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Regional Case Study

Determining the Location of Solar Power Plant in Indonesia Using Fuzzy-AHP TOPSIS

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Abstract
Solar is a promising renewable energy source for Indonesia's increasing electricity demand, which grows at the rate of 3.3% annually. However, high investment costs and unclear policies hinder Solar Power Plant (SPP) development. Considering the potential for growth in energy demand and the low long-term operational costs, it is imperative to foster SPP expansion in Indonesia. This study aims to identify location criteria and potential SPP development sites in Indonesia. We employ Multi-Criteria Decision-Making (MCDM) combining Fuzzy-AHP and Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) methodologies to assign criteria weights and prioritize alternative SPP locations. Results show that, from all respondents using the geometric mean in the Fuzzy Analytic Hierarchy Process (AHP), it is found that the Economic criteria give the highest weight at 31%, and subcriteria of Land Availability, Peak Sun Hours, Geographic Location, Distance from Transportation Networks, Construction Costs, and Government Regulations contribute significantly. The ranking of alternative solutions indicates that South Sumatra Province holds the highest priority for SPP development with a 0.572 score, closely followed by North Sumatra at 0.571.

Keywords: Solar power plant; renewable energy; location criteria; Fuzzy-AHP; TOPSIS

1. Introduction

The energy demand in Indonesia is growing by 3.3% per year, in line with population and economic growth (International Renewable Energy Agency, 2022). In 2019, the use of fossil energy to meet energy demand in Indonesia reached 90.7% of the total energy demand. Not only in Indonesia but according to (Mehmet Sait Cengiz and Mamiş, 2016), global energy needs still depend on fossil energy sources, which are predicted to deplete in the next century and harm the environment. Therefore, there is a need to diversify environmentally friendly and sustainable energy sources to meet energy demand, especially in Indonesia (Jeffrey T Dellosa, 2016).

Indonesia possesses numerous renewable energy (RE) sources that can be utilized including geothermal, hydro, mini-hydro, solar, wind, and bioenergy. According to data from (Pribadi, 2023), solar energy potential in Indonesia is the most abundant renewable energy source, with a total solar energy potential of 3,295 GW, equivalent to 89% of the total national RE potential. Thus, it has the prospect of becoming the primary renewable energy source to meet the currently increasing electricity demand. However, based on the latest data from 2023 according to (Pribadi, 2023), the utilization of solar energy in Indonesia has only reached 194 MW. This suboptimal utilization of solar energy is due to hindrances in the development of Solar Power Plants (SPP) in Indonesia. The infrastructure of SPP is a power generator that utilizes sunlight to be converted into electrical energy through a series of processes. This energy conversion process employs significant technology. Generally, the technologies used to harness solar energy and convert it into electrical energy can be divided into two categories: Photovoltaic (PV)

Systems and Solar Thermal or Concentrating Solar Power (CSP) Systems. The Photovoltaic System, also known as the solar panel system, consists of solar panels, inverters, and battery power storage systems that work together to generate and store electricity. Solar panels consist of numerous photovoltaic cells made from semiconductor materials like silicon. The Concentrating Solar Power (CSP) technology is used to generate electrical energy from the thermal energy of the sun.

The biggest challenge for Indonesia in the development of Solar Power Plants (SPP) is the high capital required to build solar energy infrastructure. The construction cost of SPP structures ranges from USD 2,500,000 to 3,000,000 per MWp, excluding land costs (Kencana et al., 2018). Additionally, the planning and construction time required to generate electricity is lengthy, resulting in a longer return on investment (ROI) compared to investments in coal energy (Wahyuni, 2022). On the other hand, despite these high risks, investments in SPP offer promising power if planned correctly. This is because there is a growing demand for renewable energy, the availability of free resources, and low maintenance costs (United States Agency for International Development, 2016). Moreover, with government support through renewable energy policies and the profitability aspect, the selling price of electricity from SPP is higher, ranging from IDR2,000 to 3,000 per kWh, which is 4-6 times higher than the selling price of electricity from Coal-Fired Steam Power Plants (CSPP) (Kementerian Energi dan Sumber Daya Mineral, 2010).

Therefore, precise planning is required for the development of solar power plant (SPP) infrastructure in Indonesia to balance the high risks with the potential for high income (L. El-Katiri et al., 2019; Hamdi, 2019). One of the initial stages in planning the construction of SPP is site selection. Location allocation issues are part of the supply chain that deals with determining the location and allocation of supply and demand (Masudin, 2019). This study employs a combination of qualitative methods and quantitative Multi-Criteria Decision-Making (MCDM) analysis to address the research problem. The choice of this method aligns with the characteristics of SPP, where location criteria significantly influence the efficiency of SPP output. Moreover, this method is suitable for the research objective, which is to determine the location of new facilities to be built in a region (Sule, 2001). Given the absence of specific location data related to supply and demand, the assessment of SPP locations based on its criteria becomes an essential step. This research uses a hybrid Fuzzy-AHP TOPSIS approach, chosen for its ability to provide more objective results compared to other methods based on the research findings conducted (Heidary Dahooie et al., 2022). Similar research has been conducted in various countries, including Iraq, Spain, and Vietnam. Research by (Juan M Sánchez-Lozano et al., 2013) discussed the evaluation of SPP location selection in Spain using Geographical Information Systems (GIS) and Multi-Criteria Decision-Making (MCDM) AHP. Another study by (Asakereh et al., 2017) utilized the MCDM Fuzzy-AHP-TOPSIS approach to select SPP locations and technologies in Iran. However, both studies by (Asakereh et al., 2017; Juan M Sánchez-Lozano et al., 2013) were often limited to specific regions or provinces within their respective countries, tailoring their criteria to suit local conditions. In Vietnam, a study (C.-N. Wang et al., 2018) also employed an MDCM approach, but it combined three methods: Fuzzy-AHP, Data Envelopment Analysis (DEA), and TOPSIS. Despite these efforts, there remains a notable gap in research concerning the comprehensive evaluation of SPP locations in Indonesia, a nation abundant in solar energy potential.

