A Fuzzy Evaluation and AHP based Method for the Energy Efficiency Evaluation of EV Charging Station

Hanwu Luo
School of Electrical Engineering, Wuhan University, Wuhan, China
Email: hanwu_luo@yahoo.com

Jiangjun Ruan and Fang Li
Henan Electric Power Company, Songshan South Road, Zhengzhou, China

***Abstract*—To promote the development of electric vehicles (EVs), many charging stations have been built. The construction of charging stations costs a lot, hence it's necessary to evaluate their energy efficiency due to their main aims of energy conservation. In this paper, a fuzzy model based on the fuzzy comprehensive evaluation (FCE) and analytic hierarchy process (AHP) is presented to evaluate the energy efficiency of charging station. Firstly the evaluation system for the charging station is set up according to AHP and expert surveys, and the evaluation indices are determined by the Argument Delphi method. Then the method to establish the judgment matrix is described, and 7 judgment matrices are established. The process to calculate the weights of all indices in the evaluation system is formulated based on AHP, including the weights for the criterions in the second layer and indices in the third layer. Finally the energy efficiency evaluation on the charging station is conducted according to FCE. The energy efficiency of a charging station in Chongqing was evaluated, and results indicate that the fuzzy model in this paper is effective for the energy evaluation of charging station.**

***Index Terms*—energy efficiency evaluation, charging station, analytic hierarchy process, fuzzy comprehensive evaluation, evaluation indices**

I. Introduction

As environmental pressure and energy depletion are increasingly severe, more and more attention has been paid to electric vehicles (EVs) because of their high energy efficiency and low off-gas emission compared to conventional internal combustion engine based vehicles [1]. Ultimately, EVs will shift energy demands from crude oil to electricity for the personal transportation sector. To promote the development of EVs, many charging stations have been built, and more and more will be built [2-5].

Meanwhile many researches regarding EVs are being conducted, including the design and optimization of charging stations, investigation on the control of vehicle-to-grid (V2G)[6-13], analysis on the influence caused by the charging machines [14-17], energy storage of EV, charging techniques[18,19], and so on. And many achievements have been obtained. In China the national grid has started the construction of charging station since 2009, which aims at fasting the promotion of EVs.

The aim of the promotion of EV and construction of charging stations is energy conservation and reduction of off-gas emission. Energy efficiency evaluation has been proved to be a way to evaluate the contribution of a device or a system to energy conservation. Therefore, it is necessary to build a proper and comprehensive energy efficiency evaluation system for charging station, which can ensure that EVs and charging stations play an important role in the worldwide energy conservation & emission reduction.

Hence in this paper a fuzzy model based on the fuzzy comprehensive evaluation and analytic hierarchy process is presented to evaluate the energy efficiency of charging station.

Fuzzy comprehensive evaluation method, mainly using of evaluation results of single factor related to the evaluation object, is to form the corresponding evaluation matrix, and to do fuzzy transformation using the weighting factor for determining the important degree of each factor, and the final evaluation results of the evaluation object will be obtained. Fuzzy evaluation set is determined by the use of the factor set, membership degree, weighting factor, and the best evaluation results will be obtained from the alternative set. An AHP hierarchy is a structured means of modeling the decision. It consists of an overall goal, a group of options or alternatives for reaching the goal, and a group of factors or criteria that relate the alternatives to the goal.

Firstly the evaluation system for the charging station is set up according to AHP, which is divided into three layers: goal layer, criterion layer and indices layer. The criterions and indices in the evaluation system are obtained by expert surveys based on Delphi method.

Then the method to establish the judgment matrix is

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described, and 7 judgment matrices are established which are basic for the calculation of indices weights. And the process to calculate the weights of all indices in the evaluation indices system based on AHP is formulated, including the weights for the criterions in the second layer and indices in the third layer.

Finally the energy efficiency evaluation on the charging station is conducted according to the process of FCE, and the assessment rating can be obtained. The energy efficiency of a charging station in Chongqing is evaluated, assessment ratings for the total goal and six criterions are obtained, and according to which corresponding measures can be taken to improve the energy efficiency of EV charging station.

