Optimal site selection of electric vehicle charging station based on fuzzy AHP-TOPSIS

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Abstract
Different from previous studies which mostly utilize optimization model, optimal site selection of electric vehicle charging station was regarded as a multi-criteria decision-making problem in this paper. A comprehensive evaluation system was built and the optimal site was selected by fuzzy AHP-TOPSIS. It has been proved effective, practical and robust.

Key words: EV charging station, Optimal site selection, Fuzzy AHP-TOPSIS

INTRODUCTION

Recently, Electric vehicle (EV) has become more and more popular because of the energy crisis and all varieties of environment problems. However, when we focus on the EV research and marketing expansion, the construction of infrastructures related to EV must be considered proactively. Electric vehicle charging station (EVCS) is the most vital to electric vehicle industry development. Whether the site of EV is optimal or not have a great impact on basic infrastructure investment, the quality, safety and economy of EVCS.

At present, most of the research on optimal site of EVCS concentrate on establishing optimal model and all kinds of algorithms to decide the optimal site and size of EVCS. Mohammad H. Moradi et al. (2015) developed a multi-objective optimization problem to obtain the optimal siting and sizing of charging stations. Joana Cavadas et al. (2015) proposed an improved mathematical model for locating EV charging stations considering the successive activities of the travelers and the model is tested for the city of Coimbra

(Portugal). Kazem Khalkhali et al. (2015) employed data envelopment analysis theorem in plug-in hybrid electric vehicle charging station planning.

There are still several papers regarding the site selection of EVCS as a multi-criteria decision-making problem to study. Sen Guo et al. (2015) found out the optimal site of EVCS in Beijing by using fuzzy TOPSIS. Jiayan Yuan et al. (2014) established an evaluation system of EVCS site selection and employed AHP and fuzzy comprehensive evaluation method to analysis the optimal site of EV charging and swapping station. Chao Feng et al. (2012) integrated Delphi and GAHP to a new comprehensive evaluation method to decide optimal siting of EVCS. Zheci Tang et al. (2013) proposed Voronoi Diagram and FAHP Method to make a decision on optimal siting of EVCS.

Fuzzy AHP and TOPSIS can be also used in site selection of thermal power and gas stations. Devendra Choudhary et al. (2012) proposed an STEEP-fuzzy AHP-TOPSIS based framework for selection of optimal locations for thermal power plants. Kaboli et al. (2007) employed a fuzzy AHP method for plant location selection problem.

Different from previous studies which mostly utilize optimization model, optimal site selection of electric vehicle charging station was regarded as a multi-criteria decision-making problem in this paper. A comprehensive evaluation system was built and the optimal site was selected by fuzzy AHP-TOPSIS. It has been proved effective, practical and robust.

RESEARCH METHODOLOGY

Fuzzy Analytic Hierarchy Process (FAHP)

The membership function of a triangular fuzzy number A, denoted by triplet (l, m, n), is defined as

$$\mu_A(x)=\begin{cases}\dfrac{x-l}{m-l}, & l\le x\le m,\\ \dfrac{n-x}{n-m}, & m\le x\le n,\\ 0, & \text{otherwise}\end{cases} \qquad (1)$$

Let $A_1=(l_1,m_1,n_1)$ and $A_2=(l_2,m_2,n_2)$ are two triangular fuzzy numbers, then

$$A_1\oplus A_2=(l_1,m_1,n_1)\oplus(l_2,m_2,n_2)=(l_1+l_2,m_1+m_2,n_1+n_2) \qquad (2)$$

$$A_1\otimes A_2=(l_1,m_1,n_1)\otimes(l_2,m_2,n_2)\approx(l_1l_2,m_1m_2,n_1n_2) \qquad (3)$$

$$\lambda\otimes A=\lambda(l,m,n)=(\lambda l,\lambda m,\lambda n),(\forall\lambda\in R) \qquad (4)$$

$$A^{-1}=(l,m,n)^{-1}\approx[\frac{1}{n},\frac{1}{m},\frac{1}{l}] \qquad (5)$$

The general fuzzy-AHP process used in this paper is discussed as follows:

