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Location Suitability Analysis for Wind Farm Exploitation Using Fuzzy Analytic Hierarchy Process

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ABSTRACTS

The development of renewable energy has been constantly conducted as an attempt to increase energy diversification, improve energy sustainability and reduce greenhouse gas emissions, including the wind power plant (WPP). Suitable location selection is urgently necessary to achieve optimized output and high economic values. There are multi-criteria to be considered during the selection process, namely wind velocity, climate condition, road access, environmental impact, land use, land tilt, plain condition, distance to residential areas, etc. This study aimed to develop a software supporting multi-criteria decision-making based on artificial intelligent technology, namely fuzzy analytic hierarchy process (fuzzy-AHP) which was implemented to evaluate the WPP location suitability. The method of fuzzy-AHP is believed to be able to generate prioritized criteria supporting the location of WPP with high accuracy. Based on those criteria, there were two locations identified at Tanah Laut Regency, South Kalimantan, Indonesia, as the most suitable research sites. It is expected that studies employing fuzzy-AHP are to be further developed to determine wider renewable WPP locations.

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1. INTRODUCTION

A wind power plant (WPP) consists of a series of wind turbines in a certain location that can be used as a power plant connected to an electrical energy system. Currently, there are several large-scale wind turbines with a capacity of over hundreds of Mega Watt (MW). Selecting such a location needs particular requirements to be able to achieve the optimized and largest output (Wu *et al.,* 2016). In addition, selecting the right locations is also the primary attention in terms of sustainability and reliability (Pambudi & Nananukul, 2019). Some of the important factors of the selection involve socio-economic, geographical, ecological, and environmental aspects (Xu *et al.,* 2020). Moreover, other criteria, including wind velocity, land use, land tilt, plain condition, and distance to residential areas, also play an important role in the location selection (Talinli *et al.,* 2011).

Location selection is an important issue in the contradictory criteria, or the so-called complex multi-criteria, decision-making (Toklu & Uygun, 2018). To cope with it, an efficient energy planning method involving multi-criteria decision making (MCDM) which is the best alternative in decision making is considered. There are a lot of techniques employing the MCDM approach in selecting a WPP location, some of which are analytical hierarchy process (AHP), a technique for order of preference by similarity to ideal solution (TOPSIS), Elimination et Choix Traduisant la Realité (ELECTRE) or elimination and choice expressing reality, and VIKOR or Multicriteria Optimization and Comprise Solution (Kumar *et al.,* 2017). Toklu and Ugyun, (2018) used an AHP method to determine the location of the wind farm. Van Haaren and Fthenakis presented the location selection of turbine farms in New York-based on spatial cost-revenue optimization (Van Haaren & Fthenakis, 2011). In the meantime, Azadeh *et al.,* (2011) selected the WPP sites using data development analysis. Atici *et al.,* (2015) proposed power plant selection through geographic information system (GIS) and ELECTRE method. Latinopoulos and Kechagia, (2015) proposed a model to evaluate WPP sites using GIS and spatial multi-criteria decision analysis (SMCDA). In Southeast Pakistan, Solangi *et al.,* (2018) analyzed the location priority selection of wind farms using the Fuzzy-TOPSIS technique. Xu *et al.,* (2020) implemented the VIKOR method to select wind farm locations in Wafangdian, China. It has been proven that the MCDM approach has been widely used; however, AHP appears to be the most prominent method rooting for relative weighs of each criterion (Wu *et al.,* 2016).

AHP is often used to help to make decisions combining either qualitative or quantitative factors of complex problems with weight specification in accordance with each level of importance to be able to determine the best alternative. However, judgment from experts or respondents is considered the primary weakness for its subjectivity. To cope with the above problem, a fuzzy analytic hierarchy process (Fuzzy-AHP) offers interval judgment through the triangular fuzzy number (TFN) overcoming ambiguity and unclarity of personal knowledge. Nowadays, there is a limited number of studies on MCDM base on soft computing in selecting WPP locations. To fill in such a gap, this study developed an artificial intelligence (AI)-based software for multi-criteria decision making using the Fuzzy-AHP algorithm. The focus of this study lies in the process of determining the main attributes of factors affecting the decision of developing WPP by collecting a variety of experts' opinions which are later applied to analyze the suitability of WPP locations around Tanah Laut Regency, South Kalimantan, Indonesia.