In Indonesia, similar research has been conducted by (H S Ruiz et al., 2020), aiming to determine the optimal location for SPP in Borneo, Kalimantan, using a combination of GIS-AHP methods. However, this research still requires further development, especially regarding the criteria used in selecting alternative locations and the choice of methods for evaluating the criteria to be used. Specifically, there is a need for a more robust selection of criteria and evaluation methods to ensure the suitability of alternative SPP locations across the diverse Indonesian archipelago. Therefore, this study aims to support decision-making in SPP development in Indonesia based on appropriate location criteria. Given Indonesia's abundant solar energy potential, this study represents a novel contribution to the field, particularly in Indonesia, where the use of Fuzzy-AHP in SPP location selection is not common, as observed in previous research. Furthermore, the novelty of this research lies in its inclusive approach, which involves respondents from diverse backgrounds representing academia, industry, and government sectors. This multi-stakeholder engagement enhances the robustness and applicability of our findings, ensuring that they are relevant and actionable for all stakeholders involved in the solar energy sector in Indonesia.

This research aims to establish the specific criteria that make certain locations ideal for SPPs deployment. By establishing these criteria, the aim is to pinpoint potential sites across Indonesia where SPPs can be developed with the highest degree of success and effectiveness. The overarching goal is to ensure that once these SPPs are built, they can operate optimally and yield the best possible outcomes in terms of energy generation and efficiency. Consequently, the expected results of this research include location criteria for SPP development in Indonesia and the regions most suitable according to these criteria to meet Indonesia's energy needs. This involves a comprehensive analysis of various factors such as sunlight exposure, geographical features, infrastructure availability, and environmental considerations to determine the most suitable locations for SPP development

This information can serve as a foundation for national policy decisions regarding SPPs location determination to fulfill Indonesia's energy requirements. The data and insights generated from this research can provide a solid basis for shaping national policies. By identifying the most suitable locations for SPP development based on established criteria, policymakers can make informed decisions that align with the country's broader energy objectives. These decisions may include zoning regulations, incentives for developers, and infrastructure investments tailored to support the expansion of solar energy generation. Ultimately, leveraging this information can contribute to a more strategic and effective approach to meeting Indonesia's growing energy demands while advancing its renewable energy goals.

This study also aligns with the 2021-2030 Electricity Supply Business Plan. Furthermore, the SPP criteria examined in this research pertain to Grounded Mount SPP (power generation systems built on the ground surface, typically on massive open land areas, and are used for large-scale commercial purposes) with an on-grid system, which is an SPP system where its output is distributed to an existing electrical grid, such as the State Electricity Company (PLN) network, and the generated electricity is supplied to users and a capacity of SPP 10 MW.

2. Methods

This research employs a qualitative and quantitative Multi-Criteria Decision-Making (MCDM) approach using the Fuzzy-AHP TOPSIS method. MCDM is one of the many methods used to determine the best alternative among numerous options based on weighted criteria (Sawitri, 2016). Fuzzy-AHP is a decision-making approach that combines the concepts of Fuzzy Logic and AHP. Fuzzy-AHP is used to address uncertainties in decision-making by introducing Fuzzy values into the pairwise comparison matrix within AHP (Kengpol et al., 2013). TOPSIS is a multi-criteria decision analysis method developed by (Arvind Jayant et al., 2014). TOPSIS assumes there are several criteria used to evaluate each alternative. Scores are assigned to each alternative for each criterion. The research object comprises the criteria and alternative locations for SPP development in Indonesia. The research subjects include experts in the field of renewable energy, especially those related to SPP, from industry, academia, and government sectors who serve as respondents in this study. The data used in this research consists of primary data obtained from questionnaires and interviews with respondents, as well as secondary data obtained from literature, including research theories, the criteria used, and the designated alternative solutions.

2.1. Data Collection

The data collected in this research is divided into two, initial identification of criteria and subcriteria from the literature review, and primary data from the respondents. These data sets are used in data processing to achieve predefined research objectives.

2.1.1. Initial Identification of Criteria and Subcriteria

The secondary data in this research consists of criteria and subcriteria data for SPP location selection, as well as data regarding alternative SPP development locations in Indonesia, obtained from existing literature. Table 1 resumes the criteria and subcriteria data used in this study.

