Energy efficiency evaluation of consumer based on fuzzy comprehensive evaluation method

Shaoyu Han*, Pengcheng Xu, Yan Li, Shuang Ji, Dongxu Han, Le Yang
Siping Power Supply Company of State Grid Jilin Electric Power Co., Ltd., Siping, China
*Corresponding author: 13843403898@163.com

Abstract. Aiming at the problems of lack of complete evaluation index system and low evaluation accuracy, a consumer energy efficiency evaluation method based on fuzzy comprehensive fuzzy evaluation is proposed. Firstly, establish a consumer energy efficiency index system. Then the weight of the index is determined by the combination of analytic hierarchy process and entropy weight method. Finally, the energy efficiency of consumer is evaluated by fuzzy comprehensive evaluation method. Through the analysis of experimental examples, it is verified that the proposed method can evaluate the level of electricity energy efficiency accurately, and improve the residential electricity efficiency effectively.

Keywords: energy efficiency evaluation method, analytic hierarchy process, fuzzy comprehensive evaluation

1. Introduction
In recent years, facing the increasing demand for electricity, most areas of our country appear regional, seasonal, and uncertain power supply shortage. On the one hand, it is related to the seasonality, time period, and structure of electric energy use, on the other hand, it is also related to the lack of scientific and reasonable guidance and low of electricity efficiency [1]. With the popularization of energy construction and smart grids in China, more and more individuals and enterprises have paid attention to energy efficiency indexes. China’s power sector has also made remarkable achievements through the study of energy saving and consumption reduction index system. However, with the increasing proportion of consumer energy consumption in the whole society [2], consumer energy consumption management is still faced with the lack of a complete index system, important indexes cannot be quantified, and the evaluation results are difficult to reflect the overall energy consumption. In view of the above problems, it is necessary to design a more comprehensive evaluation method of consumer energy efficiency, and improve the efficiency of consumer by evaluating energy consumption.

The literature [3-5] adopted the entropy weight method to establish an energy efficiency evaluation model, and analyzed the indexes affecting the comprehensive energy efficiency, and ranked the importance of indexes. Literature [6] established an evaluation model, and introduced the algorithm in the model, using the ladder-based comprehensive energy efficiency evaluation method, but it did not
improve the evaluation index system. Literature [7-9] established an energy efficiency evaluation model and proposed suggestions for improving energy efficiency, but it ignored the influence of different factors on energy efficiency evaluation indexes.

In view of the above problems, this paper establishes a reasonable index system based on the characteristics of consumer electricity behavior and the time period characteristics of consumer appliances. According to the different influencing factors, the weight of the energy efficiency evaluation index system is determined by using the analytic hierarchy process and the entropy weight method, and to solve the problem that the weight determination depends on subjective experience. The fuzzy comprehensive evaluation method is used to evaluate the energy efficiency of consumer, and the effectiveness and reliability of the method are verified by experiments.

2. Energy efficiency evaluation index system

Energy efficiency evaluation index is the main symbol to measure the efficiency of consumer electricity consumption, and the design of the index system is the premise of energy efficiency evaluation. The energy efficiency evaluation index system is a series of influencing factors that can reflect the nature or characteristics of energy efficiency. Therefore, the better the system, the higher the accuracy of the evaluation results. Moreover, the energy efficiency evaluation is based on the index system. The establishment of an evaluation index system must also consider all factors, which lead to changes in energy efficiency. So that the index system can reflect the energy efficiency level comprehensively and accurately. Summarizing the previous design principles and experience of the index system [1-4], in order to ensure the scientific accuracy of the evaluation results, the established energy efficiency evaluation index system should be able to reflect the energy efficiency directly and comprehensively.

![Fig. 1. Consumer Electricity Energy Efficiency Evaluation Index System](image)

The construction of the index system should integrate the characteristics of consumer electricity consumption behavior, and the use period of consumer appliances. The evaluation indexes are highly classified, and different indexes are affected by different factors. Such as consumer electrical appliances
information, energy-saving equipment information, and environmental factors. The combination of analytic hierarchy process and entropy weight method can be used for energy efficiency evaluation. Therefore, this paper combines expert experience to establish a two-level evaluation index system. The first-level indexes include four kinds of indexes: consumer information, energy-saving equipment index, general electrical equipment information, and environmental influence index, and the quantifiable indexes are mined from these indexes as the secondary indexes. The energy efficiency evaluation index system is shown in Fig. 1.

