Optimization Solar Farm Site Selection Using Multi-Criteria Decision Making Fuzzy AHP and PROMETHEE: Case Study in Bali

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***Abstract*—The process of Solar Farm site selection is a complex issue because it involves many criteria and many factors that are classified as problem Multi-Criteria Decision Making (MCDM). With computer technology, it is possible to analyze systematically the MCDM complex problems through computational intelligence techniques.**

Many methods have been developed to solve optimization problems of Solar Farm site selection such as Fuzzy AHP - PROMETHEE. However, these methods have not integrated directly into GIS software. In this research this methods will be integrated into GIS software especially ArcGIS as a toolbox. With this toolbox, determining the location of the solar farm will be more effective and easily. This research provide the methodology and decision support so that decision makers can more easily and quickly to determine the best location of solar farm.

***Keywords*—Solar farm; Geographic Information System(GIS); Renewable Energy; Multi-Criteria Decision Making(MDCM); Fuzzy AHP; Promethee; ArcGIS toolbox.**

I. INTRODUCTION

The use of renewable energy is growing very rapidly over time [1]. Solar energy is one renewable energy very rapid development [2]. Indonesia is a country that has high levels of radiation throughout the year. The Indonesian government is currently planning the construction of renewable energy power plants of 8,800 MW with Bali as a pilot area.Bali is one of Indonesia's tourism center which is famous for its natural beauty, therefore it is necessary to develop a renewable energy source that does not cause pollution and environmental damage.

The utilization of solar energy in Indonesia frequently encountered is in the form of solar power plants (Solar Farm). Solar Farm energy capacity greatly influenced by the place, therefore it is necessary to do the optimization of the selection of the Solar Farm location[3]. Solar Farm site selection process is a complex problem to consider many criteria. Errors on the site selection stage will have an impact on the less optimal solar power that will be built.

Solar Farm site selection process is a complex issue because it involves many criteria and many of the actors that are classified as problem Multi-Criteria Decision Making (MCDM)[4]. With computer technology, it is possible to analyze systematically the MCDM complex problems through computational intelligence techniques. Many methods have been developed to solve optimization problems Solar Farm site selection such as Fuzzy AHP-PROMETHEE. But each of these methods has not been integrated directly intoa Geographic Information System (GIS) software that make it difficult to perform direct ranking process the GIS software.

In this research will be made Fuzzy AHP-PROMETHEE toolbox in ArcGIS software so it can be to automate and simplify the process of ranking the Solar Farm alternatives [5].

II. GEOGRAPHIC INFORMATION SYSTEM(GIS)

Geographic Information System (GIS) can be defined as an information system of spatial data processing. In GIS, we can edit the data in the form of maps or specific information, analyze spatial information, maps of the area and present all of the results of operations. In this present era, GIS is a tool that is very useful to analyze the suitability of the land. [6].

There are two types of data in a GIS is the data vector and raster data. Vector data is data in the form of points, lines or polygons. Vector data is usually used to create a map of an administrative or development plans. Raster data is spatial data that shows the appearance of the earth's surface obtained from remote sensing satellite imagery [7].

GIS combination with multi-criteria decision making methods is an excellent tool for analyzing the suitability of the land that will be used for the Solar Farm[7].

III. MULTI-CRITERIA DECISION MAKING METHOD

MCDM is the decision-making process with many criteria and the criteria usually have a conflict. MCDM common in everyday life, for example in the car buying process, one considers the price, size, style, etc. MCMD too many uncertainties connected with as many rely on the subjective view of a person against specific criteria [8].

Based on the goal. MCDM is divided into two, namely the Multi Attribute Decision Making and Multi Objective Decision Making [9]. MCDM and MADM often used to

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describe the same class or category. MADM used to solve problems in discrete space. Therefore, the MADM typically used to conduct the assessment or selection of some alternatives in limited quantities [10]. MODM used to solve problems that are continuous (such as in mathematical programming). Some common terms used in MCDM, among them:

1) Alternative

Alternatives are different objects and have an equal chance to be selected by the decision maker.

2) Attribute

Attributes are often also referred to as the characteristic, component, or decision criteria. Although in the majority of the criteria are one level, but did not rule out the existence of sub-criteria relating to the criteria that have been given[11].

3) Conflict between Criteria

Some of the criteria usually have conflicts with each other, for example, will benefit criteria conflict with the criteria of cost.