2. METHODS

As a developing archipelagic country, in terms of both economy and population,

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Indonesia is in increasing need of energy. In addition, it is necessary to replace conventional energy with renewable one. The demography of Indonesia has become a great potential for energy diversification, one of which is by establishing more WPP sites on its islands. The most crucial issue in WPP location suitability analysis is the existence of various variables, either on technical or non-technical decision making. Indonesia has to come up with the right decision-making of WPP establishment to give the best solutions of multi-variable input considering economic problems, energy needs, environmental issues, and technology.

This study proposed a conventional AHP method in combination with fuzzy logic in selecting the best locations of WPP. A literature survey identifying global researchers' opinions regarding prioritized factors in selecting WPP sites was conducted. There were 18 related journal articles from such trusted databases as Scopus, Web of Science, and Google Scholar. Buckley's Fuzzy-AHP algorithm was used to obtain the weight of criteria and sub-criteria through a pairwise matrix of the literature synthesis. The results of the order were then used in analyzing the location suitability of WPP in Tanah Laut Regency, South Kalimantan, Indonesia.

2.1. Fuzzy Analytic Hierarchy Process (Fuzzy-AHP)

The conventional analytical hierarchy process (AHP) method appears to have a weakness in the accuracy of pairwise comparison values (Chang, 1996). There are unclarities and uncertainties related to the characteristics of decision-making to be considered (Levary & Wan, 1998). Techniques in acquiring and extracting vectors of one criterion to another which are unclear are called Fuzzy-AHP (Yu, 2002). The Fuzzy-AHP was developed to overcome subjectivity values in the conventional AHP method.

In Fuzzy-AHP, the weighing of TFN scale pairwise comparison matrix is calculated and then used to rank available criteria and alternatives. Therefore, the weight determination of the pairwise comparison matrix significantly influences the stages of the process. There are Fuzzy-AHP algorithms frequently referred to previous studies and considered to be easier to implement in comparison with other methods (Ahmed & Kilic, 2019), such as fuzzy extent analysis (FEA) (Chang, 1996), FEA with normalization modification (Wang *et al.,* 2008), and Buckley's geometric mean method (Buckley, 1985).

2.2. Triangular Fuzzy Number (TFN)

The scale of AHP is converted into a fuzzification scale as shown in **Table 1** (Deng, 1999). The numbers of TFN are symbolized as (l, m, u), in which l ≤ m ≤u. When l = m = u, it is considered nonfuzzy numbers (Chang, 1996). The AHP scale can be converted into TFN is interpreted into a pairwise comparison matrix as follows (Wang *et al.,* 2008):

$$A = (a_{ij})_{nxn} = \begin{pmatrix} (1,1,1) & (l_{12}, m_{12}, u_{12}) & \cdots & (l_{1n}, m_{1n}, u_{1n}) \\ (l_{21}, m_{21}, u_{21}) & (1,1,1) & \vdots & (l_{2n}, m_{2n}, u_{2n}) \\ \vdots & \vdots & \vdots & \vdots \\ (l_{n1}, m_{n1}, u_{n1}) & (l_{n2}, m_{n2}, u_{n2}) & \cdots & (1,1,1) \end{pmatrix}$$

In which,

$$a_{ij} = (l_{ij}, m_{ij}, u_{ij}) = a_{ji}^{-1} = \left(\frac{1}{u_{ji}}, \frac{1}{m_{ji}}, \frac{1}{l_{ji}} \right)$$

where i,j = 1,...,n and i ≠ j.

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Table 1. AHP and triangular fuzzy number (TFN) scale.