The remaining parts of the paper are arranged as follows: The evaluation system of energy efficiency is set up in Section II, and the process to evaluate the energy efficiency based on fuzzy comprehensive method is described in Section III, and the energy efficiency evaluation on a charging station in Chongqing is conducted in Section IV. Finally conclusions end the paper.

II. Setup of the Evaluation System

A. *Delphi Method*

Delphi method is a survey technique for achieving consensus among isolated anonymous participants with a controlled feedback of opinions. This technique is being increasingly used in many complex areas in which a consensus is to be reached. Some of these areas included the development of residential areas, theory and design application, and bridge condition rating and effects of improvements. Moreover, the Delphi method is a highly formalized method of communication that is designed the maximum amount of unbiased information from a panel of experts. Therefore, this method is adopted and used for obtaining a set of selection criteria for the selection of the procurement system.

Delphi method means asking a number of experts for advice on some questions, and then collecting the opinions of each adviser and distributing them to experts as reference materials. It is a method in which the experiences, knowledge, and presumptions of expert panelists on an issue or development process under study are collected in an interactive process, normally by interview or survey [20, 21]. As a data collection method, the Delphi can fall in the category of both a quantitative and qualitative study. It is useful when the phenomenon under study is complex or when the topic is somehow delicate – difficult to define, awkward to talk about, politically delicate, etc – or the number of members in the focus group is relatively small.

In this study the Argument Delphi method is used to set up the evaluation system for the energy efficiency of charging station, including the determination of criterions and evaluation indices. The Delphi method process was conducted mainly following the Argument Delphi method, and the whole process took about four months, the process is shown in Table I.

TABLE I.
PROCESS TO SET UP THE EVALUATION SYSTEM BASED ON ARGUMENT DELPHI METHOD

Phase	Purpose and content	Participants
First round: - Selection of the expert panel - Semi-structured interviews	- Identify the key issues in the evaluation and assist in formulating the topics - Find meaningful questions and future statements	15 in-depth interviews
Second round: - Questionnaire to the panelists - 43 future statements	- Evaluate the statements and argumentation for the evaluation indices	37 panelists representing - Specialists (13/13) - Generalists (12/14) - Industry (7/10) 32 responses
Third round: - Questionnaire to the panelists - 29 future statements	- Determine the evaluation indices	30 panelists representing - Technical experts (15/15) - Management experts (12/15) -27 responses

B. *Energy Efficiency Evaluation System for Charging Station*

According to the results obtained by the expert survey based on Argument Delphi method and the principle of AHP[21-25], the energy efficiency evaluation system for the charging station is set up as shown in Fig.1.

Analytic hierarchy process (AHP) is a systematic analysis method which was proposed by a professor in the University of Pittsburgh named Satai in the70 years of 20th century. It regards the evaluation subjects or problems as a system, and breaks down the problems into different elements according to the nature of question and the expected overall objective, and gathers those elements at different levels in accordance with the correlation and subordination among the elements, to form a multilevel analysis system which makes the problems organized and hierarchical. This research adopts AHP and makes pairwise comparison and forms a matrix to calculate the relative compared weight, and makes the consistency test of the matrix.

The evaluation system for the energy efficiency of charging station is composed of three layers. The top layer is the goal of the system - energy efficiency of the charging station (G0).

The second layer contains six criterions as follows:

B1-Departments & strategies, is the division of the department and strategies for management and energy conservation in the charging station. B1 contains 3 indices C1 to C3.

B2-Management & training of staff, incorporates 2 indices C4 and C5.

B3-Management of equipment, is related to 3 indices-C6 to C8.

B4-Efficiency of power supply system, is related with the efficiency of power supply equipment, such as transformers, switchgear. Four indices C9 to C12 are contained in B4.

B5-Efficiency of charging equipment, is comprised of three indices C13 to C15.

B6-Efficiency of monitoring system, is composed of three indices C16 to C18.