4) Weight of the Decision

The weight of the decision determining the relative importance of each criterion, W = (w1, w2, ..., wn). MCDM will be sought on the weight of the interests of each of the criteria.

5) Decision Matrix

A decision matrix X measuring m x n, contains elements xij, which represents the rating of the alternative Ai (i = 1,2, ..., m) to the criterion Cj (j = 1,2, ..., n).

A. Fuzzy Analytic Hierarchy Process

Fuzzy AHP is a method that is a combination method of ranking the AHP with fuzzy concept approach. Fuzzy AHP covers the weaknesses found in AHP, namely the problem of the subjective nature of the criteria that have more [12] [13]. Uncertainty number represented by a sequence of scale. To determine the degree of membership in the Fuzzy AHP, used rule functions in the form of Triangular Fuzzy Number (TFN) which is based on the set of linguistic. So, the numbers on the intensity level of interest in AHP are transformed into the set of scale TFN.

Buckley (2001) defines the intensity values AHP into triangular fuzzy scale in the following table:

TABLE 1 TRIANGULAR FUZZY SCALE

Intensity Values AHP	Definition	Triangular Fuzzy Scale
1	(*Equal Important*)	(1, 1, 1)
3	(*Moderate Important*)	(2 ,3 4)
5	(*Strong importance*)	(4 ,5, 6)
7	(*Very Strong or Demonstrated importance*)	(6 ,7, 8)
9	(*Extreme importance*)	(9, 9, 9)
2	(*Weak*)	(1 ,2, 3)
4	(*Moderate Plus*)	(3,4, 5)
6	(*Strong Plus*)	(5,6,77)
8	(*Very, Very Strong*)	(7,8,9)

Weighting procedures proposed by Buckley are as follows:

1) Convert the pairwise comparison matrix into triangular fuzzy numbers matrix M by using table 1.

2) The average arithmetic (d_{ij}) is calculated by the following equation 1:

$$\tilde{d}_{ij} = \frac{\sum_{k-1}^{K} \tilde{d}_{ij}^{k}}{K} \qquad (1)$$

Where:

$\tilde{d}_{ij}^{k}$ represents the kth decision maker's preference of ith criterion over jth criterion by fuzzy triangular members and K represents number of decision makers.

3) Fuzzy Weights for each criterion obtained from geometry equation as follows:

$$\tilde{r}_i = \left(\prod_{j-1}^{n} \tilde{d}_{ij} \right)^{1/n}, \ i = 1,2,\ldots n. \qquad (2)$$

Where $\tilde{r}_i$ represents triangular values, $\left(\prod_{j-1}^{n} \tilde{d}_{ij} \right)^{1/n}$ represent geometric mean of fuzzy comparison values for each criteria and n mean number of decision makers.

Then, based on the weight of Fuzzy triangular fuzzy numbers obtained from the following equation:

$$\tilde{w}_i = \tilde{r}_i \otimes \left(\tilde{r}_1 \oplus \tilde{r}_2 \oplus \cdots \oplus \tilde{r}_n \right)^{-1} = \left(lw_i, mw_i, uw_i \right) \qquad (3)$$

Where $\tilde{w}_i$ represent fuzzy weight criteria. There are 3 types of mathematical operations in the TFN namely addition, multiplication and inverse. Suppose r_1 and r_2 are TFNs where $r_1 = (l_1, m_1, u_1)$ and $r_2 = (l_2, m_2, u_2)$ then

Addition: $r_1 \oplus r_2 = \left(l_1 + l_2, m_1 + m_2, u_1 + u_2 \right)$

Multiplication: $r_1 \otimes r_2 = \left(l_1 . l_2, m_1 . m_2, u_1 . u_2 \right)$

Inverse: $r_1 = \left(l_1, m_1, u_1 \right)^{-1}$

4) Defuzzification method used Method Centre of Area (COA). Non-fuzzy value of M from fuzzy numbers of w can be obtained from the following equation:

$$M_i = \frac{lw_i + mw_i + uw_i}{3} \qquad (4)$$

Mi is a non fuzzy number, lw_i is lower weight, mw_i is medium weight and uw_i is upper weight.The normalized weights of Ni obtained from normalization.

5) After getting each value of N_i, global weighting of the criteria is obtained by multiplying the local weight with weight-related within the same dimension.