Step 1: Calculation of fuzzy synthetic extent

Let $X = \{x_1, x_2, ..., x_n\}$ be an object set, and $U = \{u_1, u_2, ..., u_m\}$ be a goal set. Using Chang's extent analysis approach, m extent analysis values for each object can be calculated, and are denoted as:

$A_{g_i}^1, A_{g_i}^2, ..., A_{g_i}^m \quad (i = 1,2,......, n)$

where all the are triangular fuzzy numbers. With respect to the ith object, the value of fuzzy synthetic extent is defined as:

$$S_i = \sum_{j=1}^{m} A_{g_i}^j \otimes [\sum_{i=1}^{n} \sum_{j=1}^{m} A_{g_i}^j]^{-1} \tag{6}$$

Step 2: Comparison of fuzzy values

For the two triangular fuzzy numbers $A_2 = (l_2, m_2, n_2)$ and $A_2 = (l_2, m_2, n_2)$, the degree of possibility of is defined as:

$$V(A_2 \geq A_1) = \begin{cases} 1, & m_2 \geq m_1 \\ \dfrac{l_1 - n_2}{(m_2 - n_2) - (m_1 - l_1)} & \text{otherwise} \\ 0, & l_1 \geq n_2 \end{cases} \tag{7}$$

Step 3: Calculation of fuzzy weights

The degree possibility of convex fuzzy number to be greater than K convex fuzzy numbers can be defined by:

$$V(A \geq A_1, A_2, ..., A_K) = V[(A \geq A_1) \cap (A \geq A_2) \cap ... \cap (A \geq A_K)] \tag{8}$$

$$V(A \geq A_1, A_2, ...A_K) = \min V(A \geq A_i) \quad \text{for } i = 1,2,..., k \tag{9}$$

$$m(p_i) = \min V(S_i \geq S_k) \quad \text{for } k = 1,2,...n; k \neq i \tag{10}$$

Then, the fuzzy weights vector is

$$w_p = (m(p_1), m(p_2), ...m(p_n))^T \tag{11}$$

Step 4: Calculation of normalized weight vector:

We get the normalized weight vectors

$$W = (w(p_1), w(p_2), ...w(p_n))^T \tag{12}$$

Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS)

Let $A = \{A_1, A_2, ... A_m\}$ be a set of alternative, $F = \{f_1, f_2, ..., f_n\}$ be a set of attribute, and $X = (x_{ij})_{m*n}$ be a decision matrix, for $i \in M$, $j \in N$, $M = \{1,2,...,m\}$, $N = \{1,2,...,n\}$.

The general TOPSIS process used in this paper is discussed as follows:

Step 1: Construct normalized decision matrix. The normalized value $Y = (y_{ij})_{m*n}$ is calculated as

$$y_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}}, i \in M, j \in N \quad (13)$$

Step 2: Construct the weighted normalized decision matrix $Z = (z_{ij})_{m*n}$.Assume we have a set of weights for each criteria $w = (w_1, w_2, ..., w_n)$, and, then

$$z_{ij} = w_j y_{ij}, i \in M, j \in N; \quad (14)$$

Step 3: Determine the positive ideal and negative ideal solutions.

$$A^+ = (z_1^+, z_2^+, ..., z_n^+), \quad z_j^+ = \max_i z_{ij}, j \in T_1; z_j^+ = \min_i z_{ij}, j \in T_2; \quad (15)$$

$$A^- = (z_1^-, z_2^-, ..., z_n^-), \quad z_j^- = \min_i z_{ij}, j \in T_1; z_j^- = \max_i z_{ij}, j \in T_2 \quad (16)$$

Step 4: Calculate the separation distances for each alternative from the positive ideal alternative and the negative ideal alternative respectively.

$$d_i^+ = \sqrt{\sum_{j=1}^{n} (z_{ij} - z_j^+)^2}; \quad d_i^- = \sqrt{\sum_{j=1}^{n} (z_{ij} - z_j^-)^2}, i \in M \quad (17)$$

Step 5: Calculate the relative closeness to the ideal solution.

$$C_i^+ = \frac{d_i^-}{d_i^+ + d_i^-}, i \in M \quad (18)$$

Where C_i^+ denotes the final performance score in TOPSIS method.