AHP Scale	Linguistic Variables	TFN Scale	Opposite
1	Equally important	(1,1,1)	(1,1,1)
2	Between equal or rather more important	(1,2,3)	$\left(\frac{1}{3},\frac{1}{2},1\right)$
3	Rather more important	(2,3,4)	$\left(\frac{1}{4},\frac{1}{3},\frac{1}{2}\right)$
4	Between rather more important and more important	(3,4,5)	$\left(\frac{1}{5},\frac{1}{4},\frac{1}{3}\right)$
5	More important	(4,5,6)	$\left(\frac{1}{6},\frac{1}{5},\frac{1}{4}\right)$
6	Between more important and strongly important	(5,6,7)	$\left(\frac{1}{7},\frac{1}{6},\frac{1}{5}\right)$
7	Strongly important	(6,7,8)	$\left(\frac{1}{8},\frac{1}{7},\frac{1}{6}\right)$
8	Between strongly important and ultimately more important	(7,8,9)	$\left(\frac{1}{9},\frac{1}{8},\frac{1}{7}\right)$
9	Ultimately more important	(8,9,9)	$\left(\frac{1}{9},\frac{1}{9},\frac{1}{8}\right)$

2.3. Buckley's Fuzzy-AHP Algorithm

Buckley's Fuzzy-AHP algorithm is used to determine the weight of criteria due to its practicality in expanding the fuzzy cases and ensuring a single solution for matrix comparison. In the Buckley method, the negative judgment element is treated as the opposite of fuzzy numbers of the positive values (Pan, 2008). Calculation of the weight of W_i is administered through geometric mean techniques easily by expanding the fuzzy matrix of reciprocal positive $\bar{A}$. The given matrix of the reciprocal positive A is [a_{ij}]. Below are the stages of criteria ranking using this method (Buckley, 1985):

- Calculation of the geometric mean of each line as Equation [1]:

$$r_i = \left(\prod_{j=1}^{m} a_{ij}\right)^{1/m} \quad (1)$$

where $\tilde{a}_{ij}$ is the fuzzy comparison of criterion i towards criterion j; therefore, $\tilde{r}_i$ is the geometric mean of the fuzzy comparison value of criterion i for each of the criteria. The results of fuzzy geometric mean $\tilde{r}_i$ is written as follows Equation [2].

$$\tilde{r}_i = (l_{ri}, m_{ri}, u_{ri}) = \left[\left(\prod_{j=1}^{n} l_{ij}\right)^{\frac{1}{n}}, \left(\prod_{j=1}^{n} m_{ij}\right)^{\frac{1}{n}}, \left(\prod_{j=1}^{n} u_{ij}\right)^{\frac{1}{n}}\right] \quad (2)$$

In other words, the level of importance can be calculated by calculating the geometric mean of each line, which is by revealing the square of n by multiplying the values of the cells on the matrix lines. n is the number of criteria/ alternatives. In addition, $W_i = r_i / (r_1 + ... + r_m)$, if A is constant, the method of geometric mean results in an equal weight of that of λmax Saaty's technique for $m = 3$; therefore, both of the methods calculate the same weight (Saaty & Vargas, 1984). It is proven that when $m > 3$, the numerical results of weight in both the procedures are close to each other.

- Calculation of fuzzy weight of each criterion with the following Equation [3].

$$w_i = \tilde{r}_i \otimes \left(\tilde{r}_1 \oplus \tilde{r}_2 \oplus ... \oplus \tilde{r}_n\right)^{-1} \quad (3)$$

In other words, it is the vertical sum of the lower (l), middle (m), and upper (u) values for all the criteria's levels of importance. For each criterion: the lower value is divided by the sum of the upper value, the middle value is divided by the sum of the middle value, and the upper value is divided by the sum of the lower value.

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- Defuzzification is a process of output change in a form of *fuzzy* $\widetilde{w}_i$ into a single value output (*crisp*) w_i. After identifying the crisp of each criterion, the weight of each criterion is also identifiable by normalizing the crisp value through the sum of all the crisp values of each of the crisps from each criterion divided by the sum of the crisps.

2.4. Case Study

The suitability analysis of WPP location is conducted in an area around Tanah Laut Regency, South Kalimantan province, Indonesia (114°30'20 BT – 115°23'31 BT and 3°30'33 LS - 4°11'38 LS) with administrative boundaries shown in **Table 2**.

