Optimizing renewable energy potential in island areas based on analytical hierarchy process

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ABSTRACT

The decreasing availability of fossil fuels and their contribution to environmental degradation and emissions of harmful gases has encouraged a shift to renewable energy sources. This change aims to produce electricity without using fossil fuels. Banyak Islands, a new tourist destination in Aceh Singkil, Indonesia, is experiencing an increase in visitors, increasing electricity demand currently supplied by diesel power plants. Therefore, this research aims to examine the possibilities of wind and solar power plants and assess their energy output. The four factors used to determine the potential of renewable energy are technology, economics, environment, and social politics, with 13 sub-criteria. Analytical hierarchy process techniques prioritize potential alternative energy sources such as wind and solar power facilities. Research findings show that environmental criteria have a higher value (0.3455) than financial criteria (0.2861), next is technological criteria (0.1734), then socio-political criteria (0.1603). Based on the results of the requirements and sub-requirements, wind power generation is the most effective and efficient alternative energy used in the Banyak Islands region (0.549), followed by solar power generation (0.451). This data shows that the area is prone to medium to high wind speeds, specifically in geographic locations facing the Indian Ocean which is located offshore.

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1. INTRODUCTION

Indonesia's electricity generation capacity reached 64 gigawatts (GW) in 2008, coal-fired power plants contributed 45%, renewable energy contributed 15% and the rest was gas and oil-fired power plants. In 2018, electricity consumption in Indonesia exceeded 1,064 kWh per capita and is projected to increase by 6.5% per year in 2020 [1], [2]. With excessive energy consumption, carbon emissions will increase [3]. Accumulating data on energy use patterns underscores the need for increased sustainable energy to find solutions to the threat of diminishing fossil fuels [4], [5]. State administrators continue to encourage the use of sustainable energy sources as written in the National Energy Management Strategy and National Electricity Policy 2010-2025 [6], [7]. Promoting energy from renewable sources as energy that is feasible and safe for the environment compared to petroleum and coal [8], [9].

The Banyak Islands region faces an increasing trend in total energy consumption of 6% per year [10], [11]. Worryingly, this has put significant pressure on government budgets over the past two decades. This presents a major challenge for the Aceh Singkil economy, which relies heavily on diesel power plants due to the scarcity of domestic economic energy sources. Considering that Banyak Islands is a leading tourist location, the increase in visitors is expected to have an impact on increasing energy consumption, especially electricity [12]. Currently, diesel power plants supply all the electricity in the region. Communities in the region often experience disruptive daily rolling power outages, causing significant inconvenience and hindering progress and development in the affected areas. Frequent power outages due to regional integration of electricity distribution have an impact on community activities, and have the impact of hampering progress in the affected areas. This dilemma is exacerbated by the fact that some islands are difficult to reach, thus exacerbating the problem and making it even more difficult to resolve. Therefore, extensive research in this area is needed to investigate alternative types of energy that can help alleviate the situation and maintain a consistent and sustainable electricity supply for local communities [10]. The following data on the number of electricity customers on this island in 2017-2020 can be seen in Table 1.

Table 1. There were many electricity customers on the island in 2017-2020

Subdistrict	2017	2018	2019	2020
Banyak Island	170	196	1,236	1,097
West Banyak Island	512	527	467	415
Total	682	723	1,703	1,512

Based on electricity customer data in the Banyak Islands, there was an increase in the number of consumers in 2017-2019, but there was a decrease of 11% in 2020 which was caused by customers not getting sufficient electricity supply and switching to solar power systems. Therefore, to overcome this problem it is necessary to fulfill the electricity needs in the region, one potential that can be fulfilled is by utilizing natural energy sources such as sun and wind [13]. The Banyak Islands, which faces the Indian Ocean, has an annual average wind speed of around 10 m/s and solar radiation of 6.7375 kWh/m2 /day [14].

