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Research Article

Determining Solar Power Plant Location Using Hesitant Fuzzy AHP Method

Gökçe Candan, Ph.D. *

Assoc. Prof., Department of Financial Econometrics, Faculty of Political Sciences, Sakarya University, Sakarya, Turkey, gcandan@sakarya.edu.tr

Merve Cengiz Toklu, Ph.D.

Assist. Prof., Department of Industrial Engineering, Faculty of Engineering, Sakarya University, Sakarya, Turkey, mtoklu@sakarya.edu.tr

* Sakarya Üniversitesi, Siyasal Bilgiler Fakültesi, Esentepe Kampüsü, 54187 Sakarya Türkiye

ABSTRACT

The fossil resource consumption, which is scarce for the solution of the increasing energy demand problem as the population increases, is replaced by the consumption of renewable energy resources. Solar energy from renewable energy sources is the type of energy with the highest potential on earth. The maximization of the efficiency to be taken from solar energy is possible with the correct selection of the location. The decision to decide on more than one criterion for multiple alternatives is a very difficult problem. Therefore, the problem of choosing a solar power plant is a complex decision problem, and this study aims to solve the problem of the most appropriate location for the Solar Power Plant by using Hesitant Fuzzy AHP. Based on linguistic expressions of three different decision makers, three alternative locations were evaluated by considering four different evaluation criteria.

Keywords: Solar Power, Multi-Criteria Decision Making, Hesitant Fuzzy AHP, Location Decision

1. Introduction

The depletion of fossil resources is the main reason for the search for new energy sources. These new energy sources must be suitable for renewable use without being exhausted, which the least is damaging to the environment so that they can be a modern type of energy compatible with developing technology and energy source.

Solar energy, which is one of the renewable energy sources used for this purpose, has been preferred for countries with high sunshine rates. In Turkey, Mediterranean, Central Anatolia, East Anatolia, and Eastern Anatolia regions in the south, the high rate of sun, here makes it advantageous to set up solar plants.

The high solar potential of the power plant locations is not sufficient by itself. At the same time the criteria for proximity to energy lines and water resources, distance to earthquake fault line and settlement areas should be taken into consideration. There are studies related to solar power plant selection using various methods in the literature. Some of these can be summarized as follows; Kengpol et.al. (2012), used the fuzzy Analytic Hierarchy Process (AHP) method for solar power plant site selection in Thailand. Choudhary and Shankar (2012) used an integrated fuzzy AHP-TOPSIS approach for thermal power plant location selection in India. The evaluation criteria are; cost, availability of resources, accessibility, biological environment, physical environment, socio-economic development.

Yunna and Geng (2014), determined the optimal location for a hybrid solar-wind power station in China by using AHP. The main evaluation criteria are; Accessibility, Resource, Economy, Risk, and Environment. Wu et.al. (2014), created a decision framework for solar thermal power plant location selection with Linguistic Choquet integral method. The evaluation criteria are Energy factor, Infrastructure factor, Land factor, Environmental factor, and Social factor. Jun et.al. (2014), studied about hybrid wind-solar power station location selection problem with ELECTRE 2 Method. Lee et.al. (2015), used fuzzy AHP and data envelopment analysis methods for Solar Power Plant location selection. Aragonés-Beltrán et. al. (2014), used AHP and ANP based method for selecting investment projects about the solar-thermal power plant. Akkas et.al. (2017), determined the optimal Solar Power Plant location in Turkey by using AHP, ELECTRE, TOPSIS, and VIKOR. Özdemir et.al. (2017), studied about Solar Power Plant location selection in Turkey using AHP and VIKOR and Konya was the optimal alternative. Al Garni and Awasthi (2017), studied about solar power plant selection in Saudi Arabia by using geographic information systems and AHP. The evaluation criteria are; environmental, location, economic, climatic and orography. Lee et.al. (2017), studied about Solar Power Plant location selection using fuzzy ANP and VIKOR methods.