B. Preference Ranking Organization Method for Enrichment Evaluation

PROMETHEEis one method used to determine the order or priority of some alternatives in the use of multi-criteria problems [14]. PROMETHEE method developed by JP.Brans and published in 1982. PROMETHEE method can be run through several stages, namely (Brans & Mareschal, 2009):

1) Determine the criteria that will be used along with the weight of each criterion.

2) Determine all the alternatives.

3) Determine preference type for each criterion. Type preferences used in PROMETHEE method is the membership function of fuzzy sets [14]. Membership functions of fuzzy sets is map each domain set to every member of the set of real numbers has the interval from 0 to 1. Type of preference is determined based on the characteristics of these criteria. There are six types of preference forms are often used, which is usual criterion, quasi criterion, linear preference criterion, level criterion, linear preference and indifference area criterion and Gausian criterion.

4) Calculate the preferences of each criterion.

5) Calculate directions preference based on index values of leaving flow and entering flow. For each alternative, leaving flow value can be calculated using this equation:

$$\Phi^{+}(a) = \frac{1}{n-1}\sum_{x \in A} \wp(a,x) \tag{5}$$

Where $\Phi^{+}(a)$ is the number of which has a direction approaching from a node and $\wp(a,x)$ is preference between a and x.

Value of entering flow calculated using the equation:

$$\Phi^{-}(a) = \frac{1}{n-1}\sum_{x \in A} \wp(a,x) \tag{6}$$

Where $\Phi^{-}(a)$ is the number of which has a direction away from a node and $\wp(a,x)$ is preference between a and x.

6. Compute net flow value.

Net flow is calculated by using the equation:

$$\Phi = \Phi^{+}(a) - \Phi^{-}(a) \tag{7}$$

Sort the alternatives based on net flow (ranking).

IV. GIS–MCDM METHODOLOGY IN SOLAR FARM SITE SELECTION

This research was conducted in two stages, the first is focused on developing a model to be able to obtain the location of areas suitable for solar farm in the area under investigation. The weight of each criterion determine by the implementation of Fuzzy AHP method and PROMETHEE method used to determine the best solar farm alternative.

A. Determining Suitable Plots

1. Definition of Criteria and Factors

a) Distance from residential areas.

Building a solar farm close to population centers will have a negative impact on the environment in terms of beauty. In this study, area less than 500 meters from residential area are not allowed. Areas 500-1000 meters from residential got a score of 1, 1000–2000m got a score of 2, 2000–5000m got a score of 3 and >5000m got a score of 4 [2].

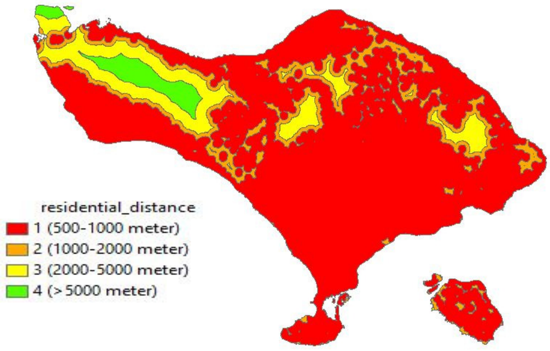

Fig 1. Distance from Residential

b) Distance from roads.

The closer to the road, then access to the construction site solar farm will be the closer, thus saving the cost to build the solar farm [1]. In this study, Areas 100-200 metersfrom roadsgot a score of 1, 200–1000 metersgot a score of 2, 1000–3000metersgot a score of 3, 3000–5000metersgot a score of 4and > 5000metersgot a score of 5 [2].

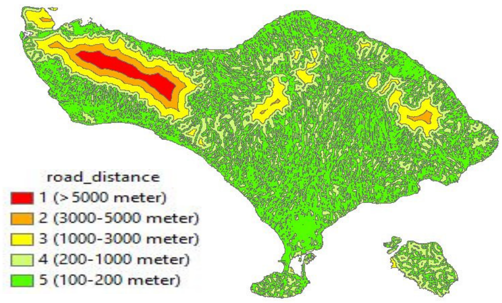

Fig 2. Distance from Road

c) Slope

The slope of the land affects the energy generated by the solar farm. In addition to the resulting effect on the energy, build solar farm in a flat will also reduce costs.Slope was divided into 3 classes.Areas that have a slope 0-3%got a score of 1,3–8% got a score of 2, 8–15% got a score of 1.