An extensive study has been carried out to assess the most suitable sustainable energy in various regions. For example, research conducted in Iran using a combination of strengths, weaknesses, opportunities, and threats (SWOT) analysis, a multi-criteria decision-making approach, and game theory with the stepwise weight assessment ratio analysis (SWARA) technique, determined that solar and wind energy are the best environmentally friendly energy solutions in the province [15], [16]. The RetScreen method is used in Merauke to identify biomass, which is the most appropriate solution for the region. In Taiwan, determining the potential of wind energy as the best solution for this region was carried out using machine learning technology [17]. This study looked into the effects of optimizing renewable energy potential using the hierarchy structure method. While previous studies investigated the impact of optimizing renewable energy potential using technical and economic methods, they did not explicitly address its influence on the selection of renewable energy power plants, both solar power plants, and wind power plants, optimally through technology, economic, environmental, and socio-political considerations. This research focuses on optimizing renewable energy using the analytical hierarchy process (AHP) method, where AHP is a method that can make decisions effectively and efficiently compared to other similar methods.

To take advantage of Banyak Islands's existing assets, the selection of renewable energy power plant locations must be done carefully, as well as the intensity of sunlight. This research uses AHP as a decision-making instrument to identify optimal renewable energy potential in the province. The study provides comprehensive data regarding regional energy potential from renewable sources for electricity generation. We found that the potential for renewable energy in Banyak Islands is very high, both from wind energy and solar radiation sources. This correlates with the high energy consumption in island regions and the difficulty of integrating electricity across each island. Therefore, a study is needed to determine the optimal renewable energy power plant for application in island areas. The proposed method in this research tends to have a higher proportion of resource prioritization suitability and assessment accuracy through a hierarchical structure mechanism compared to conventional assessment methods. These insights can also be used to create plans for relevant agencies, including tourism and mineral resources. The data collected is very valuable for spatial planning and determining the economic, technological, social, and environmental efficiency of power plant areas. In the future, this research will become a reference for the government in developing renewable energy potential in the form of electrical energy in the island region.

2. METHOD

2.1. Study method

The method used is a method for hierarchical decision-making with several criteria. After a hypothesis is created, data is collected, examined, and processed. Quantitative approaches produce estimates that utilize the previous, quantitative data accompanied by a series of mathematical rules [18]. The respondents in this survey were divided into three types depending on their skills and trustworthiness in energy from renewable sources: Aceh Singkil district government, academics, and energy practitioners, each with four people involved. This research employed a sample of 12 respondents drawn from each of the three contributing categories. The variables of study depend on field research, which includes the dependent variables: solar energy and wind energy. Meanwhile, the independent variables can be seen in Table 2.

In this research, several systematic stages were undertaken and organized into a flowchart as shown in Figure 1. Each step outlines the progression from the initial problem identification through data collection, analysis, and interpretation, concluding with a set of actionable insights or findings. This visual representation helps to clarify the logical sequence of actions and decisions made throughout the research process, ensuring clarity and ease of understanding for both the researcher and the audience.

Table 2. Independent variable

Aspects of technological	Aspects of economic	Aspects of environmental	Aspects of social and political
Efficiency in the use of energy	Investment costs	Gas emissions	Workforce
The risk of security	Operation and maintenance costs	Land use	Political support/policies
Energy production capacity	Financial risk		Impact on human health
	Payback period		Social benefits

2.2. Data analysis methods

AHP functions as a decision-making tool. When creating strategies that prove useful and efficient in uncovering complex problems. AHP can solve decision-making problems with difficult criteria consisting of many sub-criteria [19]. The application of AHP includes pairwise comparisons of each criterion, subcriteria, and alternative based on a hierarchical structure. In AHP, the elements of pairwise comparison whose main criteria are technical, economic, then environmental, and customer factors are shown in Table 3 [20].

The AHP method combines quantitative and qualitative criteria, making it effective for complex real-world decision-making. Accurate standard-setting is crucial to avoid errors that may skew results. The process involves a pairwise comparison matrix to assess criteria and alternatives.