Table 1. Criteria and subcriteria for solar power plant locations

Criteria and Subcriteria	Description	References
C1. Climate		
C11. Peak Sun Hour	This reflects the duration during which sunlight has a maximum intensity at a certain level, necessary for generating optimal power or electricity from solar panels. The higher the PSH, the more beneficial it is for solar power systems (SPP).	(Ghasempour et al., 2019; Kengpol et al., 2013; Kocabaldir and Yücel, 2020; Megantoro et al., 2022)
C12. Average Temperature	The average temperature of the solar panel surface, studies indicate that for every 1°C increase in solar panel temperature, the amount of energy generated decreases by 0.4% to 0.5%.	(L. El-Katiri et al., 2019; Kencana et al., 2018; Pribadi, 2023)
C13. Relative Humidity	Comparison of the maximum amount of water vapor present in the air at a particular temperature. In conditions of high humidity, solar panels can be more efficient because the temperature is lower.	(Kocabaldir and Yücel, 2020; Vallada and Ruiz, 2011; C.-N. Wang et al., 2018)
C2. Geographic		
C21. Slope	The slope that directs the angle of PV installation to the horizontal plane. The direction of the PV installation slope is set between 8-10 degrees, adjusted to face the equator. The slope affects the amount of solar energy reaching the PV panels.	(Alqaderi et al., 2018; Heidary Dahooie et al., 2022; Kocabaldir and Yücel, 2020; Merrouni et al., 2018; Vallada and Ruiz, 2011)
C22. Geographic Location	The geographic position is represented by the longitude and latitude of the PV location. Differences in location will affect the variation in available solar energy sources.	(Kengpol et al., 2013)
C23. Average Elevation	The elevation position of the PV location is above sea level. The elevation of the PV location is closely related to the average surface temperature of PV panels.	(Heidary Dahooie et al., 2022; C.-N. Wang et al., 2018; Wang et al., 2020)
C3. Infrastructure		
C31. Distance from Transportation Networks	The distance between the PV system and transportation networks such as highways, ports, or airports. This is related to the ease of logistics and transportation access.	(Wang et al., 2020)

C32. Distance from Electrical Grids	The distance between the PV system and the location of the electricity transmission network and substations that are ready for use.	(L. El-Katiri et al., 2019; Heidary Dahooie et al., 2022; Kementerian Energi dan Sumber Daya Mineral, 2010; Pribadi, 2023; Sule, 2001)
C33. Distance from the City	The distance between the PV system location and urban areas for ease of access to information, materials, and manpower.	(Wang et al., 2020)
C4. Environment		
C41. Availability of Land	The availability of land for PV system installation.	(Kengpol et al., 2013; Setyono et al., 2019; Wang et al., 2020)
C42. Distance from Conservation Areas.	The distance of the PV system location from protected areas, historical sites, and tourist destinations.	(Kengpol et al., 2013; Wang et al., 2020)
C43. Impact on Habitat	The impact on the habitat and wildlife in the PV system's construction location.	(Wang et al., 2020)
C5. Economic		
C51. Construction Cost	Land cost, PV material cost, installation cost, and transportation cost for PV system construction.	(L. El-Katiri et al., 2019; Heidary Dahooie et al., 2022; Pribadi, 2023; Sule, 2001)
C52. Operational and Maintenance Cost	Operational, maintenance, and repair costs for the installed PV system.	(L. El-Katiri et al., 2019; Heidary Dahooie et al., 2022; Pribadi, 2023; Sule, 2001)
C53. Distribution Cost	The cost of transmitting electricity from the PV system to the consumers.	(Wang et al., 2020)
C6. Social and Regulatory		
C61. Social Regulations	The influence of customs, culture, and public acceptance on the development of PV solar power plants.	(Wang et al., 2020)
C62. Government Regulations and Laws	The influence of laws, politics, regulations, and government policies on the development of PV solar power plants.	(Wang et al., 2020)

The candidate alternative locations used in this study are based on the potential SPP locations in Indonesia, as determined by the Electricity Supply Business Plan (RUPTL) for 2021-2030, the IESR report, and electricity consumption data from BPS for the year 2020. It is known that five provinces in Indonesia have the highest solar energy potential and significant electricity consumption levels. These provinces are North Sumatra, West Java, East Java, South Sumatra, and Central Java.

2.1.2. Primary Data

The primary data used in this research comprises the assessments provided by respondents regarding the criteria and alternative solutions from the distributed questionnaires. The use of questionnaires as tools in data collection aligns with the data needs of the research method employed, where the required data come from a variety of stakeholders to understand perceptions, preferences, and priorities regarding the criteria for Solar Power Plant location selection. The research questionnaire is designed using a pairwise comparison system among criteria, subcriteria, and locations. This questionnaire utilizes the Saaty scale of 1–9 to depict the importance level of criteria and subcriteria, as well as the compatibility level of alternative locations with criteria and subcriteria. A total of 8 experts in renewable energy, focusing on SPP development in Indonesia from the academic, industry, and government sectors, with a minimum of 5 years of experience (S.-H. Lin et al., 2022), were used as respondents in this study. The respondent data for this research can be found in Table 2.