By using Hesitant fuzzy sets, the linguistic assessments of the different experts are taken into consideration without any loss of information, and all hesitations are made clear (Boltürk et. al., 2016). Thanks to such advantages, Hesitant Fuzzy AHP is a very advantageous method used in making an optimum selection in complex decision problems. Boltürk et.al. (2016), used Hesitant Fuzzy AHP to select optimum warehouse location. Ayhan (2017), used Hesitant Fuzzy AHP in summer school selection. Öztayşi et al. (2015), solved a multi-criteria decision-making problem consisting of 3 alternatives with Hesitant Fuzzy AHP.

In recent studies, the Hesitant Fuzzy AHP method has been used in selection and criteria weighting problems in various sectors and topics: Samanlioglu and Kaya (2020) determined the importance of applied intervention strategy alternatives for the COVID-19 pandemic by using Hesitant Fuzzy AHP Method. Candan (2020) evaluated 15 OECD member countries' economics researches performances with Hesitant Fuzzy AHP Method. Adem et.al. (2020) determined the safety risk weights by using Hesitant Fuzzy AHP method for industry 4.0. Colak and Kaya (2020) used Hesitant Fuzzy AHP for energy storage technologies selection problem. Büyüközkan and Mukul (2020) determined smart health technology criteria weights with Hesitant Fuzzy AHP Method.

In this study, Hesitant Fuzzy AHP method is used to determine optimum solar power plant location. A case study was discussed that contains 3 alternative locations (Kayseri, Konya, and Adana in Turkey) and 4 decision criteria and 3 experts. In the literature, there is no other study related to solar power plant location selection with Hesitant Fuzzy AHP method.

2. Hesitant Fuzzy AHP Method

Hesitant Fuzzy AHP method was developed by Torra (2010) in 2010, for use in Hesitant situations where the decision maker's preferences cannot be determined by classical fuzzy set theory. For the linguistic variables of this method, Rodriguez et al. (2012), developed a linguistic scale where variables are more flexible and better expressed than classical fuzzy sets (see in Table 1). This makes it easier to choose among the options. The steps of the Hesitant Fuzzy AHP based on Buckley's AHP method are given in the following:

Step 1: By obtaining expert evaluations, binary comparison matrices for criteria and decision alternatives are created.

Step 2: Using the scale given in Table 1, linguistic terms are converted to triangular fuzzy numbers and the pairwise comparison matrix is formed as follows. Here; $\hat{a}_{ij}^{k}$ is the k. expert's evaluation on comparison of i. element to j. element.

$$\hat{A}^k = \begin{vmatrix} 1 & \hat{a}_{12}^k & \cdots & \hat{a}_{1n}^k \\ \hat{a}_{21}^k & 1 & \cdots & \hat{a}_{2n}^k \\ \vdots & \vdots & \vdots & \vdots \\ \hat{a}_{n1}^k & \hat{a}_{n2}^k & \cdots & 1 \end{vmatrix}$$

S	Linguistic Term	Abbreviation	Triangular Fuzzy Number
10	Absolutely High İmportance	(AHI)	(7,9,9)
9	Very High Importance	(VHI)	(5,7,9)
8	Essentially High Importance	(ESHI)	(3,5,7)
7	Weakly High Importance	(WHI)	(1,3,5)
6	Equally High Importance	(EHI)	(1,1,3)
5	Exactly Equal	(EE)	(1,1,1)
4	Equally Low Importance	(ELI)	(0.33,1,1)
3	Weakly Low Importance	(WLI)	(0.2,0.33,1)
2	Essentially Low Importance	(ESLI)	(0.14,0.2,0.33)
1	Very Low Importance	(VLI)	(0.11,0.14,0.2)
0	Absolutely Low Importance	(ALI)	(0.11,0.11,0.14)

Table 1. Hesitant Fuzzy AHP Linguistic Scale (Kahraman et al., 2018)

For evaluate the consistency of each fuzzy pairwise comparison matrix, matrix's values are defuzzified by the graded mean integration approach. If the comparisons are not consistent, experts should re-evaluate pairwise comparisons. A triangular fuzzy number ($\hat{A}$ = (l,m,u)) can be transformed into a crisp number by this equation:

$$A = \frac{l+4*m+u}{6} \tag{1}$$

Step 3: Conflicts are identified and evaluations are renewed if they exist among experts. At this step, it is checked whether the evaluations of the experts are close to each other. If the assessments are not close, experts are advised to discuss the situation and renew the assessments.