Table 3. Hierarchy of criteria

Level	Criteria	Sub-criteria	Alternative
Objective	The best renewable energy		Solar power plant
Criteria	Technology	– Economic efficiency	Wind power plant
		– Security risks	
		– Production capacity	
	Economics	– Investment costs	
		– Operation and maintenance costs	
		– Financial risks	
		– Payback period	
	Environment	– Gas emissions	
		– Land use	
	Social-Politic	– Labor	
		– Political support/policy	
		– Human health support	
		– Social benefits	

3. RESULTS AND DISCUSSION

3.1. Criteria and sub-criteria

Renewable energy solutions for Banyak Islands are evaluated using criteria such as technology, economics, environment, and socio-political factors. These are informed by prior testing and observations to align with local conditions and electricity demands, as detailed in Table 4. The priority criteria show that natural characteristics have the highest level of 34.55%, which shows the need to preserve the beauty of natural resources as a tourist attraction on Banyak Islands. The economic aspect was ranked second with a value of 28.61%, then the technological aspect was 17.34%, and finally the socio-political aspect was

16.03%. A research project in Iran with almost the same criteria, where environmental aspects come first, then economic, technological, and finally socio-political aspects due to the high levels of emissions and pollution produced by manufacturing and transportation in urban areas [21].

In Figure 1, the order of priority in the needs section is according to its criteria, with environmental factors being more important. The environmental separation criterion received the highest assessment weight, with natural gas emissions taking first place at 52.4%. This emphasizes the importance of looking at the impact of gas emissions arising from the use of sustainable energy sources, especially considering the need to save the environment and ecosystem. Several conservation areas are used as locations for sustainable energy installations but still have to control polluting gas emissions [22]. The second highest priority sub-criterion in the environmental aspect is land use, where effective land use for energy sustainability projects is very important because of the limited space available on these islands. However, national energy security is also a consideration in determining land use priorities. From a technology perspective, the sub-criteria that is more prioritized is a security risk with a score of 36.9%. This needs attention because this is a new technology known in Indonesia so it requires careful supervision by trained professionals to work safely. However, the risks of security can be minimized with government support, an appropriate environment, and competent experts [23]. The production capacity sub-criterion has the lowest value in the technological aspect, this is because the potential for energy from renewable sources in island areas is still uncertain and only a few regions have implemented it. Production capacity becomes more important when implemented, where renewable energy contributes to national energy security and is not installed in vain [24].

Table 4. Priority criteria

No	Criteria	Value
1	Environment	0.3455
2	Economic	0.2861
3	Technology	0.1734
4	Social-politic	0.1603