The third layer is composed of 18 indices, including: C1- Energy conservation department, C2- Energy conservation strategy, C3- Energy efficiency management, C4 - Energy conservation operation training, C5 - Energy conservation management training , C6 - Equipment depreciation degree, C7- Equipment technical rating, C8 - Equipment maintenance plan, C9 - Distribution transformers, C10 - Distribution switchgears, C11 - Electricity meters, C12 - Harmonic processing equipment, C13 – Rectifiers, C14 - DC charging machines, C15 - Billing equipment, C16 - Security monitoring system, C17 - Charging monitoring system, C18 - Intelligent charging monitoring system.

III. EVALUATION PROCESS FOR THE ENERGY EFFICIENCY OF CHARGING STATION

When the evaluation system for the energy efficiency of the charging station is established, the weights for the indices C1 to C18 in the third layer and criterions B1 to B6 should be calculated, and the evaluation based on fuzzy comprehensive evaluation can be carried out.

In this part, the establishment of the judgment matrix, method to calculate the weights of indices and evaluation process based on FCE will be described.

A. Establishment of Judgment Matrix for the Evaluation System

To calculate the weight of the indices in the evaluation system, firstly the judgment matrix $A=(a_{ij})_{n\times n}$ for each layer in the evaluation system should be set up. In AHP model, judgment matrix can be constructed by pair-wise comparisons between factors at the same level. The judgment matrix is the analysis basic of AHP and the weight of factors to top goal can be obtained from it. The value of element a_{ij} in the judgment matrix is determined by the relationship between indice *i* and indice *j*, the value set of a_{ij} is {1, 3, 5, 7, 9}, which represents different relationships between two components in the evaluation system, and the details for the value of a_{ij} is listed in Table II. A matrix of judgments A= (a_{ij}) is constructed with respect to a particular property the elements have in common. It is reciprocal, that is $a_{ij}=1/a_{ji}$, and $a_{ii}=1$.

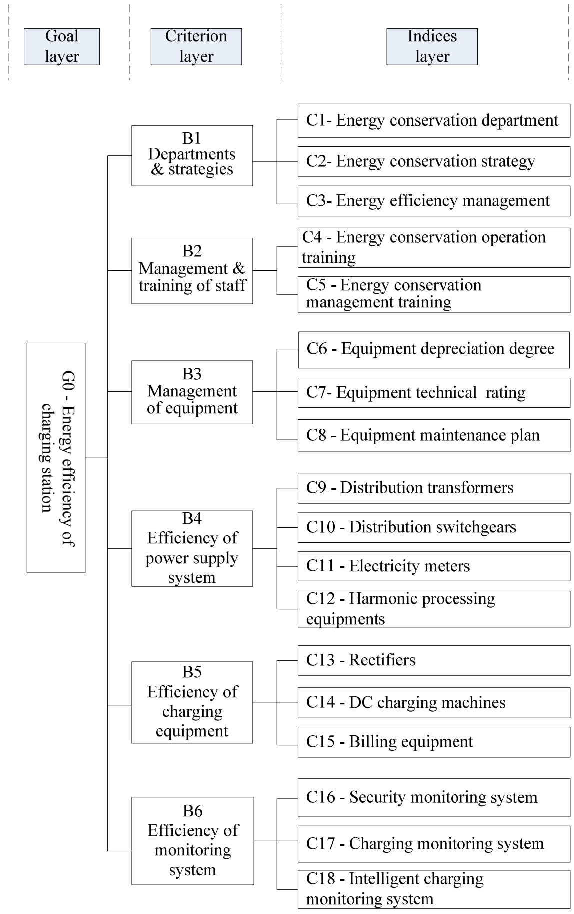

Figure 1. Structure of evaluation system based on AHP and Delphi method

TABLE II.
VALUE OF a_{ij} FOR DIFFERENT RELATION BETWEEN INDICE i AND INDICE j

a_{ij}	Relation between indice *i* and indice *j*
1	indice *i* and indice *j* are equally important for the objective
3	indice *i* is a little important than indice *j* for the objective
5	indice *i* is much important than indice *j* for the objective
7	indice *i* is much more important than indice *j* for the objective
9	indice *i* is extremely important than indice *j* for the objective
2,4,6,8	indice value between two corresponding status.