Step 6: Rank the alternatives using C_i^+ index value in decreasing order.

CASE STUDY

Application of Fuzzy AHP in Determining Weights of Criteria

In this paper, we establish a comprehensive evaluation index system of EVCS site selection which consists of environment, economy, society and technology criteria and a total of 14 sub-criteria, and is shown in Table 1. And we employ the method defined by Gumus (2009) to determine linguistic comparison terms and their equivalent triangular fuzzy numbers (TFN) in Table 2.

The fuzzy comparison matrices of criteria and sub-criteria along with calculated weights are shown in Table 3-9. The weight calculations using Chang's (1996) extent analysis approach for Table 3 are given below.

Table 1 Comprehensive evaluation index system of EVCS site selection

Criteria	sub-Criteria
Environment C_1	Destruction degree on vegetation and water C_{11}
	Waste discharge C_{12}
	Greenhouse gas emission reduction C_{13}
	Fine particulate matter emission reduction C_{14}
Economy C_2	Construction cost C_{21}
	Annual operation and maintenance cost C_{22}
	Investment pay-back period C_{23}
Society C_3	Harmonization of EVCS with the development planning of urban road network and power grid C_{31}
	Traffic convenience C_{32}
	Impact on people's lives C_{33}
Technology C_4	Permissible power grid capacity C_{41}
	Distance from power grid C_{42}
	Condition of geology C_{43}
	Service capacity C_{44}

Table 2 Triangular fuzzy numbers of linguistic comparison measures

Linguistic terms	Triangular fuzzy numbers (TFN)
Perfect	(8, 9, 10)
Absolute	(7, 8, 9)
Very good	(6, 7, 8)
Fairly good	(5, 6, 7)
Good	(4, 5, 6)
Preferable	(3, 4, 5)

Not bad	(2, 3, 4)
Weak advantage	(1, 2, 3)
Equal	(1, 1, 1)

Table 3 Fuzzy comparison matrix of criteria

	C_1	C_2	C_3	C_4
C_1	(1,1,1)	(2,3,4)	(1,2,3)	(1,2,3)
C_2	(1/4,1/3,1/2)	(1,1,1)	(1/3,1/2,1/1)	(1/3,1/2,1/1)
C_3	(1/3,1/2,1/1)	(1,2,3)	(1,1,1)	(1,2,3)
C_4	(1/3,1/2,1/1)	(1,2,3)	(1/3,1/2,1/1)	(1,1,1)

The values of fuzzy synthetic extent of six criteria with respect to the goal are calculated as below by using Eq.(6)

$$S_1 = (5.00,8.00,11.00) \otimes (12.90,19.83,28.50)^{-1} = (0.1754,0.4034,0.8527)$$

$$S_2 = (1.91,2.33,3.50) \otimes (12.90,19.83,28.50)^{-1} = (0.0670,0.1175,0.2713)$$

$$S_3 = (3.33,5.50,8.00) \otimes (12.90,19.83,28.50)^{-1} = (0.1168,0.2774,0.6202)$$

$$S_4 = (2.66,4.00,6.00) \otimes (12.90,19.83,28.50)^{-1} = (0.0933,0.2017,0.4651)$$

The V values calculated using Eq.(7) are shown in Table 4.