3. Weight of index

3.1 Weight Calculation of Index Based on analytic hierarchy process

The first-level index weight of the energy efficiency evaluation index system is determined based on analytic hierarchy process (AHP). The analytic hierarchy process mathematicalizes the thinking process of decision-making, which is conducive to solving complex decision-making problems with unstructured characteristics. It is suitable for occasions where people's qualitative judgment plays an important role, and it is difficult to measure decision-making results directly and accurately. The analytic hierarchy process is used to determine the energy efficiency evaluation index system, which ensures the comprehensiveness of the energy efficiency evaluation index. At the same time, less quantitative information is used, and the influence of qualitative factors is taken into account. Combined with expert experience, the weight of the index is determined, and the unified quantification of the index is realized, so as to achieve the purpose of scientific and reasonable evaluation of energy efficiency.

The basic information of analytic hierarchy process is to judge the relative importance of each element in each level, and at the same time, the elements are appropriately scaled to construct a judgment matrix. The judgment matrix constructed is a positive and negative matrix, and the judgment matrix is applied in pairs comparison method and 1-9 scale structure. The definition of judgment matrix $B$ is shown as formula (1):

$$B = (C_{ij})_{n \times n} = \begin{bmatrix} C_{11} & C_{12} & \cdots & C_{1n} \\ C_{21} & C_{22} & \cdots & C_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ C_{n1} & C_{n2} & \cdots & C_{nn} \end{bmatrix}$$ (1)

$n$ is the number of indexes; $C_{ij} = f(x_i, x_j)$ represents the importance scale of the comparison between indexes $x_i$ and $x_j$, when $i = j$, $C_{ij} = 1$, when $i \neq j$, $C_{ij} = \frac{1}{C_{ji}}$; The selection method of $f(x_i, x_j)$ is based on the importance of the index $x_i$ and $x_j$, is shown in Table 1.

After the judgment matrix is constructed, the hierarchical single sorting is carried out first. The hierarchical single sorting is to calculate the weights of the importance order of the elements, and related to the previous layer according to the judgment matrix. The eigenvectors of the judgment matrix are normalized to be the index weight vector. The construction of the index judgment matrix is a formal expression of people's subjective judgments, and there is an error between the importance of objective in indexes. Therefore, the consistency check of the judgment matrix is required. The index to measure the deviation of the judgment matrix is shown as formula (2):

$$CI = (\lambda_{\text{max}} - n) / (n - 1)$$ (2)

In the formula, $\lambda_{\text{max}}$ is the maximum characteristic root of the judgment matrix; $n$ is the order of the judgment matrix. The random consistency ratio is shown as formula (3):

$$CR = CI / RI$$ (3)

In the formula, $RI$ is the average random consistency index. When $CR < 0.1$, the constructed judgment matrix is considered to be consistent, otherwise the judgment matrix needs to be adjusted until it meets the consistency. After the hierarchical single sorting is finished, the hierarchical total sorting is carried out to obtain the sorting weight of the lowest level indexes for the total target.
Table 1 Evaluation Index Importance Comparison Scale

| $C_{ij}$ value | Meaning                                                                 |
|----------------|------------------------------------------------------------------------|
| 1              | The $i$ factor is as important as the $j$ factor                       |
| 3              | The $i$ factor is slightly more important than the $j$ factor           |
| 5              | The $i$ factor is significantly more important than the $j$ factor      |
| 7              | The $i$ factor is more important than the $j$ factor                    |
| 9              | The $i$ factor is absolutely important than the $j$ factor              |
| 2, 4, 6, 8     | The median value between the two adjacent judgments                      |
| Reciprocal     | $C_{il} = 1/C_{ij}$                                                     |