Again the expert surveys were carried out for the judgment matrix, in which 37 questionnaires were collected. Based on the results obtained in the expert surveys and rules shown in Table II, 7 judgment matrices A_0 to A_6 are established as shown in Table III.

Here A_0 is the judgment matrix for the goal G0 in the evaluation system, A_1 is the judgment matrix for the criterion B1 in the evaluation system, A_2 is the judgment matrix for the criterion B2 in the evaluation system, A_3 is the judgment matrix for the criterion B3 in the evaluation system, A_4 is the judgment matrix for the criterion B4 in the evaluation system, A_5 is the judgment matrix for the criterion B5 in the evaluation system, A_6 is the judgment matrix for the criterion B6 in the evaluation system.

TABLE III.
JUDGMENT MATRICES

A_0						
G0	B1	B2	B3	B4	B5	B6
B1	1	3	3	1/3	1/5	1
B2	1/3	1	1	1/5	1/7	1/3
B3	1/3	1	1	1/5	1/7	1/3
B4	3	5	5	1	1/3	3
B5	5	7	7	3	1	5
B6	1	3	3	1/3	1/5	1

A_1				A_3			
B1	C1	C2	C3	B3	C6	C7	C8
C1	1	5	3	C6	1	1/7	1/3
C2	1/5	1	1/3	C7	7	1	3
C3	1/3	3	1	C8	3	1/3	1

A_2			A_4				
B2	C4	C5	B4	C9	C10	C11	C12
C4	1	1/5	C9	1	5	7	5
C5	5	1	C10	1/5	1	3	1
			C11	1/7	1/3	1	1/3
			C12	1/5	1	3	1

A_5				A_6			
B5	C13	C14	C15	B6	C16	C17	C18
C13	1	3	9	C16	1	3	9
C14	1/3	1	7	C17	1/3	1	5
C15	1/9	1/7	1	C18	1/9	1/5	1

B. Method to Compute the Weights of Indices

Because the evaluation is divided into three layers, thus the goal layer, criterion layer and indices layer, hence three weights of all the indices should be computed. The first one is the weights of the second layer B1 - B6 to the top layer G0, the second one is the weights of the third layer to the criterions in the second layer, such as weight of C1 - C3 to B1 and weight C4-C5 to B2, and the last one is the weights of indices in the third layer to the goal G0. The following is the process to calculate the weights.

1) Normalize the judgment matrix $A = (a_{ij})_{n\times n}$ according to equation (1),

$$\overline{a_{ij}} = \frac{a_{ij}}{\sum_{k=1}^{n} a_{kj}} \quad (i, j = 1, 2, ..., n) \tag{1}$$

2) Calculate the normalized weight $\overline{W_i}$ according to equation (2), which is the sum of the $\overline{a_{ij}}$ in one row of normalized A.

$$\overline{W_i} = \sum_{j=1}^{n} \overline{a_{ij}} \quad (j = 1, 2, ..., n) \tag{2}$$

3) With the calculated $\overline{W_i}$ the indicator weight W_i can be computed as shown in equation (3), and then the weight vector can be obtained.

$$W_i = \frac{\overline{W_i}}{\sum_{i=1}^{n} \overline{W_i}} \tag{3}$$

4) Compute the maximum characteristic root $\lambda_{\max}$ for the judgment matrix according to equation (4).

$$\lambda_{\max} = \frac{1}{n} \sum_{i=1}^{n} \frac{(AW)_i}{W_i} \tag{4}$$

where A is the judgment matrix, W is the column vector for the weight, W_i is the ith component of the weight vector.

5) When the pair-wise comparisons are taken to construct judgment matrix, whose order is larger than two, there will be judgment errors as calculation process develops. Therefore, to ensure the accuracy of the method, the consistency check should be carried out, for which the checking factor CI should be computed as follows:

$$CI = \frac{\lambda_{\max} - n}{n - 1}, CR = \frac{CI}{RI} \tag{5}$$

where CI is consistency checking factor, RI is average random consistency factor, CR is the consistency ratio, if $CR < 0.1$, the consistency of the weights is acceptable, otherwise corresponding matrix A should be adjusted, and the following progresses should be conducted [21]:

(1) Find the most inconsistent judgment in the matrix;

(2) Determine the range in which the judgment can be changed, then improve the inconsistency judgment;

(3) If the decision maker can change the judgment to a plausible value in that range, change the judgment; Otherwise use the second most inconsistent judgment. If no judgment is changed the decision is postponed until better criteria is obtained.