Table 2. Research respondents

Background	No.	Expertise	Years Experiences	Occupation	Service Units
Academia	1	Energy Systems And Renewable Energy	5	Researcher	RNE Research Institution
	2	Solar Cells	5	Lecturer	Education Institution
	3	Artificial Intelligence for Renewable Energy	14	Lecturer and Researcher	Education Institution
Industry	1	Renewable Energy	5	Consultant and Researcher	Solar Energy Development
	2	Operations Management	20	Lecturer and Director	Solar Energy Development
	3	Renewable Energy	15	Director	Solar Energy Development
Government Institution	1	Energy Development and Conservation	15	Civil Servant	National Power Plant
	2	Energy Development and Conservation	17	Civil Servant	National Power Plant

2.2. Fuzzy-AHP

Fuzzy-AHP is utilized to determine criteria weights based on expert questionnaires. In this research, Fuzzy-AHP is employed in the evaluation process of criteria, subcriteria, and SPP location alternatives. Generally, there are several data processing steps using Fuzzy-AHP, including the following (Kengpol et al., 2013).

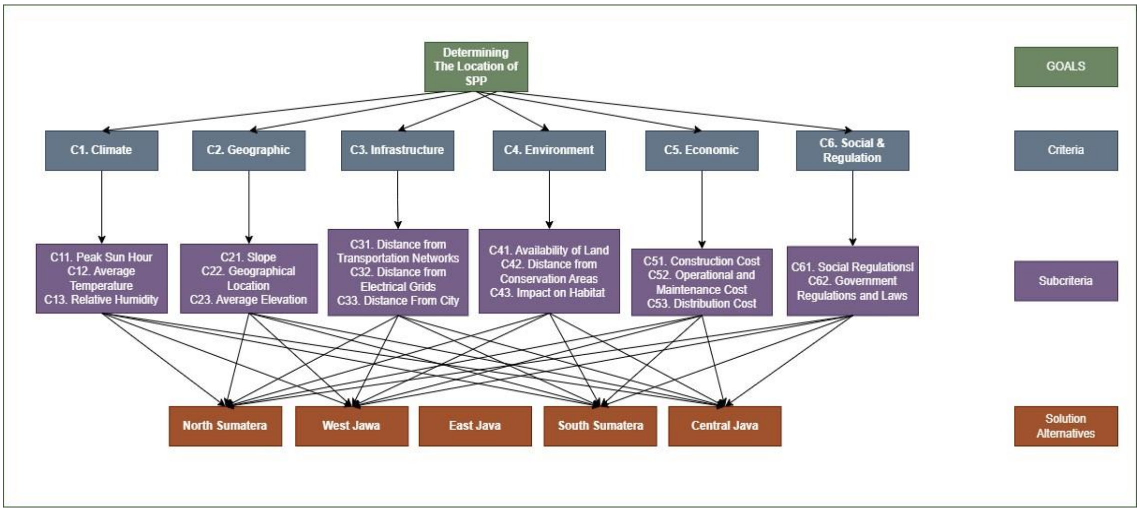

Figure 3. Decision-making hierarchy

2.2.1. Identification of Criteria and Alternative Solutions

In this stage, the criteria, subcriteria, and alternative solutions used in the research are determined at first. Subsequently, the established criteria and alternative solutions are transformed into a decision-making hierarchy as shown in Figure 3.

2.2.2. Consistency Testing

Consistency testing is performed to assess the level of consistency in the assessments provided by the respondents using Equation (1). In this research, consistency testing is conducted with the assistance of Expert Choice software.

$$CI = \frac{\lambda_{max}-n}{n-1} CI = \frac{\lambda_{max}-n}{n-1}. \quad (1)$$

2.2.3. Creating Pairwise Comparison Matrices

These matrices are obtained from the pairwise comparison assessments provided by expert judgment through questionnaires distributed to the respondents.

2.2.4. Converting Pairwise Comparison Matrix Values to Triangular Fuzzy Numbers

In this research, TFN values are used, consisting of lower (l), middle (m), and upper (u) values, as shown in Table 3.

Table 3. Triangular Fuzzy number scale

AHP Scale	Description	TFN Scale	Inverse TFN Scale
1	*Just Equal*	(1.1.1)	(1.1.1)
2	*Intermediate*	(1.2.3)	(1/3.1/2.1)
3	*Moderately Important*	(2.3.4)	(1/4.1/3.1/2)
4	*Intermdiate*	(3.4.5)	(1/5.1/4.1/3)
5	*Strongly Important*	(4.5.6)	(1/6.1/5.1/4)
6	*Intermediate*	(5.6.7)	(1/7.1/6.1/5)
7	*Very Strong*	(6.7.8)	(1/8.1/7.1/6)
8	*Intermediate*	(7.8.9)	(1/9.1/8.1/7)
9	*Extremely Strong*	(9.9.9)	(1/9.1/9.1/9)

2.2.5. Combining Respondent Assessment

In this research, the combination of opinions from respondents is performed either before calculating the criteria weights or after converting the pairwise comparison matrix values into TFN. This approach is chosen because it provides comprehensive results considering various respondent backgrounds and avoids bias from any dominant respondent. Combining assessments from various respondents can be accomplished by calculating the average values from all the respondents (Kar, 2014).