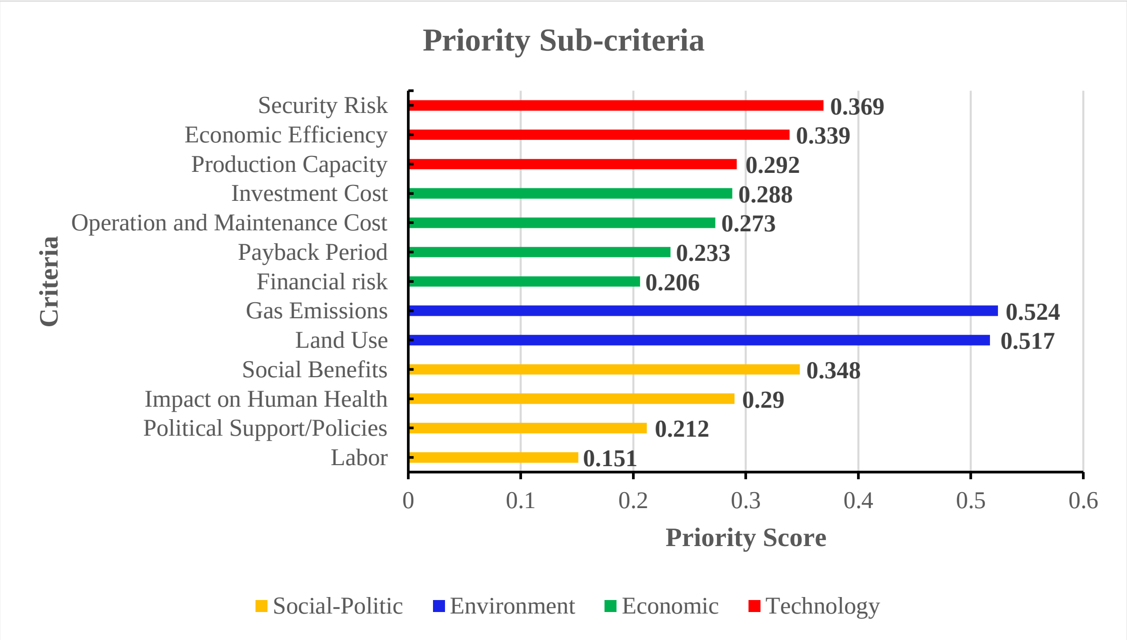

Figure 1. Priority sub-criteria

Investment costs are a sub-criterion that is highly prioritized in the economic aspect at 28.8%, this is due to the high costs incurred when implementing renewable energy in remote island areas with difficult access. Therefore, it is important to ensure that its implementation can be accounted for comprehensively and does not require excessive costs. Failure to properly control investment costs can result in losses and potentially impact national energy security. The lowest priority scale is financial risk with a value of 20.6% because it is still uncertain until implementation is carried out. However, in its application, it is necessary to assess the magnitude of prospective financial risks to avoid financial issues. In the socio-political aspect, social benefits are the highest priority sub-criteria, where in its implementation it must have a positive impact on society, especially on the social activities of local communities and the availability of sufficient energy in the surrounding area. This is critical to avoid pushed migration of citizens and strengthen the local economy. Meanwhile, the employment sub-criterion has the lowest priority at 15.1%, because there are still limited experts in the field of renewable energy. Finding professionals is a challenge because this is still something new in the energy sector [25]. To test the consistency of the criteria applied, the consistency level (CR), see Table 5. The CR of the criteria used can be checked in Table 5, where the level 1 value for the main criteria is obtained at 0.059. At level 2 the sub-criteria for the technology aspect is 0.048, economics is 0.069, environment is 0, and social politics is 0.066. Each CR value at level 1 or level 2 remains consistent, indicating that the criteria and sub-criteria meet the requirements and problem constraints. The CR value is lower than alpha (0.10).

Table 5. The level of consistency of criteria at two levels

Level	Category	CR
Level 1	Main criteria	0.059
Level 2	Technology	0.048
	Economical	0.069
	Environment	0
	Social politics	0.066

3.2. Pairwise comparison

The priority scale ranking of sub-criteria for selecting appropriate alternative energy sources in the island cluster the region between photovoltaic power plants and wind power plants is defined by global sub-criterion weights are calculated through confidence interval (CI) and eigenvalues. The alternative priority scale is shown in Table 6. Following the sub-criteria priority scale, emissions are the main thing that needs to be considered in determining alternative energy sources, especially solar power plants (SPP) and wind power plants (WPP). Gas emissions are regarded as crucial in the development of power plants, particularly in the island cluster area, which is one of the regions where the ecosystem and ecology are preserved. As a result, it is critical to analyze the implications of gas emissions generated when replenishing energy. In terms of the environment, gas emission sub-criteria are the most important considerations for deploying solar and wind as alternative energy sources to meet energy needs on the outer islands. Table 7 explains the determination of suitable alternative energy between solar and wind power based on certain weighted criteria. Table 8 shows the renewable energy selection decision.

It is stated that WPP is the most efficient and effective energy from renewable sources solution, and it is deemed suited for use as an alternative power source in island communities with a score of 0.549 (54.9%). SPP is the second alternative with a score of 0.451 (45.1%). This was obtained after considering island areas that have quite high wind speeds, especially in their geographical location which is located offshore facing the Indian Ocean. WPP was chosen as a feasible alternative energy for this location based on a variety of considerations, including It is perfect for use in this location because of the large number of uninhabited islands and the possibility of significant wind speeds in the surrounding islands. It is important to remember that wind power produces noise pollution, poses issues in areas with high population density, and loses effectiveness and efficiency when installation locations are chosen improperly. Prioritizing this condition should come before putting in the power plant, considering a variety of factors to ensure the success of the WPP implementation.