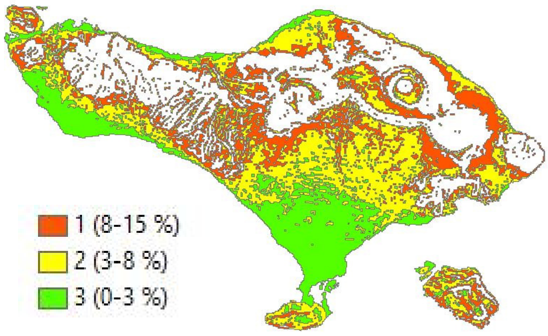

Fig 3. Slope

d) Orientation

Orientation is the direction of the slope. Orientation of the best is the longest sunlight. In Bali is under the Equator, the best orientation is leading to the north. Orientation is divided into five parts. The north got a score of 1, the northeast and northwest got a score of 2, the west and the east got a score of 3 the southwest and southeast got a score of 4 and south got a score of 5 [6].

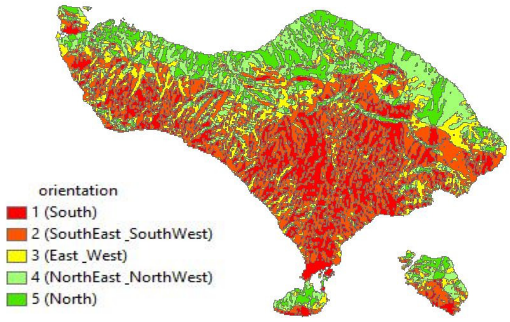

Fig 4. Orientation

e) Transmission Line and Substation Distance

Distance from transmission lines and substation is one of the most important criteria in the construction of Solar Farm because Solar Farm which is built must be connected to power grid. The closer to transmission lines and substation, it will be more economic [2]. Areas<1000m from transmission line and substation got a score of 1, 1000–2000m got a score of 2, 2000–3000m got a score of 3, 4000–5000m got a score of 4 and > 5000m got a score of 5 [2].

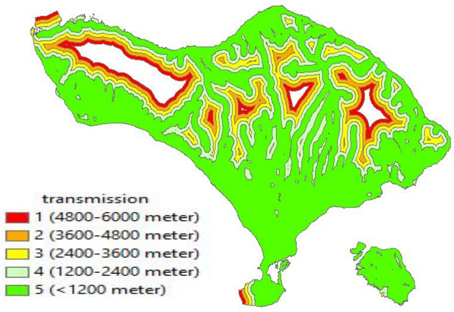

Fig 5. Distance from Transmission Line

f) Solar Radiation

Solar radiation is radiant energy from the sun. The higher the solar radiation, the greater the energy produced [6]. To get a map of solar radiation in Bali, in this study will be used Landsat 8 imagery and processed in ArcGIS software. After that, the whole solar radiation maps converted into a polygon and classified. In this study, Areas<600 kWh/m^2/year got a score of got a score of 1, 600-800 kWh/m^2/year buffer zone was scored as 2, 800-900 kWh/m^2/year buffer zone scored as 3, 900-1000 kWh/m^2/year buffer zone scored as 4 and > 1100 kWh/m^2/year buffer zone scored as 5.

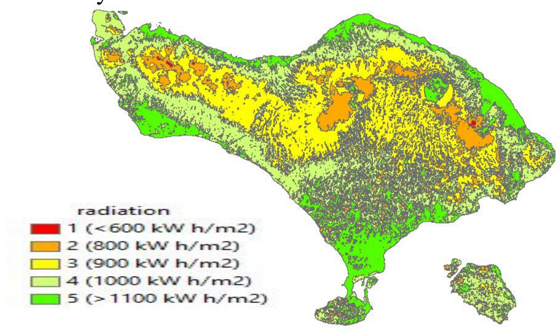

Fig 6. Solar Radiation

2. Create Restriction Area Model

In building Solar Farm, there are areas that are prohibited from use as a Solar Farm. To avoid errors in determining the location of Solar Farm, it should be made a restriction map area. A place that is not allowed as a place to Solar Farm is determined according to local regulations in Bali. Restrictions were used to create this model is:

a) Buffer from rivers, lakes is 300m
b) Buffer from residential area is 500m
c) Buffer from protected area is 500m
d) Buffer from road is 100m
e) Buffer from coastline is 1000m
f) Buffer from transmission line and substation is 6000m
g) Slope must be less than 15%
h) Buffer from main temple in Bali is 8000m

Restriction Area Model was created using ModelBuilder tools in ArcGIS 10.3. Models created in this study can be changed in accordance with regulations established in each region.