3.2 Weights Calculation of Indexes based on entropy weight method

The entropy weight method is an objective weighting method. Compared with subjective weighting method, it is not affected by human factors. Therefore, the result obtained by entropy weight method is more accurate and objective, and it is a more excellent and reliable weighting method. The basic idea of the entropy method is to determine the index weight according to the amount of information provided by the observation value of each index. The entropy weight method is used to determine the index weight value, and the specific calculation steps are as follows:

1. Calculate the characteristic proportion $t_{ij}$ of the $i$-th system in the $j$-th index, is shown as formula (4):
   $$ t_{ij} = \frac{x_{ij}}{\sum_{i=1}^{n} x_{ij}} $$

2. Calculate the entropy weight $e_j$ of the evaluation index $j$, is shown as formula (5):
   $$ e_j = -k \sum_{i=1}^{m} t_{ij} \ln t_{ij} $$

3. Calculate the difference coefficient $g_i$ of the evaluation index $x_i$, is shown as formula (6):
   $$ g_i = 1 - e_i $$

4. The final calculated weight $q_i$, is shown as formula (7):
   $$ q_i = \frac{g_i}{\sum_{i=1}^{n} g_i} $$

For the secondary indexes in the energy efficiency evaluation model, based on the relationship of the evaluation indexes, formulas (4) to (7) are used to determine the weight of each secondary evaluation index.

3.3 Comprehensive weight calculation

Assuming the weight of the first-level index at the upper level is $w = [w_1, w_2, \cdots, w_m]$, and the weight of the secondary index at the lower level is $w = [w_{i1}, w_{i2}, \cdots, w_{in}]$, the comprehensive weight is shown as formula (8):

$$ G = w_i \cdot w_{ij} (i = 1, 2, \cdots, m; j = 1, 2, \cdots, n) $$

According to the above model, the weight of each index is calculated, and the comprehensive weight of the index is obtained.

4. Energy efficiency evaluation method based on fuzzy comprehensive evaluation

The fuzzy comprehensive evaluation method is the most used evaluation method in the actual production environment. This method can realize the transformation from qualitative evaluation to quantitative evaluation, and can quantify complex and difficult problems. Due to the qualitative judgment of the index system, the boundaries are often fuzzy. Therefore, the comprehensive evaluation based on fuzzy mathematics theory can better solve the problem of energy efficiency evaluation. The steps of fuzzy comprehensive evaluation are as follows:

Step1: Establish a energy efficiency factor set A. The energy efficiency factor set refers to the first-level and secondary indexes of the energy efficiency evaluation index system. In this paper, the energy efficiency evaluation index system is composed of two levels. In the concentration of energy efficiency factors, the first-level factor $A_i$ (i=1, 2, 3, ..., n) corresponds to the first-level index, and the secondary
factor $A_{ij}$ $(j=1, 2, ..., k)$ corresponds to the secondary index.

Step2: Establish the energy efficiency evaluation set $V$. In this paper, the energy efficiency is divided into 5 levels, corresponding to $V = \{v_1, v_2, v_3, v_4, v_5\}$. Five levels from high to low describe the difference of energy efficiency level.

Step3: Calculate the fuzzy comprehensive evaluation result $B$ of energy efficiency. In this paper, the index system has 4 first-level indexes, each of which contains several secondary indexes as a subsystem. The index system has 4 subsystems. When determining the fuzzy comprehensive evaluation results of each subsystem, the evaluation formula is shown as formula (9):

$$B_i = W_i F_i = (b_{i1}, b_{i2}, b_{i3}, b_{i4}, b_{i5})$$  

In the formula: $B_i$ is the evaluation result of subsystem $i$; $W_i$ is the fuzzy weight vector of subsystem $i$, which is composed of the secondary index weight of subsystem $i$; $F_i$ is the evaluation matrix of subsystem $i$.