The installation of WPP is projected to benefit society by providing a more stable electricity supply in the region. Diesel power plants are currently the region's primary energy source, however, they are more expensive and environmentally destructive.WPP increases access to renewable energy, leading to a more sustainable energy supply. This has a favorable impact on the local economy and regional welfare, as well as increasing the number of domestic and international tourists visiting the new tourist attraction. Meanwhile, the priority for renewable energy sources varies in other nations, such as Malaysia, Pakistan, and Turkey, which prioritize solar power plants above wind power plants, Hydroelectric power is commonly used in developing nations with coasts [25]. However, wind energy estimates must be taken into account because they provide national energy capacity [26]. Our findings suggest that higher feasibility of WPP was not associated with poor performance in renewable energy efficiency for island communities. The proposed AHP method may benefit from prioritizing WPP without negatively impacting alternative renewable solutions such as SPP, especially when considering the unique geographical and climatic characteristics of offshore island locations.

This study evaluated WPP as the most effective renewable energy solution for the Banyak Islands, achieving a score of 0.549 (54.9%). However, limitations include the specificity of the geographical and climatic conditions, which may not generalize to other regions. Challenges such as noise pollution in densely populated areas and the potential inefficiency due to improper site selection highlight the need for more detailed feasibility studies to ensure accurate applicability and optimal implementation strategies. The results demonstrate that WPP is more efficient than SPP in island settings. Future research could explore hybrid renewable systems combining WPP and SPP to address limitations and improve resilience. Investigating methods for minimizing noise pollution and enhancing site selection criteria for WPP could further optimize their implementation in diverse settings.

Table 6. Global weight of sub-criteria

Sub criteria	Global weight	Rating
Gas emissions	0.507	1
Land use	0.448	2
Security risk	0.369	3
Social benefits	0.348	4
Economic efficiency	0.339	5
Investment costs	0.292	6
Production capacity	0.287	7
Human health impact	0.276	8
Operation and maintenance costs	0.254	9
Payback period	0.247	10
Political support/policies	0.221	11
Financial risk	0.216	12
Labor	0.186	13

Table 7. Renewable energy sub-criteria performance

Sub-criteria	Alternative	
	SPP	WPP
Economic efficiency	0.44	0.56
Security risk	0.41	0.59
Production capacity	0.46	0.54
Investment costs	0.46	0.54
Operation and maintenance costs	0.45	0.55
Financial risk	0.45	0.55
Payback period	0.41	0.59
Gas emissions	0.43	0.57
Land use	0.49	0.51
Labor	0.52	0.48
Political support/policies	0.49	0.51
Human health impact	0.50	0.50
Social benefits	0.47	0.53

Table 8. Renewable energy selection decisions

Alternative	Priority weight	Rank
WPP	0.549	1
SPP	0.451	2

4. CONCLUSION

Recent observations indicate that WPP is the most effective and efficient renewable energy solution for the Banyak Islands, achieving a score of 0.549 (54.9%). Our findings offer definitive proof that this feasibility is linked to high offshore wind speeds and geographical suitability rather than being caused by the availability of large land masses or population density. However, to maximize its effectiveness, it is crucial to consider several key factors during implementation. First, proper site selection is critical to ensure optimal performance and to mitigate challenges such as noise pollution, which could affect nearby communities. Additionally, geographic surveys and wind assessments are essential to identify areas with the highest wind potential, avoiding regions where environmental or social conditions might reduce efficiency. Addressing these challenges proactively not only enhances the sustainability of WPP but also ensures its acceptance among local populations. Furthermore, integrating WPP into hybrid renewable systems with SPP can further enhance the reliability of energy supply in the Banyak Islands, adapting to varying weather conditions and energy demands. By prioritizing these considerations, WPP can become a cornerstone for achieving long-term renewable energy goals in island communities.

The conclusion of this research suggests practical steps and recommendations, including the prioritization of site selection and mitigation of noise pollution for the effective implementation of WPP. Future research could focus on developing hybrid renewable systems, combining WPP with SPP, and refining the AHP to address technical, environmental, and economic challenges specific to island communities. This approach would enhance renewable energy strategies and provide a more comprehensive framework for sustainable energy planning in similar regions.

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