B By using fuzzy envelope approach (Liu and Rodriguez, 2014), comparison data are transformed to trapezoidal fuzzy data sets. First, the s scale in Table 1 is sorted low to high and a trapezoidal fuzzy membership function $\hat{A}$ = (a,b,c,d) is calculated where "a" is the minimum and "d" is the maximum value but b and c values are calculated by OWA operator with following equations

$$a = \min\{a_L^i, a_M^i, a_M^{i+1} \ldots\ldots a_M^j, a_R^j\} = a_L^i \tag{2}$$

$$d = \max\{a_L^i, a_M^i, a_M^{i+1} \ldots\ldots a_M^j, a_R^j\} = a_R^i \tag{3}$$

$$b = \begin{cases} a_m^i \;, \; if\ i+1=j \\ OWA_{W^2}\left(a_m^i, \ldots . a_m^{\frac{i+j}{2}}\right), \text{if } i+j \text{ is even} \\ OWA_{W^2}\left(a_m^i, \ldots . a_m^{\frac{i+j-1}{2}}\right), \text{if } i+j \text{ is odd} \end{cases} \tag{4}$$

$$c = \begin{cases} a_m^{i+1} \;, \; if\ i+1=j \\ OWA_{W^1}\left(a_m^j, a_m^{j-1} \ldots . a_m^{\frac{i+j}{2}}\right), \text{if } i+j \text{ is even} \\ OWA_{W^1}\left(a_m^i, a_m^{j-1} \ldots . a_m^{\frac{i+j-1}{2}}\right), \text{if } i+j \text{ is odd} \end{cases} \tag{5}$$

Filev and Yager (1998), assume that the α parameter from [0,1], calculated the weights w_1 and w_2 as in equation 6 and equation 7.

$$w_1^1 = \alpha 2\,,\; w_2^1 = \alpha 2(1-\alpha 2), \ldots\ldots, w_n^1 = \alpha 2(1-\alpha 2)n-2 \tag{6}$$

$$w_1^2 = \alpha_1^{\,n-1},\; w_2^2 = (1-\alpha 1)\alpha_1^{n-2}, \ldots\ldots, w_n^2 = 1-\alpha 1 \tag{7}$$

Here; $\alpha 1 = \frac{g-(j-i)}{g-1}$ and $\alpha 2 = \frac{(j-i)-1}{g-1}$ g is the number of terms in the evaluation scale, j is the highest evaluation order of the given range and i is the lowest evaluation value order of the given range.

Step 5: Pairwise comparison matrix is created with (Ĉ)

$$\hat{C} = \begin{bmatrix} 1 & \hat{c}_{12} & \cdots & \hat{c}_{1n} \\ \hat{c}_{21} & 1 & \cdots & \hat{c}_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ \hat{c}_{n1} & \hat{c}_{n2} & \cdots & 1 \end{bmatrix}$$

$$\hat{c}_{ij} = (\hat{c}_{ij_1}, \hat{c}_{ij_{m1}}, \hat{c}_{ij_{m2}}, \hat{c}_{ij_u}) \quad (8)$$

$$\hat{c}_{ji} = \left(\frac{1}{\hat{c}_{ij_u}}, \frac{1}{\hat{c}_{ij_{m2}}}, \frac{1}{\hat{c}_{ij_{m1}}}, \frac{1}{\hat{c}_{ij_l}}\right) \quad (9)$$

Step 6: The geometric mean is calculated by equation 10 for each row.

$$\hat{r}_i = (\hat{c}_{i1} \otimes \hat{c}_{i2} \ldots \otimes \hat{c}_{in})^{1/n} \quad (10)$$

$$\hat{w}_i = \hat{r}_i \otimes (\hat{r}1 + \hat{r}2 \ldots + \hat{r}n)-1$$

Step 7: The weights of the criteria are obtained by defuzzifing the trapezoidal fuzzy values.

$$D = \frac{c_1 + 2\,c_{m1} + 2\,c_{m2} + c_u}{6} \quad (11)$$

Step 8: The alternatives are ranked according to the weight values and the alternative with the highest weight is selected.