2.2.6. The Weighting of Criteria, Sub Criteria, and Alternative Locations

In this research, the geometric mean approach is used for weighting because the extent analysis method cannot represent the relative importance of the used criteria and alternatives. This method is simple, easy to implement, and not influenced by changes in the order of pairwise comparison matrices, making it a consistent and efficient choice for weighting in Fuzzy-AHP (Liu et al., 2020). The weighting of the geometric mean is carried out as follows (Abdul Rashid et al., 2020). Calculate the geometric mean values for weighing each criterion using Equations (2) to (5)

$$\tilde{r}_i = (l_i, m_i, u_i) \tag{2}$$

$$l_i = (l_{i1} \text{Ä} l_{i1} \text{Ä} \dots \text{Ä} l_{ik})^{\frac{1}{k}} \tag{3}$$

$$m_i = (m_{i1} \text{Ä} m_{i1} \text{Ä} \dots \text{Ä} m_{ik})^{\frac{1}{k}} \tag{4}$$

$$u_i = (u_{i1} \text{Ä} u_{i1} \text{Ä} \dots \text{Ä} u_{ik})^{\frac{1}{k}} \tag{5}$$

With the condition $i = 1,2, \dots, k$

Next, calculate the normalization values for each criterion using the following Equation (6):

$$\widetilde{w} = \frac{\tilde{r}_i}{\tilde{r}_T} = \left[\frac{l_i}{\sum_{i=1}^{k} u_i}, \frac{m_i}{\sum_{i=1}^{k} m_i}, \frac{u_i}{\sum_{i=1}^{k} l_i}\right] \tag{6}$$

Then, perform defuzzification of the weights after obtaining the values of each criterion in Fuzzy numbers and proceed to calculate the normalization for the weights of each element to obtain the final weights for criteria, subcriteria, and initial preferences for alternative solutions. The calculation of defuzzification and weight normalization is carried out using the following Equations (7) and (8):

$$W_i = \frac{(w_{il} + w_{im} + w_{iu})}{3} \tag{7}$$

$$\widetilde{W} = \frac{W_i}{\sum_{i=1}^{k} W_i} \tag{8}$$

2.3. TOPSIS

This method is used to make decisions in choosing an alternative solution that is closest to the positive ideal solution and furthest from the negative ideal solution. The data processing steps using TOPSIS are as follows (Arvind Jayant et al., 2014).

2.3.1. Designing Normalization of Decision Matrix

The results of weighting criteria and subcriteria from the previous stage are constructed into a normalized decision matrix, which is calculated using the following Equation 9.

$$R_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}} \tag{9}$$

2.3.2. Constructing a Weighted Normalized Decision Matrix

The weighted matrix from the normalized decision matrix is obtained by multiplying the weight of each criterion with each alternative using Equation 10.

$$V_{ij} = W_j \times R_{ij} \tag{10}$$

2.3.3. Calculating the Distance Between the Positive and Negative Ideal Solution Values

The calculation of the distance between ideal solutions is done using the matrices for the positive and negative ideal solutions for each alternative using Equations 11 and 12. To determination of the values of the positive ideal solution and negative ideal solution for each subcriterion is based on the following criteria:

$$y_j^+ = \begin{cases} \max i \ \ y_{ij}: if\ j\ is\ the\ profit\ attribute \\ \min i \ \ y_{ij}: if\ j\ is\ the\ cost\ attribute \end{cases}$$

$$y_j^- = \begin{cases} \min i \ \ y_{ij}: if\ j\ is\ the\ profit\ attribute \\ \max i \ \ y_{ij}: if\ j\ is\ the\ cost\ attribute \end{cases}$$

$$y_j^+ = \sqrt{\sum_{j=1}^{n}(y_i^+ - y_{ij})^2} \tag{11}$$

$$y_j^- = \sqrt{\sum_{j=1}^{n}(y_{ij} - y_i^-)^2} \tag{12}$$

2.3.4. *Determining the Preference Value for Each Alternative and Ranking the Alternative Solutions*

The preference value for each alternative is determined using the following Equation 13: Ranking is performed to determine the most suitable location alternatives based on the established criteria.

$$V_i = \frac{D_i^+}{D_i^- + D_i^+} \tag{13}$$

2.4. **Sensitivity Analysis**

This sensitivity analysis is carried out to understand how significant changes in the ranking of alternative solutions are when there are changes in the weights of criteria. The sensitivity test to be performed in this study uses sensitivity analysis by changing the weights of criteria based on the unitary variation ratio (β) (Li et al., 2013) with the following Equation (14)

$$\omega_a{}' = \frac{\omega_a}{1+(\gamma c-1)\omega c} \tag{14}$$

3. Result and Discussion

This research focuses on determining the optimal locations for Solar Power Plant (SPP) development in Indonesia, specifically using the Fuzzy Analytic Hierarchy Process (Fuzzy-AHP) and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS). The goal is to assess various criteria and sub-criteria to rank potential locations based on their suitability for SPP installations. The study provides a detailed analysis of the weights assigned to each criterion and sub-criterion and the priority rankings of alternative locations.

According to Figure 4, the results of data processing show that the most important or influential criterion in determining the location of SPP in Indonesia, based on the data processing using Fuzzy-AHP, is the Economic criterion with a weight of 0.31 or 31%. This criterion is related to installation costs, operational and maintenance costs, and the cost of transmitting or distributing electrical energy. Considerations related to economic aspects are crucial for assessing the feasibility and investment attractiveness of an SPP project in a specific location. For the other criteria, the Sociegulation, Geographic, Infrastructure, Environmental, and Climate criteria have percentage weights of 25%, 24%, 23%, 12%, and 11%, respectively. Furthermore, based on the questionnaire analysis for subcriteria, the most important criteria in determining the location of SPP are those with the highest weights. These include Land Availability, Peak Sun Hour, Geographic Location, Distance from Transportation Networks, Construction Costs, and Government Regulations, which have the highest weights for their respective criteria.