C. Principle of Fuzzy Comprehensive Evaluation

Fuzzy comprehensive evaluation is a decision making process that under the fuzzy environment, apply the fuzzy set theory, and make a comprehensive quantity evaluation on a system restrained from many uncertain factors.

When a subject is difficult to evaluate, a big system can be decomposed into small systems. These small systems are further decomposed into some elements. Because the importance of the smallest elements is easy to percept or to calculate, it is easy and accurate to evaluate on these elements. And when the smallest elements are weighed, the importance of the overall system is deduced. Thus the whole evaluation on the subject is scientific correspondingly. For example, someone's quality is decomposed into communication ability, learning capability, cultural level, operation ability, and so on. Then communication ability is decomposed into ability of communication with acquaintance, ability of communication with strangers, and so on; learning capability is decomposed into learning ability of new things, learning ability of common things, and so on. And then some experts are in this field invited to weight the subdivided abilities of this person to deduce this person's overall quality. Fuzzy comprehensive evaluation is suitable generally to evaluate and choose subjects with incomplete information. That is to say, when the subject evaluated is not well-informed, this method is usually adopted. Its prerequisite is that the evaluation indexes of subject investigated can be decomposable.

Fuzzy comprehensive evaluation has three advantages [27-30]. Firstly, it does not depend directly on a certain index, neither excessively on the absolute index. But comparative method can prevent from the inaccuracy of evaluation result resulted from unreasonable standard. Secondly, the important intensity of indexes is embodied by the weight, and the weight allows some certain discrepancy, but it will not change the final evaluation result. Technologically, it avoids the influence of accumulative error. Thirdly, the establishment of the membership function and the selection of operators establish connection among non-quantized indexes in index evaluation, which makes the evaluation result reflect well the whole characteristic and trend of the subject.

D. Process of Fuzzy Method for the Energy Efficiency Evaluation of Charging Station

In this study the evaluation on the energy efficiency of charging station is set up according to fuzzy comprehensive evaluation [26-29]. According to the basic principle of FCE, the main process is as follows:

1) Set up the domain for the factors affecting the evaluation objective $U=(u_1,u_2,...u_p)$, and for the evaluation system for the energy efficiency of charging station, U is composed of 18 indices in the third layer[30,31];

2) Establish the domain for the evaluation rating. No matter how many the levels of factors there are, there is only one evaluation rating. This evaluation rating is suitable for all factors, by which the evaluation standard is confirmed. This evaluation set is expressed by $V=(v_1,v_2,...v_n)$ and the corresponding membership function set $J=(J_1,J_2,...J_m)$. In this study the membership function set J is set as J= {5 (Excellent), 4 (Good), 3(Average), 2 (Qualified), 1 (Unqualified)};

3) Calculate the weights vector $W=(w_1,w_2,...w_p)$;

4) Set up the fuzzy relation matrix $R=(r_{ij})_{m\times n}$, here r_{ij} is the membership between the ith element in U and jth element in V;

5) Calculate the composite operator K according to W and R as follows:

$$K=WR=\begin{bmatrix} w_1 \\ w_2 \\ \cdots \\ w_m \end{bmatrix}^T \cdot \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{2n} \\ \cdots & \cdots & r_{ij} & \cdots \\ r_{m1} & r_{m2} & \cdots & r_{mn} \end{bmatrix} \tag{6}$$

6) Compute the final evaluation score according to the weights and corresponding rating as follows:

$$G=\frac{\sum_{i=1}^{m} k_i J_i}{\sum_{i=1}^{m} k_i} \tag{7}$$

To make the final evaluation rating more intuitive, the evaluation rating is quantified as listed in Table IV.