After the subsystem results are known, the energy efficiency of consumer can be evaluated comprehensively, and the comprehensive energy efficiency can be obtained, is shown as formula (10):

$$B = WF = \{b_1, b_2, b_3, b_4, b_5\}$$  

In the formula: the comprehensive evaluation vector $B$ is the evaluation result, and the comprehensive evaluation matrix can be converted into energy efficiency score; the fuzzy weight vector $W$ is composed of the weights of 4 first-level indexes; $F$ is a comprehensive fuzzy evaluation matrix, which is composed of the evaluation results of each subsystem $B_i$. The specific structure is shown as formula (11):

$$F_A = \begin{bmatrix} B_1 \\ B_2 \\ B_3 \\ B_4 \end{bmatrix} = \begin{bmatrix} b_{11} & b_{12} & b_{13} & b_{14} & b_{15} \\ b_{21} & b_{22} & b_{23} & b_{24} & b_{25} \\ b_{31} & b_{32} & b_{33} & b_{34} & b_{35} \\ b_{41} & b_{42} & b_{43} & b_{44} & b_{45} \end{bmatrix}$$

Calculate the fuzzy comprehensive evaluation score $S$. The evaluation matrix $B_i$ is obtained by each subsystem, and the scores of each subsystem can be determined by the energy efficiency evaluation set $V$. The subsystem score $S_i$ is shown as formula (12):

$$S_i = B_i V^T$$

$V^T$ is the transposition of the energy efficiency comment set $V$; $S_i$ is the score for subsystem $i$. The calculation formula of the overall energy efficiency evaluation score of electricity consumer is shown in formula (13):

$$S = BV^T$$

In the formula: $S$ is the overall energy efficiency evaluation score; $B$ is the comprehensive evaluation vector; $V^T$ is the transposition of the energy efficiency comment set $V$.

5. Case analysis

This paper verifies the proposed method based on the real electricity consumption data of consumer in a certain city of Jilin Province. Firstly, apply the analytic hierarchy process and entropy weight method to calculate the weights of the first-level index and secondary index of energy efficiency evaluation index system, as shown in Table 2.

According to the data in Table 2, the fuzzy comprehensive evaluation method is used for evaluation. Firstly, divide the index set. According to the constructed evaluation index system, the corresponding first-level index and secondary index sets are divided into two levels. Considering that the 3 evaluation sets are too rough and the 9 evaluation sets are too cumbersome, the evaluation set $F$ in this paper is divided into the commonly used 5 grades, namely $V = \{v_1, v_2, v_3, v_4, v_5\} = \{good, general, relatively bad, bad\}$. The scoring table is shown in Table 3.
Table 2 Index Weight Based on Weight Method

| First level index | Weights | Secondary indexes | Weights | Comprehensive weight |
|-------------------|---------|-------------------|---------|----------------------|
| A                 | 0.106   | A₁                | 0.215   | 0.023                |
|                   |         | A₂                | 0.464   | 0.049                |
|                   |         | A₃                | 0.109   | 0.012                |
|                   |         | A₄                | 0.211   | 0.022                |
| B                 | 0.415   | B₁                | 0.474   | 0.197                |
|                   |         | B₂                | 0.166   | 0.069                |
|                   |         | B₃                | 0.183   | 0.076                |
|                   |         | B₄                | 0.176   | 0.073                |
| C                 | 0.184   | C₁                | 0.018   | 0.003                |
|                   |         | C₂                | 0.471   | 0.087                |
|                   |         | C₃                | 0.284   | 0.052                |
|                   |         | C₄                | 0.159   | 0.029                |
|                   |         | C₅                | 0.016   | 0.003                |
|                   |         | C₆                | 0.017   | 0.003                |
|                   |         | C₇                | 0.019   | 0.004                |
|                   |         | C₈                | 0.015   | 0.003                |
|                   |         | C₉                | 0.017   | 0.003                |
|                   |         | C₁₀               | 0.019   | 0.004                |
|                   |         | C₁₁               | 0.015   | 0.003                |
|                   |         | D₁                | 0.695   | 0.204                |
|                   |         | D₂                | 0.262   | 0.077                |
|                   |         | D₃                | 0.043   | 0.013                |

Table 3 Grade Scoring Table

| Fractional segment | 90-100 | 80-90 | 70-80 | 60-70 | 60 or less |
|--------------------|--------|-------|-------|-------|------------|
| Rating             | great  | good  | general | Relatively bad | bad |

The expert scoring questionnaire is made according to each index set and evaluation grade scoring table, and the frequency of each index in different evaluation grades is obtained. The membership degree of each index is obtained by normalization. On the basis of the calculation results of the membership degree of the existing index, the fuzzy evaluation matrix corresponding to each index set is constructed. The evaluation score is calculated layer by layer according to the order of the level from small to large.