These criteria and their highest-weighted subcriteria are of paramount importance and will significantly influence the outcome of the SPP built. Before conducting a more in-depth assessment of the planned SPP location, ensuring the availability of land in the target location is a primary consideration. This is because SPP Grounded Mount Ongrid requires vast, flat, and open land. In this research, the land area required for the development of a 10 MW Solar Power Plant (SPP) is 10 hectares.

This is based on data from the Indonesian Directorate General of New, Renewable Energy and Energy Conservation, Ministry of Mineral Resources (Pribadi, 2023), which states that building a 1 MW Solar Power Plant requires 1 hectare (ha). Additionally, ensuring that the SPP location is strategic both in terms of geographic position and peak sun hours is another critical consideration when choosing a site for SPP development. Given the high initial investment in SPP construction, a detailed consideration of the Economic criteria, particularly construction costs related to installation, material costs, and logistical expenses during construction, is essential. Lastly, in planning SPP development in a particular area, government regulations are a crucial factor to consider. This is because SPP Ongrid is closely linked to the government, so ensuring that SPP development plans align with government initiatives is a crucial consideration.

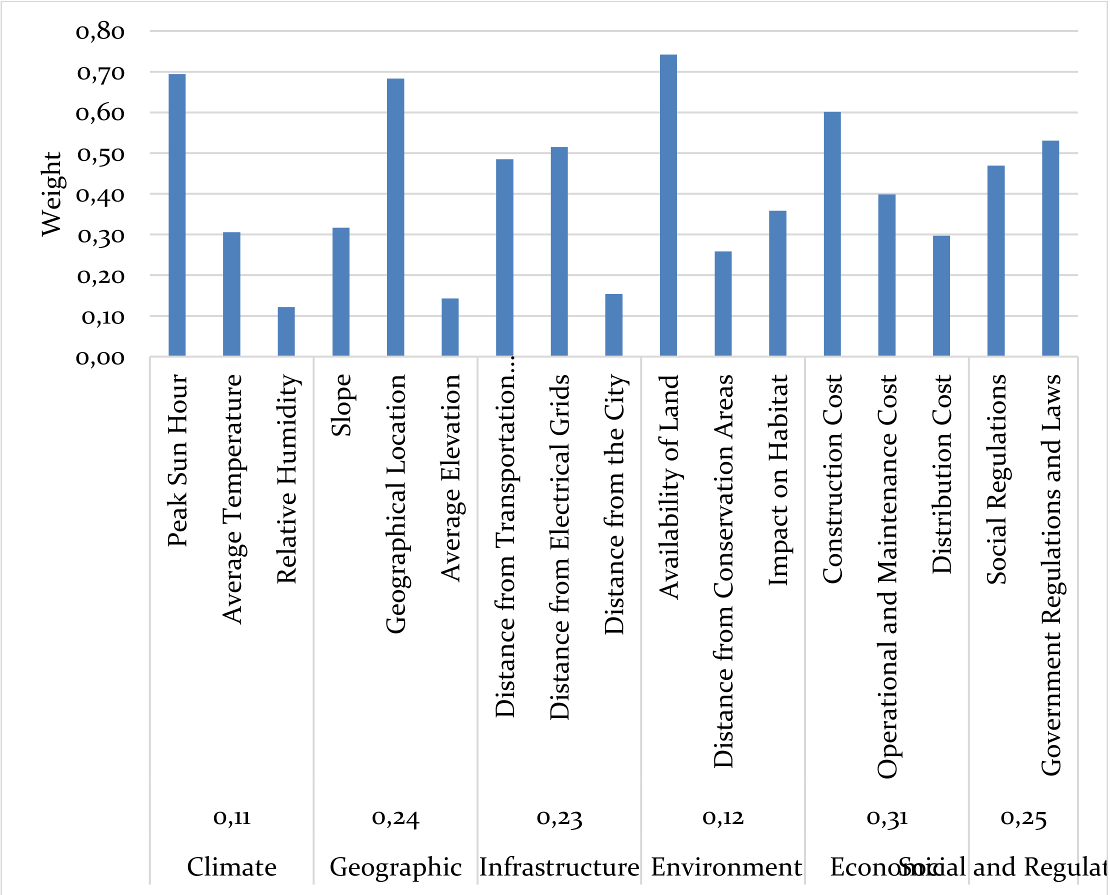

Figure 4. Weight of criteria and sub-criteria

Furthermore, after processing the data using the TOPSIS method to obtain the priority of alternative SPP locations in Indonesia based on the previously assessed criteria and subcriteria, the TOPSIS data processing results indicate that among the five provinces in Indonesia considered as alternative priority solutions. Figure 5 presents the values of each alternative along with their priority levels. North Sumatra and South Sumatra, with the highest weights of 0.571 and 0.572 respectively, are indicated as the most suitable locations, likely due to favorable conditions such as high solar irradiance or advantageous economic factors. East Java, while moderately suitable, and West Java, with significantly lower suitability, suggest that factors such as lower solar potential or economic challenges may be present. Central Java, with the lowest weight, is deemed the least suitable, which could influence stakeholders to deprioritize it for SPP development. These results are crucial for the research as they provide a quantified comparison of potential SPP locations, guiding investments and policy-making towards the regions with the greatest potential for successful and efficient solar energy production in Indonesia.