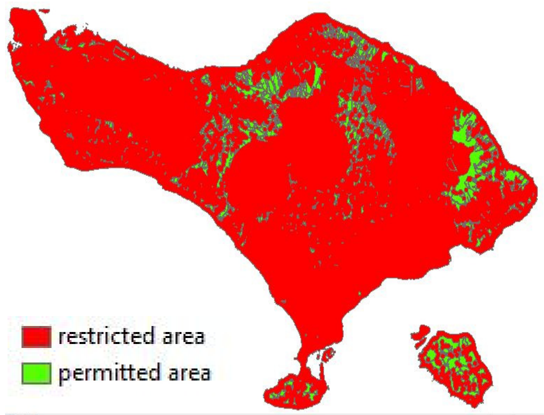

Fig 7. Restriction Area Model

In figure 7,green color indicates areas that can be used as a Solar Farm, and the red color indicates areas that are prohibited.

3. Create Suitable Area Model

To get an alternative Solar Farm, combine restriction model that has been created with all the criteria. In this study, an alternative which has an area of less than 1 hectare will not be included in the ranking process.

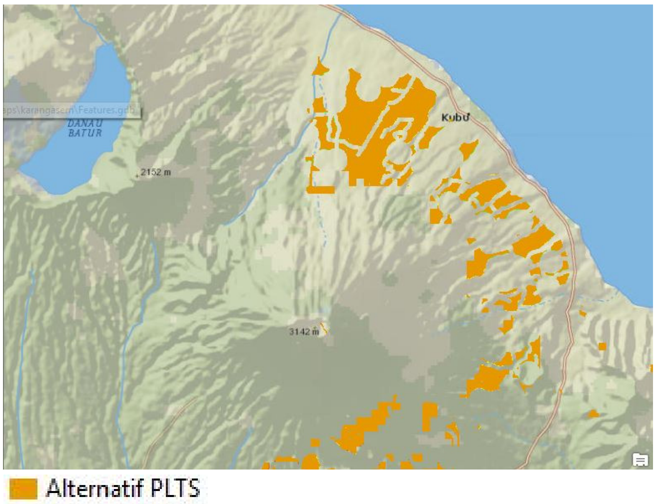

Fig 8. Alternative Solar Farm.

B. Assesing Suitable Area

1. Implementation of Fuzzy AHP-PROMETHEE Method in GIS

Implementation of Fuzzy AHP-PROMETHEE is in the form of a toolbox in ArcGIS 10.3 software. The programming language used is Python. Weight of each criterion determine by the implementation of Fuzzy AHP method. The process begins with creating a toolbox to generate inter-criteria decision table. This table will be filled by the decision maker. The weight of each criterion was calculated based on the decision table. The weights of each criteria in Fuzzy AHP will be used to perform the process of ranking alternative in PROMETHEE [15]. In the process of PROMETHEE, solar farm alternative will be in the rankings by considering the weighting of criteria from the Fuzzy AHP and alternative values for each criterion. PROMETHEE rankings value calculation based on the value of leaving flow, entering flow and net flow [14] [15] [16].

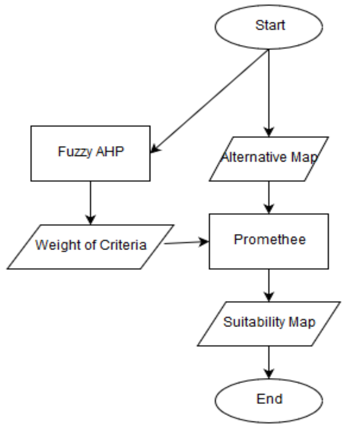

Fig 3. Flow Diagram Fuzzy AHP-PROMETHEE

V. RESULT AND DISCUSSION

This study shows how the method of Fuzzy AHP-PROMETHEE can be integrated directly inside ArcGIS, and can facilitate the process of determining the best solar farm locations in Bali.