We obtain the minimum degree of possibility and finally get the weight vector with the help of Eqs.(8), (9) and (10).

$$m(C_1) = \min V(S_i \geq S_k) = \min(1.00,1.00,1.00) = 1.00$$

$$m(C_2) = \min(0.25,0.49,0.68) = 0.25$$

$$m(C_3) = \min(0.78,1.00,1.00) = 0.78$$

$$m(C_4) = \min(0.59,1.00,0.82) = 0.59$$

Then the weight vector is calculated as

$$w_p = (1.00,0.25,0.78,0.59)^T$$

We get the normalized weight vectors by using Eq.(11), which is shown below.

$$w = (0.38,0.10,0.30,0.22)^T$$

Table 4 V values for criteria

	1	2	3	4
1		0.25	0.78	0.59
2	1.00		1.00	1.00
3	1.00	0.49		0.82
4	1.00	0.68	1.00	

Table 5 The fuzzy comparison matrix and weights of C_{11}-C_{14}

	C_{11}	C_{12}	C_{13}	C_{14}	Weight
C_{11}	(1,1,1)	(1,2,3)	(1/4,1/3,1/2)	(1/3,1/2,1)	0.19
C_{12}	(1/3,1/2,1)	(1,1,1)	(1/4,1/3,1/2)	(1/3,1/2,1)	0.06
C_{13}	(2,3,4)	(2,3,4)	(1,1,1)	(1,2,3)	0.44
C_{14}	(1,2,3)	(1,2,3)	(1/3,1/2,1)	(1,1,1)	0.31

Table 6 The fuzzy comparison matrix and weights of C_{21}-C_{23}

	C_{21}	C_{22}	C_{23}	Weight
C_{21}	(1,1,1)	(1/3,1/2,1)	(1/3,1/2,1)	0.20
C_{22}	(1,2,3)	(1,1,1)	(1/3,1/2,1)	0.34
C_{23}	(1,2,3)	(1,2,3)	(1,1,1)	0.46

Table 7 The fuzzy comparison matrix and weights of C_{31}-C_{33}

	C_{31}	C_{32}	C_{33}	Weight
C_{31}	(1,1,1)	(1,2,3)	(1/3,1/2,1)	0.35
C_{32}	(1/3,1/2,1)	(1,1,1)	(1/3,1/2,1)	0.20
C_{33}	(1,2,3)	(1,2,3)	(1,1,1)	0.45

Table 8 The fuzzy comparison matrix and weights of C_{41}-C_{44}

	C_{41}	C_{42}	C_{43}	C_{44}	Weight
C_{41}	(1,1,1)	(2,3,4)	(1,2,3)	(1,2,3)	0.45
C_{42}	(1/4,1/3,1/2)	(1,1,1)	(1/4,1/3,1/2)	(1,1,1)	0.04
C_{43}	(1/3,1//2,1)	(2,3,4)	(1,1,1)	(1,2,3)	0.39
C_{44}	(1/3,1//2,1)	(1,1,1)	(1/3,1/2,1)	(1,1,1)	0.12

Application of TOPSIS in Ranking of Alternatives

TOPSIS is used in this phase to rank the alternatives. Firstly, in order to select several potential locations to plant EVCS, related experts are invited to make a choice according to their experience and feasibility report, and finally they select four districts as the alternative locations in this paper, which are East and West district (L1), Hanyang district (L2), Jiangxia district (L3) and Hongshan district (L4) in Wuhan.

Table 9 is the fuzzy comparison matrix of the alternative locations with respect to sub-criterion C_{11}. And the weights of the locations with respect to criteria C_1-C_4 are shown in Table 10. We can get the weighted normalized decision matrix and the final evaluation and ranking of alternative locations with the help of Table 10, which are shown in Table 11 and Table 12.