The province of South Sumatra has a solar energy potential of up to 285.2 GW, making it the third-highest solar energy potential province in Indonesia (Sekretariat Jenderal Dewan Energi Nasional, 2022). According to data (Badan Pusat Statistik, 2024), electricity consumption in South Sumatra in 2021 was approximately 5,594 GWh and is predicted to increase by 6.1% annually over the next 10 years. Nearly 97% of the electricity supply in South Sumatra is sourced from gas and diesel power plants. The current installed capacity of solar power in South Sumatra is only 2 MW (Perusahaan Listrik Negara (Persero), 2021).

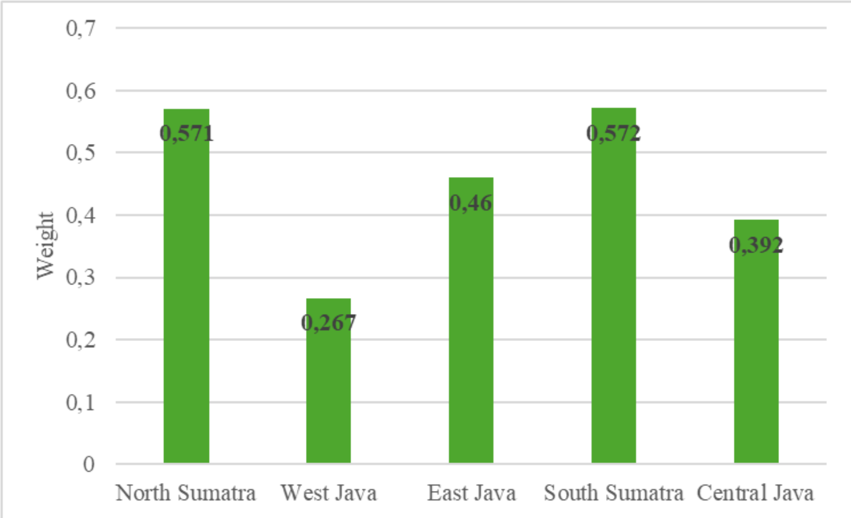

Figure 5. Alternatives final weight

Based on the Economic criteria analysis, South Sumatra has a Direct Cost Index of 0.915, which is lower than North Sumatra's 0.939 but higher than the other three candidates (Perusahaan Listrik Negara (Persero), 2021). In terms of the Social and Regulation criteria, the planning for a 55 MW solar power project in South Sumatra is currently in the planning phase and is expected to increase following feasibility studies (Perusahaan Listrik Negara (Persero), 2021). South Sumatra's geographic position offers advantages, especially in terms of the environment and climate, leading to land availability and potential Peak Sun Hours. Therefore, further assessment and planning for solar power development in South Sumatra should be considered, as the criteria evaluated earlier suggest that it has high potential and is supported by environmental demand and government policies.

3.1. Sensitivity Analysis

The sensitivity analysis performed in this study involved changing the weights for the Economic, Social, and Regulation criteria and the Climate criteria based on the unitary variant ratio (β). The β values used for this analysis were 0.01, 0.02, 0.05, 0.10, 0.20, 0.30, 0.40, 0.50, 0.60, 0.70, and 0.80. Here are some graphs showing the changes in the priority of alternative solutions after conducting sensitivity analysis (Figures 6, 7, and 8). Based on Figures 6 to 8, it can be observed that there are significant changes in the alternatives when one criterion is altered. This can happen because the weight distances between alternatives are not significantly different, so a slight or significant change in the criterion's value can affect the priority order of alternatives in the initial conditions.

In Figure 6, it can be seen that the order of alternative priorities begins to change when the climate criterion is changed with a weight value $\beta > 1.5$, and when the criterion weight is below this β value, the priority order of alternatives does not change. Furthermore, in Figure 8, which shows the results of sensitivity analysis for changes in the Social and Regulatory criteria, the priority of alternative solutions changes when $\beta < 0.02$ and $\beta > 1.5$. The sensitivity analysis results for the Economic criterion indicate that this criterion is highly sensitive to changes, so when the criterion weight changes slightly, the priority of alternatives also changes, as shown in Figure 7. The sensitivity analysis represented in Figures 6, 7, and 8 of the study reveals how susceptible the ranking of potential locations for Solar Power Plants (SPP) is to changes in weightings for different criteria. The results suggest that the economic factors are highly sensitive, with minor adjustments causing significant changes in the ranking of locations. These findings underscore the high sensitivity of the economic criterion, which aligns with the study's emphasis on economic factors as a critical determinant in SPP location selection.