Taking the first level index A as an example:

\[ F_{A} = \begin{bmatrix} 0.17 & 0.17 & 0.33 & 0.17 & 0.17 \\ 0.33 & 0.33 & 0.17 & 0.17 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 0.17 & 0 & 0.67 & 0.17 & 0 \end{bmatrix} \]

Obtain the consumer information fuzzy judgment vector \[ f_{A} = \omega_A^T F_A = [0.2983, 0.1689, 0.2856, 0.1502, 0.1038] \] from the combined weight \[ \omega_A = [0.023, 0.049, 0.012, 0.022] \]

Similarly, the evaluation vectors of other first-level indexes can be obtained:

\[ f_{B} = \omega_B^T F_B = [0.4686, 0.3198, 0.2032, 0, 0] \]
\[ f_{C} = \omega_C^T F_C = [0.7703, 0.1456, 0.0895, 0, 0] \]
\[ f_{D} = \omega_D^T F_D = [0.6487, 0.3514, 0, 0, 0] \]

Therefore, the fuzzy comprehensive evaluation matrix composed of the fuzzy evaluation vectors of each first-level index:

\[ F_U = \begin{bmatrix} 0.2983 & 0.1689 & 0.2856 & 0.1502 & 0.1038 \\ 0.4686 & 0.3198 & 0.2032 & 0 & 0 \\ 0.7703 & 0.1456 & 0.0895 & 0 & 0 \\ 0.6487 & 0.3514 & 0 & 0 & 0 \end{bmatrix} \]
From the weight \( \omega = (0.106,0.415,0.184,0.293)^T \), the total fuzzy judgment vector is:

\[ B = \omega^T F = [0.558,0.2804,0.131,0.016,0.011] \]

Known evaluation set \( V = [100,90,80,70,60] \), convert the evaluation result into percentile system:

\[ S = BV^T = 93.296 \]

The fuzzy comprehensive evaluation method was used to evaluate the consumer energy efficiency level, and the final evaluation score was 93.296 points. The analysis of the evaluation results adopts the principle of maximum membership degree, and it can be concluded that the energy efficiency level is in a "great" state.

Through actual research on the overall energy efficiency of consumer and the energy efficiency of each first-level index, it is found that the energy efficiency evaluation trend calculated is similar. The combination of subjectivity and objectiveness can improve the accuracy and reliability of consumer energy efficiency evaluation. In addition, in order to test the evaluation effect of consumer, 3 groups are selected from the existing data arbitrarily, and a comprehensive energy efficiency evaluation is conducted on the established consumer energy efficiency evaluation model. The comprehensive energy efficiency evaluation results are shown in Fig. 2.

![Radar Chart](image)

**Fig. 2.** Evaluation results of index set by radar chart.

6. Conclusion
In order to evaluate the energy efficiency of consumer electricity consumption more accurately and promote energy conservation and consumption reduction, this paper proposes a consumer electricity energy efficiency evaluation method based on fuzzy comprehensive evaluation, which conducts a comprehensive evaluation of the electricity consumption efficiency. It can enable to better understand the overall electricity consumption of consumer, and at the same time provide a basis for future energy-saving strategies. The main application prospects are as follows:

- Provide a scientific reference for the smooth implementation of time-of-use tariffs and peak-valley tariffs;
- Enhance consumer’s comprehensive understanding of electricity usage information, and increase the power of independent choice of electricity usage patterns;
- Exploit the energy-saving potential of consumer and promote the further implementation of energy-saving work on the power demand side;
- Form a relatively complete consumer energy efficiency evaluation system.

Through experimental verification, this method can evaluate and monitor the energy efficiency effectively, and can improve the energy efficiency of consumer effectively. This method is not only easy to operate, strong in applicability, but also has good practical value.

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