The width of Tanah Laut Regency is 3,631.35 km² (363.135 ha) or around 9.71% of the entire area of South Kalimantan province. Administratively, the area of Tanah Laut Regency consists of 11 sub-districts (*Kecamatan*), 5 townships (*kelurahan*), and 130 villages (*desa*). We agree to choose two alternative locations at Pamalongan village, Bajun sub-district, and Batakan village, Panyipatan sub-district due to the supportive condition of the wind velocity. However, both locations are different in terms of geographical conditions as Pamolangan village is a highland while Batakan village is a lowland (see **Figure 1**).

Table 2. Administrative boundaries of Tanah Laut Regency.

North	Banjar Regency and Banjarbaru City
East	Tanah Bumbu City and Java Sea
South	Java Sea
West	Java Sea

Figure 1. Map of Tanah Laut Regency, South Kalimantan Selatan, Indonesia.

(Source: maps.google.com)

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3. RESULTS

This study aims at giving recommendations for location suitability analysis of WPP. Appropriate decision-making is believed to be able to give strategic impacts as it does not only have high economic values but also influences the amount of energy produced. The initial stage is the synthesis of 18 collected references to come up with the experts' consideration in determining factors influencing the decision-making of WPP location suitability selection. There are factors influencing the selection of WPP location suitability, namely wind velocity (WV), a distance of power network (DT), road access (RA), land tilt (LT), distance to residential areas (DS), land use (LU), wild animals (WA), plain condition (PC), environmental effects (EE), and climate condition (CC). The hierarchical structure of the factors is presented in **Figure 2**. It is proven that the highest hierarchy, which is similar to the objective of the study, is the evaluation of WPP location suitability analysis. Meanwhile, the second level consists of the main criteria supporting the objective of the study with four main criteria. Finally, the third level contains 10 sub-criteria and the last level is the alternative of this study with two alternative locations.

The next stage is determining the prioritized factors using Fuzzy-AHP initiated by TFN pairwise comparison matrix (see **Table 3**). Weight determination of pairwise comparison matrix is conducted by panel experts involving five energy researchers in Indonesia and the experts' criteria are based on their research experiences and scientific publication in international journals. Linguistic expressions are translated into TFN matrix as an initial stage of decision making. The weight values of each criterion have been acquired on the AHP pairwise comparison matrix, which is previously converted into TFN, as the weighing refers to **Table 1**. Using Buckley's algorithm, this study obtained geometric mean, fuzzy weight, and crispiness (see **Table 4**). Normalization of the crisp value is the final priority weight and the basis to use the priority rank of WPP location suitability analysis, in which the final results are presented in **Figure 3**.

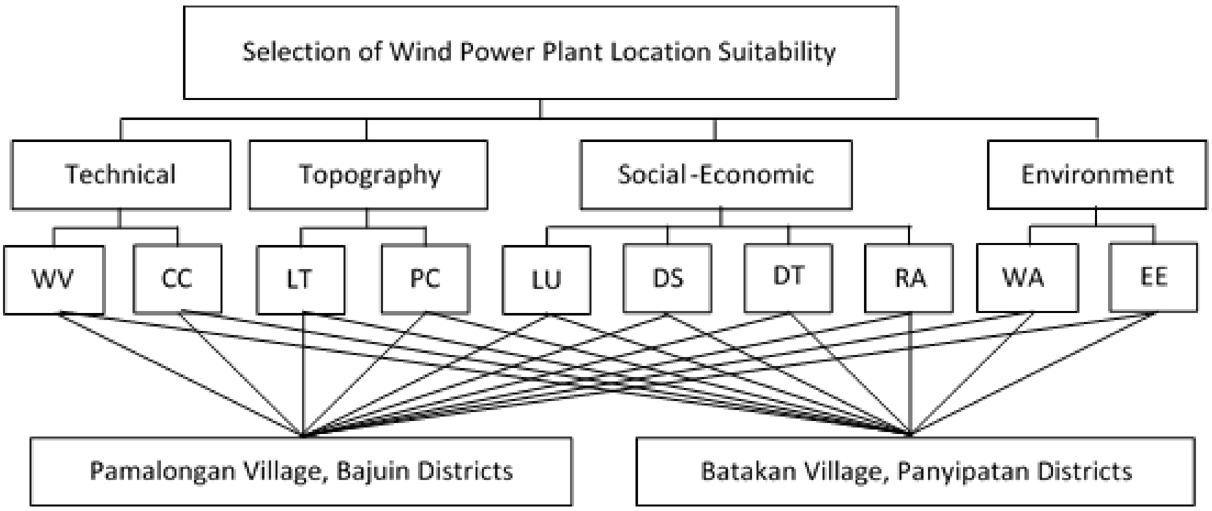

Figure 2. The hierarchical structure of evaluation of WPP location suitability.