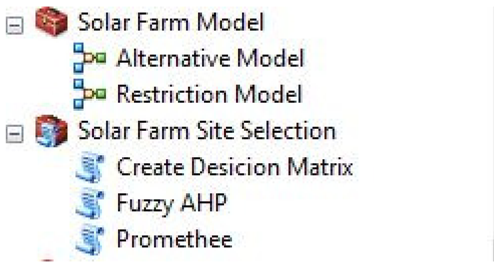

Fig 9. Fuzzy AHP-PROMTHEE toolbox

Figure 9 shows the view of the tools that have been created. There are two tools created namely Solar Farm Model to create an alternative solar farm and Solar Farm Site Selection to get the best alternative solar farm.

To determine the location of the solar farm, used six criteria: distance from the residential area, distance from the road, slope, orientation, distance from the transmission line and the level of solar radiation. The process of determining the best alternative for the solar farm begins with create a restriction models and alternative models with Solar Farm Model toolbox, the next process is to make a decision matrix to create a table that includes a comparison of importance among criteria. The resulting table further through the process of Fuzzy AHP to determine the weight of each criterion. Alternative and weight of each criterion through the process to get the best alternative with PROMETHEE toolbox.In this study, the level of importance of each criterion being equal, this means the weights to each criterion is the same, ie16.6%. Constraint layer such as distance from the river and lake, a distance of protected land, the distance from the coastline is not included in the calculation process. Based on the results obtained by using the model and Fuzzy AHP-PROMETHEE tools in ArcGIS, Bali has 2481 points which is suitable for use as a solar farm locations. Best alternative value is determined based on the value of the net flow on PROMETHEE process. Net flow value be obtained from the subtraction between the value of the leaving flow and entering flow. The highest value of leaving flow is 0.63154 and the lowest is -0.5186. The greatest net flow value is the most suitable to be a Solar Farm location. The highest alternative value in this study is 0.63154 and the lowest is -0.5168 052.Ranking for each alternative is obtained by dividing the value of net flow into 4 classes. The value of each alternative depends on the determination of criteria and weighting criteria.

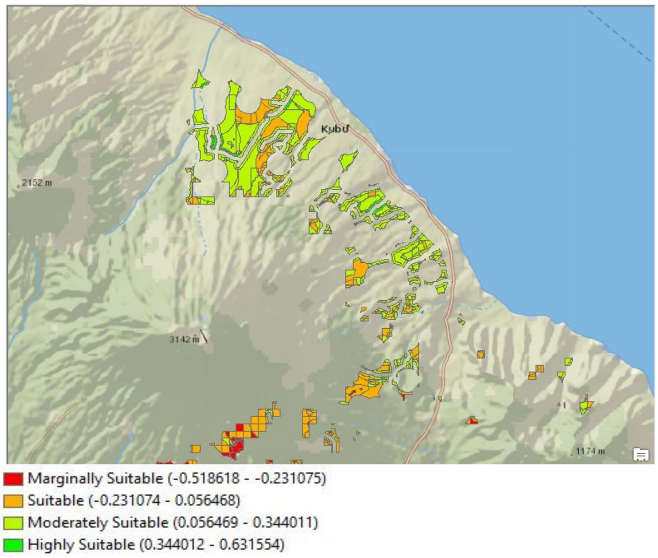

Fig 10. Alternative Ranking

Figure 10 shows an alternative that has been through the process of ranking with Fuzzy AHP-PROMETHEE tools in ArcGIS. From Figure 10, it can be seen that Bali has many places that are very suitable as a solar farm.

VI. CONCLUSIONS

Energy is one of the most important part in human life. In Indonesia, fossil fuels are the main energy sources. Although the numbers are still a lot, but over time fossil fuels will run out. In addition to issues of availability, fossil energy is also an adverse impact on the environment. Indonesia, especially Bali, solar energy is abundant, so it is suitable to be developed Solar Farm.

Many studies analyzing the suitability of the land for the location of the solar farm using MCDM method, but no one has to integrate it directly into a GIS, especially on the software ArcGIS.

This paper presents how integrated Fuzzy AHP-PROMETHEE method directly in ArcGIS can make the process of determining the location of the solar farm will be more effective and easy. The results of this study are in the form of a toolbox in an ArcGIS application that can be used to determine the best location of the solar farm. This research can provide the methodology and decision support so that decision makers can more easily and quickly determine the best location of a solar farm. This can help accelerate the growth of electricity generation coming from renewable energy, particularly solar energy in Indonesia because of the time used to analyze the suitability of the land will be reduced and the process is getting faster.

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