Table 9 The fuzzy comparison matrix of the locations with respect to sub-criterion C_{11}

C_{11}	L1	L2	L3	L4
L1	(1,1,1)	(1/4,1/3,1/2)	(1,1,1)	(1/4,1/3,1/2)
L2	(2,3,4)	(1,1,1)	(1,2,3)	(1,2,3)
L3	(1,1,1)	(1/3,1/2,1)	(1,1,1)	(1/3,1/2,1)
L4	(2,3,4)	(1/3,1/2,1)	(1,2,3)	(1,1,1)

Table 10 The weights of the locations with respect to criteria C_1-C_4

	C_1	C_2	C_3	C_4
L1	0.3069	0.1814	0.4235	0.1367
L2	0.3075	0.3182	0.3500	0.3913
L3	0.1079	0.3172	0.0830	0.2667
L4	0.2764	0.1832	0.1435	0.2053

Table 11 The weighted normalized decision matrix

	C_1	C_2	C_3	C_4
L1	0.2217	0.0350	0.2214	0.0564
L2	0.2221	0.0614	0.1830	0.1612
L3	0.0779	0.0612	0.0434	0.1099
L4	0.1996	0.0354	0.0750	0.0846

Table 12 The final evaluation and ranking of alternative locations

Location	S_i^+	S_i^-	C_i	Ranking
L1	0.1081	0.2288	0.6791	2
L2	0.0384	0.2280	0.8559	1
L3	0.2345	0.0596	0.2027	4
L4	0.1687	0.1289	0.4331	3

Results and Sensitivity Analysis

The four alternative EVCS locations are ranked by fuzzy TOPSIS, and the results show that Hangyang district is the optimal site to establish EVCS. In order to prove the robust of the results, we made the sensitivity analysis by varying the weights of all sub-criteria. Because of the limitation of pages, this paper gives only sensitivity analysis results of C_{11} and C_{14}, which are shown in Figure 1 and Figure 2. From the sensitivity analysis results, we can point out that scores of four alternatives would fluctuate with the weight fluctuation. However, L2 is always the top of all no matter what the weights are. Hence, L2 is the optimal site to establish EVCS and the method also is proved to be robust.

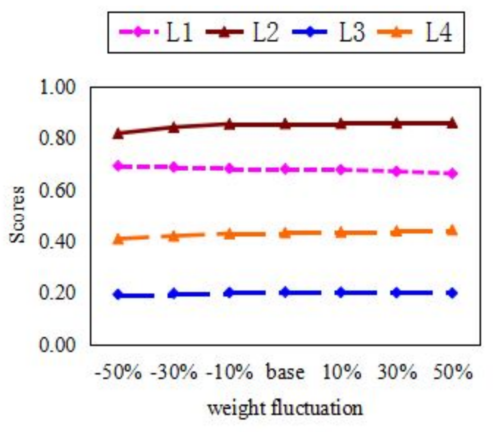

Figure 1 Sensitivity analysis result of C_{11}

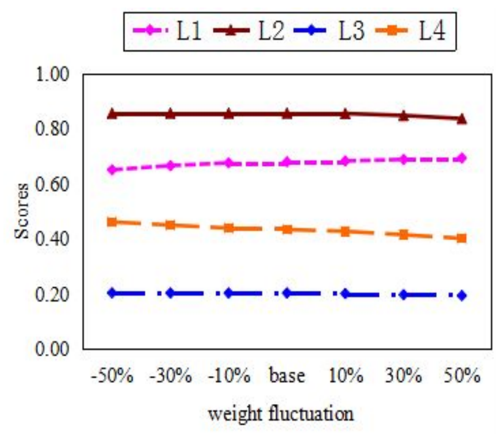

Figure 2 Sensitivity analysis result of C_{14}

CONCLUSIONS

In this paper, we established a comprehensive evaluation index system of EVCS site selection based on the related references and experts' opinions, which consists of environment, economy, society and technology criteria and a total of 14 sub-criteria.And considering the vagueness and uncertainty of qualitative criteria, we employed fuzzy AHP to calculate the fuzzy weights of all criteria and TOPSIS to rank the alternative locations to select the optimal site. Finally, we give the results of sensitivity analysis to prove the robust of the results. However, using fuzzy AHP-TOPSIS to select optimal

EVCS is effective, reasonable and stable, which can provide a valid reference for managers at the same time.

Future work can employ fuzzy VIKOR or fuzzy ELECTRE to the site selection of EVCS and also can compare different result of these methods to find out the most effective way to solve the problem.

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