diminishes capital and maintenance expenses, hence bolstering its supremacy in the cost domain.

- Regarding performance, hybrid systems that combine solar, wind, and battery storage achieved the highest grade. This design theoretically provides a continuous power supply by alleviating the intermittency of individual sources via complimentary load balancing. Wind energy can be harnessed during overcast or nocturnal periods, while battery systems can retain surplus energy for utilization during peak demand or generation deficits. Notwithstanding these performance benefits, hybrid systems were disadvantaged by cost and environmental impact considerations owing to their heightened system complexity, elevated initial capital investment, and increased embodied energy linked to the production and integration of various components. The aforementioned shortcomings diminish the overall appeal of hybrid systems in practical, budget-restricted contexts, such as rural electrification in Southern Vietnam.
- The Environmental Impact criterion further solidified solar energy's status as the most advantageous choice. Solar photovoltaic systems generate no greenhouse gas emissions during operation and exhibit a comparatively minimal lifecycle environmental impact when juxtaposed with wind turbines and particularly battery storage systems. Although wind turbines exhibit minimal operational emissions, their construction frequently necessitates extensive utilization of steel, rare earth metals, and infrastructure that can modify natural landscapes. Battery systems were evaluated as having the greatest environmental impact, chiefly owing to the mining, processing, and disposal of materials like lithium, cobalt, and nickel, which are often linked to toxic waste and non-recyclable elements. Furthermore, the limited lifespan of existing battery technology exacerbates environmental issues, especially in developing nations such as Vietnam, where recycling and hazardous waste management systems are inadequate.

Collectively, these findings emphasize the trade-offs associated with the selection of microgrid technologies and accentuate the contextual significance of each criterion. Although hybrid systems may provide enhanced technical performance, the economic and environmental conditions in Southern Vietnam render solar energy the most equitable and feasible option for extensive microgrid implementation.

Table 4: Consistency Test Results

Matrix	λ_{max}	Consistency Index (CI)	Random Index (RI)	CR
Criteria (3x3)	3.0042	0.0021	0.58	0.0036
Cost (4x4)	4.0285	0.0095	0.90	0.0106
Performance (4x4)	4.0162	0.0054	0.90	0.0060
Environmental Impact (4x4)	4.0203	0.0068	0.90	0.0075

Table 4 displays the consistency test results for the matrices utilized in the AHP model, comprising the criteria matrix (3x3) and three sub-matrices corresponding to each criterion: Cost, Performance, and Environmental Impact (all 4x4). The Consistency Ratio (CR) values for all matrices are far below the widely recognized threshold of 0.1, signifying a strong degree of consistency in the experts' paired evaluations. The consistency ratio (CR) for the criteria matrix is 0.0036, whereas the CR values for the sub-matrices are 0.0106 (Cost), 0.0060 (Performance), and 0.0075 (Environmental Impact), respectively. The λ_{max} values closely approximate the dimensions of the respective matrices, indicating negligible variation in the uniformity of assessments. The findings of the consistency test affirm the dependability of the expert inputs and verify that the built matrices are suitable for weight calculation in the AHP model.

These findings corroborate earlier research emphasizing the feasibility of solar energy in Southeast Asia [11,12]. The prevalence of solar energy in this setting is due not only to its reduced costs and favorable environmental characteristics but also to regional factors, like elevated solar irradiation in Southern Vietnam. Hybrid systems, although promising in operational performance, are disadvantaged in this decision-making situation due to their complexity and capital costs. The AHP-based assessment offers a definitive recommendation for stakeholders and energy planners in Southern Vietnam to select solar-based microgrid systems as the most advantageous initial option. However, hybrid systems may require reevaluation as technology advances and battery storage becomes increasingly economical. Additionally, wind energy, although not the foremost contributor in this assessment, may serve a complementary function, especially in coastal regions with substantial wind potential.

The results validate the actual applicability of the AHP method in organizing and addressing intricate energy planning issues within multi-criteria contexts. This method guarantees that judgments are clear, reproducible, and based on methodical integration of stakeholder preferences.

V. Discussion and Conclusion

The utilization of the Analytic Hierarchy Process (AHP) in assessing microgrid development options has produced substantial and practical insights into the ideal configuration for attaining sustainable energy objectives in Southern Vietnam. This study provides a comprehensive framework for informed decision-making in energy planning by methodically integrating expert assessments and quantifying trade-offs among conflicting elements. The evaluation was organized according to three principal criteria: Cost, Performance, and Environmental Impact, each signifying essential aspects of the viability and sustainability of microgrid systems.