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Table 3. Pairwise comparison of TFN scale.

	WV			CC			...			WA			EE		
	l	m	u	l	m	u	...	...	...	l	m	u	l	m	u
WV	1	1	1	4	5	6	...	...	...	4	5	6	4	5	6
CC	1/6	1/5	1/4	1	1	1	...	...	...	1/3	1/2	1	2	3	4
...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
WA	1/6	1/5	1/4	1	2	3	...	...	...	1	1	1	2	3	4
EE	1/6	1/5	1/4	1/4	1/3	1/2	...	...	...	1/4	1/3	1/2	1	1	1

Table 4. Fuzzy geometric mean.

	Geometric Mean			Fuzzy Weight			Crisp Value	Normalization
	l	m	u	l	m	u		
WV	3,669	4,474	5,251	0,208	0,327	0,510	1,045	0,317
CC	0,803	1,218	1,712	0,045	0,089	0,166	0,301	0,091
LT	0,699	1,018	1,431	0,040	0,075	0,139	0,253	0,077
PC	0,488	0,676	0,972	0,028	0,049	0,094	0,171	0,052
LU	1,813	2,460	3,137	0,103	0,180	0,304	0,587	0,178
DS	0,620	0,833	1,135	0,035	0,061	0,110	0,206	0,063
DT	0,448	0,581	0,812	0,025	0,043	0,079	0,147	0,045
RA	0,326	0,421	0,591	0,018	0,031	0,057	0,107	0,032
WA	1,182	1,663	2,169	0,067	0,122	0,211	0,399	0,121
EE	0,254	0,319	0,435	0,014	0,023	0,042	0,080	0,024
Total	**10,302**	**13,665**	**17,644**				**3,297**	

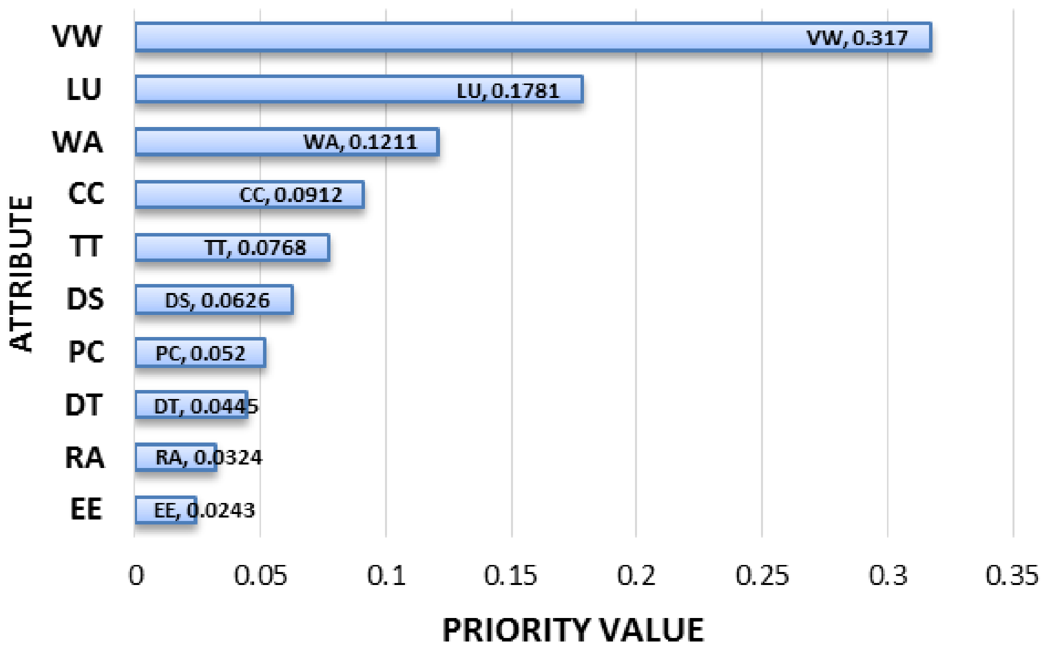

Figure 3. The results of location suitability for WPP.