Fig.2 is the flowchart of the fuzzy evaluation method for the energy efficiency of EVs charging station. The evaluation indices listed in Fig.1 comprise the influencing factor domain. The membership functions and evaluation indices weights calculation are calculated according to the results obtained by expert surveys.

TABLE IV.
QUANTIFIED EVALUATION RATING

Evaluation Rating	Excellent	Good	Average	Qualified	Unqualified
Score	[4.5 5]	[3.5 4.5]	[2.5 3.5]	[1.5 2.5]	[1 1.5]

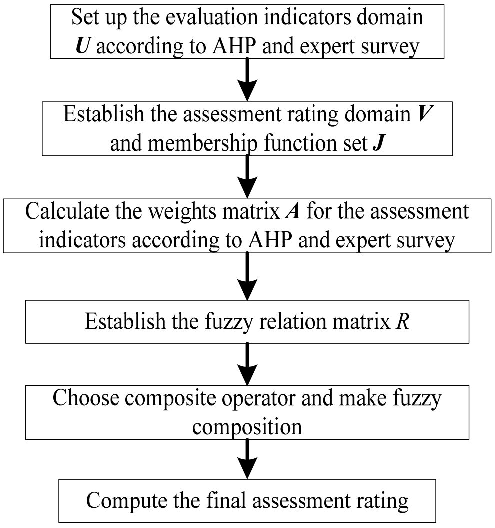

Figure 2. Flowchart of Fuzzy method for energy efficiency evaluation of electric vehicle charging station

IV. Energy Efficiency Evaluation on a Charging Station in Chongqing

To verify the method presented in the paper, an EV charging station in Chongqing was taken as an example. The main parameters of this charging station are as follows:

- Two power supply transformers: power capacity is 1600 kVA, voltage rating is 10/0.4kV;
- Outlets: two 10kV outlets and fifteen 0.4kV outlets;
- Reactive power compensation: four 200kVar capacitance compensation;
- Filters: four 300A active power filters;
- Charging machines: six high power DC charging machines.

A. Calculation of Weights Matrix

According to the structure of the charging station, evaluation system as shown in Fig.1 is established, and according to the judgment matrices shown in Table III, the weights of all components in the evaluation system are calculated.

According to the judgment matrix A_0, the weights of B1 to B6 in the second layer to G0 are 0.1052, 0.0442, 0.0442, 0.2382, 0.4628 and 0.1052 respectively, and the corresponding λ_{max} according to equation (4) is 6.1565, hence the consistency checking factor CI=0.0313, then CR=0.02524, which is far less than 0.1, hence the consistency is acceptable.

In the same way, according to the judgment matrices A1 to A6, the weighs of C1-C18 to B1-B6 can be calculated respectively. Finally the weights of 18 evaluation indices C1-C18 to the evaluation goal G0 can be obtained and the results for the weight calculation are listed in Table V.

TABLE V.
Calculated Weights of the Indices C1 to C18 for the Six Criterions B1 to B6 and the Evaluation Goal G0

criterion	weight to G0	indices	weight to criterion	weight to G0
B1	0.105	C1	0.637	0.067
		C2	0.105	0.011
		C3	0.258	0.027
B2	0.044	C4	0.167	0.007
		C5	0.833	0.037
B3	0.044	C6	0.088	0.004
		C7	0.669	0.029
		C8	0.243	0.011
B4	0.238	C9	0.635	0.151
		C10	0.151	0.036
		C11	0.062	0.015
		C12	0.151	0.036
B5	0.463	C13	0.655	0.303
		C14	0.290	0.134
		C15	0.055	0.025
B6	0.105	C16	0.672	0.071
		C17	0.265	0.028
		C18	0.063	0.007

B. Establishment of Fuzzy Relation Matrix

The fuzzy relation matrix is established according to the results obtained in the expert surveys, in which 27 related experts participated, and 23 responses are obtained. According to the data in Table V, the fuzzy relation matrix R1 for B1 can be obtained as follows:

$$R_1 = \begin{bmatrix} 0.146 & 0.375 & 0.287 & 0.157 & 0.035 \\ 0.058 & 0.632 & 0.145 & 0.165 & 0.000 \\ 0.324 & 0.467 & 0.185 & 0.024 & 0.000 \end{bmatrix} \quad (8)$$

According to its weight vector

$$W_1 = [0.637 \quad 0.105 \quad 0.258] \quad (9)$$

The composite operator K_1 is

$K_1 = W_1 \times R_1 = [0.1827 \quad 0.4257 \quad 0.2458 \quad 0.1235 \quad 0.0223]$,

The maximum element in K_1 is 0.4257, which is corresponding to “good” in the membership function set J, hence it’s can be concluded that B1 belongs to “good” according to the maximum membership degree principle.