3. Case Study: Solar Power Plant Location Selection

To simplify how a decision problem can be solved with the Hesitant Fuzzy AHP method, an exemplary Solar Power Plant Location Selection problem is discussed in this part of the study.

Kayseri (Alt-1), Konya (Alt-2) and Adana (Alt-3) locations were evaluated with 4 criteria and 3 expert evaluations were taken into consideration to determine which location is the optimum location. Based on the literature and expert advices the criteria are determined as Solar energy potential (C1), Energy cost (C2), Safety (C3), Logistics facilities (C4) (Kengpol et.al., 2012; Choudhary and Shankar, 2012; Akkas et.al., 2017; Lee et.al., 2017; Aktas and Kabak, 2019; Samanlıoğlu and Ayağ, 2017).

First of all, the experts were asked to compare the significance of the evaluation criteria in pairs. Details of the experts are as follows: 2 energy systems engineer from private sector and 1 professor specialized in energy. The linguistic expressions obtained are shown in Tables 2, 3 and 4.

1st Expert	**C_1**	**C_2**	**C_3**	**C_4**
C_1	EE	WHI	ESHI	VHI
C_2		EE	ELI	EHI
C_3			EE	WLI
C_4				EE

Table 2. Evaluation of 1st Expert

2nd Expert	**C_1**	**C_2**	**C_3**	**C_4**
C_1	EE	EE	VHI	ESHI
C_2		EE	ESLI	WLI
C_3			EE	EHI
C_4				EE

Table 3. Evaluation of 2nd Expert

3rd Expert	**C_1**	**C_2**	**C_3**	**C_4**
C_1	EE	VHI	ESHI	AHI
C_2		EE	VLI	EE
C_3			EE	VLI
C_4				EE

Table 4. Evaluation of 3rd Expert

The three comparison matrices are then grouped under a single matrix and the range of linguistic expressions is shown in Table 5.

	C1	C2	C3	C4
C1	EE	Between VHI and EE	Between VHI and ESHI	Between AHI and ESHI
C2		EE	Between ELI and VLI	Between EHI and WLI
C3			EE	Between EHI and VLI
C4				EE

Table 5. Aggregated Fuzzy Envelopes

The linguistic expressions were converted to numerical expressions through hesitant fuzzy sets and Table 6 shows normalized fuzzy criteria weights and Table 7 shows normalized defuzzified Criteria Weights. Accordingly, the order of importance of the criteria is $C_1 > C_4 > C_3 > C_2$ from highest to lowest.

C_1	0.169	0.497	0.769	1.983
C_2	0.022	0.075	0.120	0.502
C_3	0.033	0.105	0.172	0.663
C_4	0.033	0.122	0.191	0.753

Table 6. Normalized Fuzzy Criteria Weights

Criteria	W
C_1	0.567
C_2	0.110
C_3	0.151
C_4	0.171

Table 7. Criteria Weights

Experts were asked to evaluate each alternative location for each criterion and matrices consisting of individual linguistic expressions were obtained. Tables 8, 9, 10 and 11 include the combined form of these statements. Table 12 shows the priority values of criteria with respect to Alternatives and Table 13 shows fuzzy, defuzzified and normalized weights of alternatives with respect to criteria. Accordingly, among the alternatives, the one with the highest weight is Alt-2 (Konya) and it should be selected as the most suitable alternative for solar power plant.

C_1	Alt-1	Alt-2	Alt-3
Alt-1	EE	Between EHI and WLI	Between EE and ESLI
Alt-2		EE	Between WHI and ELI
Alt-3			EE

Table 8. Pairwise comparison of the alternatives with respect to C_1

C_2	Alt-1	Alt-2	Alt-3
Alt-1	EE	Between EE and WLI	Between ELI and ESLI
Alt-2		EE	Between EHI and ELI
Alt-3			EE

Table 9. Pairwise comparison of the alternatives with respect to C_2

C_3	Alt-1	Alt-2	Alt-3
Alt-1	EE	Between ELI and WLI	Between EHI and WLI
Alt-2		EE	Between EHI and EE
Alt-3			EE