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Suitability analysis of WPP location in this study was conducted in two alternative locations. Alternative 1 (A1) is at Pamalongan village and alternative 2 (A2) is at Batakan village. The analysis was performed to select which area has the most potentials for becoming WPP sites. The analysis was conducted by calculating or comparing both alternatives of each criterion. Information on the area was acquired from online official documents of Tanah Laut Regency, South Kalimantan, Indonesia.

Based on the Fuzzy-AHP decision-making, the WV aspect was the main priority of the analysis. Referring to the data in 2020, the average WV on the height of 10 m in the A1 area as high as 7.12 m/s and ion the A2 are as high as 4.75 m/s, so that the A1 area has better potentials in comparison with that in area A2 with the pairwise comparison weight by 5. In terms of LU, area A1 predominantly consists of reed fields, gardens, and residential areas which are dry areas located in highland; therefore, the soil texture is relatively soft. In the meantime, the A2 area contains bushes, grasses, beach forests, ponds, and housing which are also dry and wet areas located in lowland, so that the soil texture was mild-to-rough. Therefore, in terms of the soil texture, the entire A1 areas had soil texture irresistant to erosion, while A2 areas had one resistant to erosion. The population density in the A1 areas is 97.96 persons/km^2, while in the A2 areas is 75.30 persons/km^2 (data in 2018). Referring to the National Standard of Indonesia, both areas are categorized as having low population density; therefore, new WPP location development needs no land use reduction. However, in terms of all the evaluation from such aspects as soil type, soil texture, and population density, A1 has higher potentials so that the weight of pairwise comparison weight between A1 and A2 areas for LU is 7.

WA aspect is the third priority in the analysis. The fauna at Tanah Laut Regency has various types, such as deer, wild boars, wild cats, and monkeys. However, such real and detailed conditions of flora and fauna have not been in inventory. In terms of conservation areas, the A2 area had a nature reserve; however, the areas are 5 km away from the proposed WPP locations. Meanwhile, there was no nature reserve in the A1 area yet in terms of conservation with the possibility of wild animals, the A1 area was closer to protected forest compared to the A2 area. Thus, in terms of the WA aspect, A2 was more suitable to be WPP location as the pairwise comparison weight of the A1 area towards that of the A2 area for the WA criterion was 1/5.

Information of CC within both A1 and A2 areas could only be acquired from the amount of rainfall of South Kalimantan province, ranging from 50 to 200 mm/month, which is categorized middle to high. When it is analyzed in detail, the A1 area tended to be on normal rainfall while the A2 area was categorized to have high rainfall so that the pairwise comparison weight of A1 towards the A2 area for the CC criterion was 5.

Another important attribute in the location analysis was LT. **Table 5** shows the classification data of the studied area. Referring to the data, the A1 area had a tilt below 8 to 15% with a total area of 6,199.93 ha while the A2 area had a tilt of 0-8% with a total area of 71,675.29 ha. In conclusion, the A2 area had higher potentials in comparison to A1 with the pairwise comparison weight of ½.

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Table 5. The land tilt of Tanah Laut Regency, South Kalimantan province.

Tilt Class (%)	Description	Total area (ha)	Area
0 – 8	Plain	71.675,29	South
8 – 15	Sloping	6.199,93	Middle
15 – 25	Rather steep	6.893,52	Middle
25 – 45	Steep	6.900,90	Middle
> 45	Really steep	10.690	Middle and North

Generally, all the housing areas and villages in the studied case categorized into forests were enclaves so that there were no longer villages within the forests. In the meantime, the distance of the A1 WPP area to the closest housing was ± 1,021 m to the west and ± 1,010 m to the east. On the other hand, the distance of the A2 WPP area to the closest housing was ± 2,032 m. Therefore, both areas have adequate distance to the housing area, which was 1,000 m. In short, the weight of both areas' pairwise comparison for the distance to the area was 1. The A1 area was categorized as bumpy highland, hilly, and mountainous with an elevation class of higher than 500 m above the sea level; hence, it was considered suitable for a WPP site. The A2 area, on the other hand, was categorized as a sloping to waving lowland consisting of bushes, rivers, and beaches so that it was not suitable for a WPP site establishment. The weight of pairwise comparison for both areas in terms of PC criterion was 5.