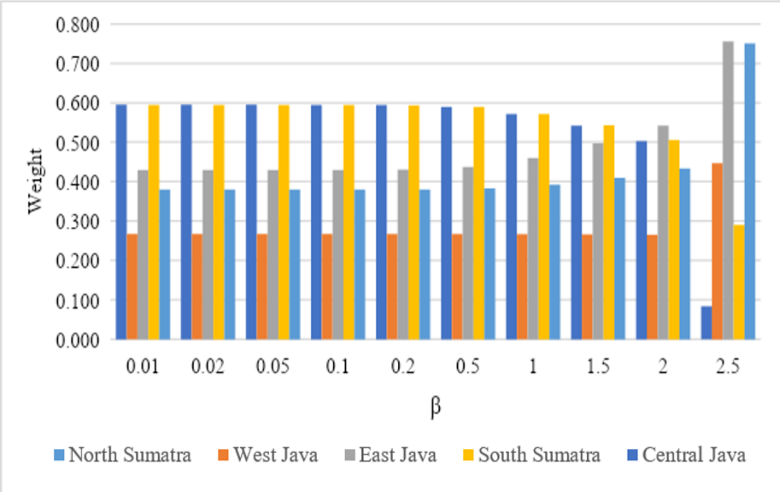

Figure 6. Sensitivity analysis for climate criteria

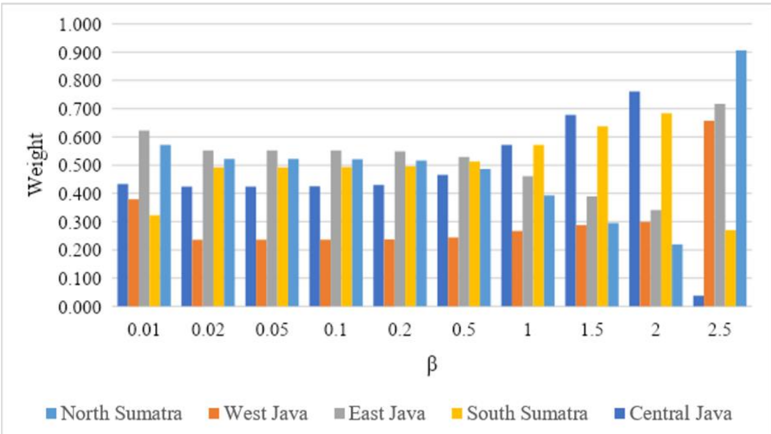

Figure 7. Sensitivity analysis for economic criteria

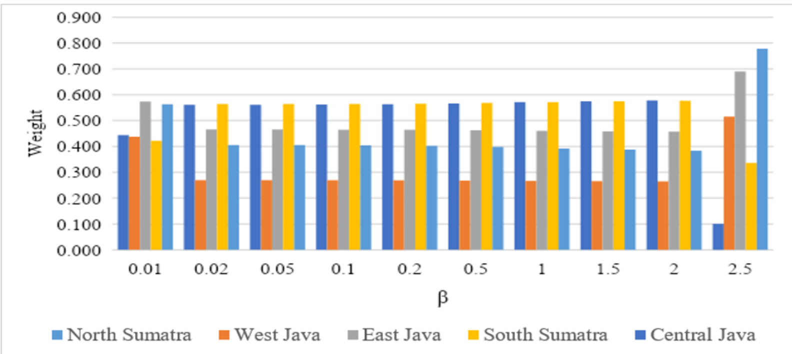

Figure 8. Sensitivity analysis for social & regulatory criteria

The implications of the sensitivity analysis delve into the nuanced understanding of how changes in criterion weightings affect the prioritization of alternative locations for Solar Power Plants (SPPs). The findings highlight the pronounced sensitivity of economic factors, where minor adjustments result in notable shifts in location rankings. These studies (Hani et al., 2023; Muñoz et al., 2016) underscore the importance of sensitivity analysis in assessing decision stability across various contexts. They emphasize how changes in criterion weightings, especially regarding economic factors, significantly impact decision outcomes. Our findings align with this literature, reinforcing the critical role of economic considerations in SPP location selection. Policymakers, investors, and stakeholders must carefully balance economic, environmental, social, and regulatory factors when identifying suitable locations for renewable energy projects.

4. Conclusions

Based on the data processing and analysis conducted in this research, the weight of criteria using Fuzzy-AHP that most significantly influences the selection of SPP locations in Indonesia are as follows: Economic criteria (31%), followed by Social and Regulatory (25%), Geography (24%), Infrastructure (23%), Environment (12%), and Climate (11%). For subcriteria, factors such as Land Availability, Peak Sun Hour, Geographic Location, Distance from Transportation Networks, Construction Costs, and Government Regulations have the highest weights within their respective criteria. After applying Fuzzy-AHP and TOPSIS methods, the final weights for each alternative – North Sumatra, West Java, East Java, South Sumatra, and Central Java – are as follows: 0.571, 0.267, 0.460, 0.572, and 0.392, respectively. These weights were then used for ranking, resulting in South Sumatra as the top-ranked location for SPP development.

The results of this study can be used as a valuable reference for future developments in getting a richer result, the research scope may equipped by utilizing other MCDM methods and conducting a more detailed examination of SPP locations in specific regions, such as South and North Sumatra down to the city level. Additionally, the study can be further improved by increasing the number of experts and expanding to involve a broader range of stakeholders, including local communities, non-governmental organizations, and other private sector entities. This would provide a more holistic perspective and enrich the analysis in assessing SPP locations. Furthermore, it is imperative to consider practical implications in actual decision-making processes when evaluating the logistical and technical consequences of selecting SPP locations. This is especially crucial in the context of distributing electricity from Sumatra to various regions across Indonesia. Challenges such as transportation infrastructure and electricity transmission technology can have a significant impact on the feasibility and operational effectiveness of SPPs at the chosen sites.

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