Table 10. Pairwise comparison of the alternatives with respect to C_3

C_4	Alt-1	Alt-2	Alt-3
Alt-1	EE	Between WHI and WLI	Between WHI and WLI
Alt-2		EE	Between EE and ELI
Alt-3			EE

Table 11. Pairwise comparison of the alternatives with respect to C_4

	C_1				C_2			
Alt-1	0.0099	0.1477	0.2835	3.6191	0.0016	0.0236	0.0424	0.4307
Alt-2	0.0143	0.1586	0.2674	4.0622	0.0027	0.0245	0.0409	0.7388
Alt-3	0.0089	0.1496	0.2870	2.5093	0.0014	0.0152	0.0444	0.3995
	C_3				C_4			
Alt-1	0.0028	0.0306	0.0638	0.6228	0.0022	0.0408	0.0637	2.0219
Alt-2	0.0058	0.0306	0.0919	0.9013	0.0024	0.0408	0.0637	1.1532
Alt-3	0.0020	0.0213	0.0638	0.5271	0.0017	0.0408	0.0637	0.7996

Table 12. Priority values of criteria with respect to alternatives

	Fuzzy Scores				Defuzzified scores	w
Alt-1	0.016	0.243	0.453	6.694	1.3503	0.368
Alt-2	0.025	0.254	0.464	6.855	1.3861	0.377
Alt-3	0.014	0.227	0.459	4.235	0.9367	0.255

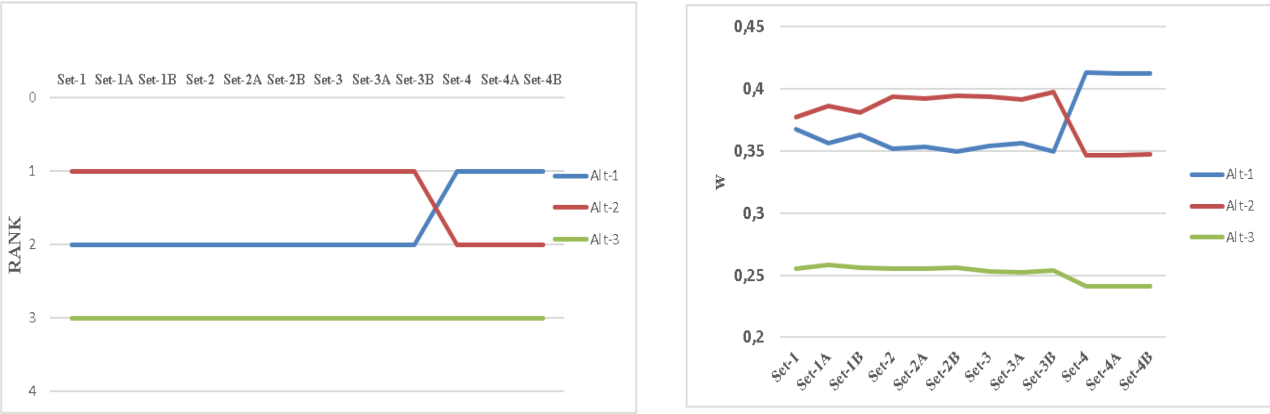
Table 13. Fuzzy, defuzzified and normalized weights of alternatives with respect to criteria

3.1. Sensitivity Analysis

A sensitivity analysis is realized to examine the robustness of the solutions and ranking of alternatives by changing the weights of criteria set. It is aimed to investigate the effects of possible changes in their weights on the final ranking of the alternatives (Kahraman et al., 2018). The alternative sets used for sensitivity analysis are shown in Table 14. Figure 1 shows the effects of possible changes in the weights on evaluation criteria.