In the same way, according to the results obtained in the expert survey, the composite operators K_2 to K_6 for B2 to B6 can be obtained as follows:

K_2 = [0.1130 0.2690 0.2254 0.3401 0.0525],

hence B2 belongs to “Qualified”;

K_3 = [0.5378 0.4041 0.0582 0.000 0.000],

hence B3 belongs to “Excellent”;

K_4 = [0.4885 0.3048 0.1681 0.0251 0.0125],

hence B4 belongs to “Excellent;

K_5 = [0.1868 0.2923 0.3583 0.0970 0.0655],

hence B5 belongs to “Average”;

K_6 = [0.1366 0.2397 0.3388 0.2121 0.0728],

hence B6 belongs to “Average”.

According to the composite operator K_1 to K_6, the fuzzy relation matrix R_0 for G0 is

$$R_0 = \begin{bmatrix} 0.1827 & 0.4257 & 0.2458 & 0.1235 & 0.0223 \\ 0.1130 & 0.2690 & 0.2254 & 0.3401 & 0.0525 \\ 0.5378 & 0.4041 & 0.0582 & 0.0000 & 0.000 \\ 0.4885 & 0.3048 & 0.1681 & 0.0251 & 0.0125 \\ 0.1868 & 0.2923 & 0.3583 & 0.0970 & 0.0655 \\ 0.1366 & 0.2397 & 0.3388 & 0.2121 & 0.0728 \end{bmatrix} \quad (10)$$

Then the corresponding composite operator K_0 can be computed.

$K_0 = W_0 \times R_0$ = [0.2652 0.3073 0.2796 0.1011 0.0460]

And the final evaluation rating score G = 3.645 according to equation (7). Hence it can be concluded that the energy efficiency assessment result is “Good” according to the quantified evaluation rating relationship in Table IV.

G = 3.645 indicates that there should be some measures can be taken to increase the energy efficiency of the charging station, and the measures should be made according to the evaluation results of six criterions and weights of different indices.

According to the evaluation results for the charging station in Chongqing, for the six criterions in the second layer, B3 and B4 got the rating of “Excellent”, B1 is “Good”, B5 and B6 are “Average”, B2 is only “Qualified”, and the evaluation result is “Good”, therefore the following suggestions are offered to improve the energy efficiency of the charging station.

- Improve the training and management of the staff, and establish the assessment mechanisms to improve the efficiency of the staff.
- Improve the efficiency of charging device, and make a more reasonable charging price.
- Improve the intelligence and efficiency of the monitoring system, which can improve the efficiency of B6.

V. Conclusions

A Fuzzy method for the energy efficiency evaluation of charging station is presented, which incorporates the setup of evaluation system based on AHP and expert surveys. The evaluation indices in the evaluation system are established based on Argument Delphi method, which is comprised of three layers, 6 criterions and 18 indices. Seven judgment matrices are established according to the results obtained in the expert surveys, then the weights of indices in the evaluation system are calculated. Expert surveys were carried out to obtain the fuzzy relation matrices. Energy efficiency evaluation for a charging station in Chongqing was conducted, the results indicate that the fuzzy method presented in the paper is effective to evaluate the energy efficiency of charging station, and according to the assessment result, measures can be taken to improve the energy efficiency.

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Hanwu Luo. He is within the school of electrical engineering, Wuhan University, his main research field focuses on the renewable resource planning. He is a Ph.D students now.

Jiangjun Ruan. Ph.D degree, professor. He is within the school of electrical engineering, Wuhan University, his main research fields focuses on the renewable resource planning, electromagnetic calculation.