Among the alternatives- solar, wind, hybrid (solar-wind-battery), and standalone battery systems- solar energy proved to be the most appropriate choice, achieving the highest final score of 0.403. This preeminent position highlights solar energy's distinct benefits, such as markedly reduced installation expenses, advantageous geographic and climatic circumstances in the southern provinces, and a negligible environmental impact throughout both operation and the system's life cycle. The AHP model indicated that solar energy regularly surpassed other alternatives, especially in terms of Environmental Impact and Cost criterion, where it possessed the highest relative weights. Conversely, although hybrid systems demonstrated enhanced performance - especially in maintaining 24/7 reliability via source diversification and storage -they faced significant drawbacks regarding economic and environmental factors due to their complexity, elevated capital demands, and resource-intensive infrastructure. Battery-only systems, while crucial as supplementary elements, were determined to be environmentally and economically unfeasible as independent solutions, mainly due to challenges associated with resource extraction, hazardous waste, and inadequate end-of-life management methods in Vietnam.

These findings are especially pertinent in light of Vietnam's national strategy for clean energy expansion and its Power Development Plan VIII (PDP8), which underscores the incorporation of renewable sources to guarantee energy security and sustainability. This study employs a transparent, multi-criteria decision-making method, specifically AHP, to ascertain that solar energy represents the most advantageous microgrid configuration for Southern Vietnam, while also illustrating the method's utility in informing policy development, infrastructure investment, and community-level energy planning.

Southern Vietnam, especially areas such as Binh Thuan, Ninh Thuan, and the Mekong Delta, exhibits some of the greatest sun irradiation levels in the nation, averaging over 5 kWh/m²/day. The declining costs of photovoltaic (PV) systems, along with these reasons, significantly advocate for the prioritizing of solar energy. The AHP model encapsulates these benefits by allocating significant weights to the environmental and financial criteria for the solar option. Solar power is not only economically feasible in the region but also corresponds with national environmental objectives, notably Vietnam's pledge to attain net-zero carbon emissions by 2050 as stipulated in the Paris Agreement. Although wind energy had a moderate score of 0.270, its potential warrants attention. Coastal provinces like Bac Lieu and Soc Trang demonstrate average wind speeds exceeding 6 m/s, rendering wind farms technically viable. Nonetheless, wind energy initiatives typically require greater initial capital and extended payback durations, adversely affecting their cost assessment in this model. Moreover, grid interconnection challenges and seasonal intermittency may further constrain independent wind applications lacking additional storagesolutions.

The hybrid solar-wind-battery systems, although attaining the greatest performance score, garnered lower overall ratings due to their elevated costs and intricate infrastructure demands. Likewise, battery-only systems were the least advantageous across all categories. While storage devices are essential for grid resilience and load balancing, existing technologies are costly and environmentally detrimental due to the mining and disposal of rare earth minerals [12]. The research underscores the relevance of AHP within the Vietnamese context, particularly in situations when trade-offs among many criteria necessitate explicit justification to guide public policy, investment, and development priorities.

In conclusion, Solar energy currently represents the most advantageous solution for microgrid deployment in Southern Vietnam, as determined through a comprehensive multi-criteria assessment based on the Analytic Hierarchy Process (AHP). These findings align closely with national policy goals outlined by the Vietnamese government, particularly those aimed at expanding renewable energy adoption and enhancing energy security in remote and underserved communities.

While solar power leads across the evaluated criteria, the potential role of wind energy and battery storage as complementary technologies should not be overlooked. As the costs of wind turbines and energy storage systems continue to decline and governmental incentive mechanisms mature, hybrid configurations are expected to become increasingly competitive in both economic and environmental terms.

By employing AHP within the context of regional energy planning, this research provides a replicable and transparent decision-support tool that can be utilized by energy planners, policymakers, and private sector stakeholders. Future investigations may expand on this framework by incorporating stakeholder engagement through surveys, adopting dynamic weighting methods such as Fuzzy AHP or AHP–TOPSIS, or applying GIS-based spatial analysis to enhance the geographic precision of site-specific recommendations.

Overall, the application of AHP has proven effective in supporting strategic energy planning and can serve as a valuable methodological foundation for other emerging economies where balancing cost-efficiency, operational performance, and environmental sustainability remains a critical challenge.

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