	C1	C2	C2	C4
Set-1	[1.732;2.982;3.69;5.196]	[0.222;0.452;0.574;1.316]	[0.332;0.632;0.824;1.736]	[0.333;0.734;0.917;1.973]
Set-1A	[1.732;2.982;3.69;5.196]	[0.332;0.632;0.824;1.736]	[0.333;0.734;0.917;1.973]	[0.222;0.452;0.574;1.316]
Set-1B	[1.732;2.982;3.69;5.196]	[0.333;0.734;0.917;1.973]	[0.222;0.452;0.574;1.316]	[0.332;0.632;0.824;1.736]
Set-2	[0.222;0.452;0.574;1.316]	[1.732;2.982;3.69;5.196]	[0.332;0.632;0.824;1.736]	[0.333;0.734;0.917;1.973]
Set-2A	[0.332;0.632;0.824;1.736]	[1.732;2.982;3.69;5.196]	[0.222;0.452;0.574;1.316]	[0.333;0.734;0.917;1.973]
Set-2B	[0.333;0.734;0.917;1.973]	[1.732;2.982;3.69;5.196]	[0.222;0.452;0.574;1.316]	[0.332;0.632;0.824;1.736]
Set-3	[0.222;0.452;0.574;1.316]	[0.332;0.632;0.824;1.736]	[1.732;2.982;3.69;5.196]	[0.333;0.734;0.917;1.973]
Set-3A	[0.332;0.632;0.824;1.736]	[0.222;0.452;0.574;1.316]	[1.732;2.982;3.69;5.196]	[0.333;0.734;0.917;1.973]
Set-3B	[0.222;0.452;0.574;1.316]	[0.333;0.734;0.917;1.973]	[1.732;2.982;3.69;5.196]	[0.332;0.632;0.824;1.736]
Set-4	[0.333;0.734;0.917;1.973]	[0.222;0.452;0.574;1.316]	[0.332;0.632;0.824;1.736]	[1.732;2.982;3.69;5.196]
Set-4A	[0.333;0.734;0.917;1.973]	[0.332;0.632;0.824;1.736]	[0.222;0.452;0.574;1.316]	[1.732;2.982;3.69;5.196]
Set-4B	[0.332;0.632;0.824;1.736]	[0.333;0.734;0.917;1.973]	[0.222;0.452;0.574;1.316]	[1.732;2.982;3.69;5.196]

Table 14. Weights for sensitivity analysis



(a) (b)

Figure 1. Result of sensitivity analysis

On defuzzifying the criteria weights, it is found that [1.732;2.982;3.69;5.196] has the highest weight value. In Table 14, the highest weight value [1.732;2.982;3.69;5.196] is allotted to Criteria-2 (Energy cost), Criteria-3 (Safety), and Criteria-4 (Logistics facilities) in set-1, set-2, set-3 and set-4 respectively. Set-1 is the criteria weights obtained from the spherical fuzzy AHP. The A, B variants in the sets were created by changing the weights of the other 3 criteria. The results of the sensitivity analysis are represented in Figure 1. In Figure 1 (a), alternatives were evaluated according to rank, and in Figure 1 (b), alternatives were evaluated according to their final weight (w). According to Figure 1, it is seen that the priority order of the alternatives changes only when the importance weights of C_1 and C_4 are changed. Alt-3 is always determined as the third alternative. According to the sensitivity analysis results, it was determined that slight changes in weight for each criterion do not affect the best alternative. This proves that a robust decision is given.

4. Conclusion

The trend towards renewable energy sources has increased in recent years with the depletion of fossil resources. While the decision to invest in power plants for solar energy, which has many advantages over renewable energy sources, the location of the establishment is very important. In addition to the high rate of sunshine duration of the location where the solar power plant will be installed, it is important that proximity to energy sources, water resources, lack of a location with security weaknesses, etc. These criteria should be evaluated and the decision should be made instead of the establishment.

Multi-criteria decision-making methods are used effectively for location selection. In this study, it has been decided which of the provinces of Kayseri, Konya, and Adana are the most suitable locations by Hesitant Fuzzy AHP method which makes transactions with Hesitant fuzzy sets and make numeric expressions composed of various expert opinions closest to reality. The opinions of 3 different experts were evaluated for alternative locations in terms of 4 different criteria and it was decided that the most suitable place for the solar power plant was Konya. In future studies, location decision problems can be addressed by using different methods using hesitant fuzzy sets, different locations and more expert opinions can be included in the evaluation. It is possible to differentiate the solar energy locations to be determined; the method used in this study can be applied to different regions of

Turkey or different countries. Criteria weights can be determined by spherical fuzzy sets integrated methods or other fuzzy sets and different multi criteria decision making approaches. Hesitant Fuzzy AHP method can also be applied to other sector-related selection and ranking problems.

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