In terms of the distance of WPP to the grid (DT), the A1 area had actually proven to be closer to the closest substation (16.2 km) in comparison with that of the A2 area (55.4 km); thus, the weight of pairwise comparison of both areas in this criterion was 3. In terms of RA, both location candidates have similar conditions from such aspects as road conditions, road width, and road surface type. The road access was adequate and had been going through road pavement with asphalt or gravel so that the road was quite solid and wide (the weight of pairwise comparison for both was equal by the value of 1). The aspect of EE for both areas had a quite far position for both location candidates. Therefore, the impact of the residents being disturbed due to the turbines and wind noise from the spoons could be reduced. It had been proven that the weight of pairwise comparison for both areas in this criterion was 1. It can be concluded that by using the Fuzzy-AHP algorithm, the A1 area had higher potentials as the WPP location candidate in comparison with the A2 area. The total weight of pairwise comparison of the A1 area was 0.658 and that of the A2 area was 0.342 with the consistency ratio of 0.09.

4. DISCUSSION

This study succeeded in developing a software of multi-criteria decision making based on AI using the Fuzzy-AHP algorithm implemented in evaluating WPO location suitability. The Fuzzy-AHP method was able to result in supporting criteria priorities as well as WPP location alternatives with high accuracy values as the Fuzzy-AHP used TFN to overcome both ambiguity and unclarities resulted from subjective AHP assessment. This method highlighted the weighing process on a pairwise comparison matrix strongly influencing the decisions of WPP establishment by collecting a variety of experts' opinions from the available literature. The results of this method had an acceptable inconsistency value (0.09).

Based on the calculation of the Fuzzy-AHP algorithm, the criterion of climate conditions placed the fourth priority and that of wild animals placed the third, meaning that these criteria included into rather important ones

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in establishing WPP locations. However, literature shows that those two criteria were not commonly used in evaluating the location; out of 20 articles, only 3 articles were using the CC criterion, and 7 of them using the WA criterion. Unlike those criteria, the WV criterion placed the first rank in evaluating the WPP location and this is in line with the existing literature as the velocity strongly affected the blade rotation on the turbines used to result in electricity (Al-shabeeb *et al.,* 2016). In the meantime, the EE criterion placed the lowest priority as little literature shows that WPP does not affect natural resource reduction and does not produce emissions during the process (Solangi *et al.,* 2018).

The limitation of this study mainly lies in the criteria selection as well as the weighing process of each of the criteria based on a literature survey and panel expert with a limited number of participants involved. Additionally, the calculation of Fuzzy-AHP merely used Buckley's method and the evaluation was limited in the areas located in South Kalimantan, Indonesia. The results show that the criteria priorities for WPP location suitability evaluation based on Fuzzy-AHP, we can have more objective decisions. In short, the Fuzzy-AHP method has been proven to be an effective tool in multi-criteria decision-making.

5. CONCLUSION

An analysis of AHP multi-criteria decision-making combined with Fuzzy-AHP was developed in this study. The Fuzzy-AHP was conducted by integrating interrelation of a series of criteria to be able to result in more accuracy. The AHP method in this study had an inconsistent value of 9%, which is acceptable as it is less than 10%. This Fuzzy-AHP method was also proven to be an effective tool in the decision-making process, in which in this study was to evaluate the suitable location of WPP. To identify WPP location suitability, the criteria priorities in order were wind velocity, land use, wild animals, climate conditions, land tilt, distance to residential areas, road access, and environmental effect. These results give an important reference to learn important factors to be considered in developing WPP. These findings can also be an important reference for WPP designers and investors. It is also expected that the results of this study are helpful to the government and power companies in formulating the policies of selection of new locations of WPP.

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7. AUTHORS' NOTE

The authors declare that there is no conflict of interest regarding the publication of this article. The authors confirmed that the paper was free of plagiarism.

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