User Deep Energy Efficiency Evaluation via Load Perception and Clustering

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Abstract. With the constantly upgrading of the living level of urban residents, the types and quantities of domestic appliances continue to increase, and the electricity consumption behaviour is becoming more and more complex. Based on the fine-grained user energy consumption data obtained by load intelligent perception, this paper proposes a user energy efficiency evaluation method through fuzzy comprehension evaluation. First, the energy consumption characteristics at appliance level which can effectively represent energy consumption behaviour of users are designed and filtered, and then the energy efficiency evaluation strategy of appliances based on fuzzy comprehensive evaluation is established. The strategy adopts two-level fuzzy comprehensive evaluation. The first appliance-level fuzzy evaluation realizes the energy efficiency evaluation of the appliances. The second level is the comprehensive evaluation of user energy efficiency based on the appliance energy efficiency assessment, and the target users are divided into different energy efficiency levels. The measured data-based analysis results prove the effectiveness of the proposed method, and the results can guide users to optimize their electricity consumption behaviour scientifically and realize energy saving and carbon reduction.

1. Introduction

With the constantly upgrading of the living level of urban residents, the proportion of household energy consumption in the total electricity consumption of the society is steadily increasing. At the same time, the types and quantities of domestic appliances continue to increase, and the electricity consumption behaviour is becoming more and more complex. In order to provide more comprehensive energy services, and realize energy conservation, emission reduction and demand response, accurate analysis of user behaviours and deep energy efficiency evaluation are becoming increasingly important. The electricity consumption behaviour analysis method proposed in [1-3] mainly analyses the behaviours based on the total electricity consumption, and unable to accurately determine the usage of appliances, which lead to the inaccurately energy efficiency evaluation of appliances. The [4-5] has not consider the energy efficiency evaluation of household appliances, and for the filtering index, it relies on expert judgment that has strongly subjective. [6] states the research and application of consumers energy efficiency analysis system. The article is mainly aimed at enterprise consumers, and only considers the energy efficiency analysis of illuminating equipment and transformer equipment.

In terms of issues above, this paper proposes an energy efficiency evaluation method for users’ appliances based on fuzzy comprehensive evaluation. This method is based on the fine-grained electricity consumption data obtained by load intelligent perception, and designs and filters the appliance-level energy consumption characteristics that can effectively characterize the user's electricity consumption behaviour, and establishes an appliance energy efficiency evaluation strategy based on fuzzy comprehensive evaluation, which can evaluate the energy efficiency of the user's components appliances. On this foundation, the energy efficiency evaluation of target users' electricity consumption...
behaviour based on energy efficiency level is obtained, and gives specific power consumption suggestions for appliances, which can effectively strengthen the friendly interaction between the grid side and the user side.

The structure of this paper is as follows: Section 2 introduces the fine-grained power consumption data and behaviour analysis based on load intelligent perception, and obtain the optimal time of use (TOU) electricity of different appliances. Section 3 constructs the energy efficiency evaluation strategy based on fuzzy comprehensive evaluation. Section 4 verifies the effectiveness of the proposed method via a practical example. Section 5 summarizes the work of this paper.

2. Fine-grained power consumption data and power consumption behaviour analysis

In this section, appliance-level power consumption is obtained via load intelligent perception, and the user and electrical characteristics which are strongly related to the difference of power consumption behaviours between different users are selected as the main factors for user classification and energy efficiency evaluation.

2.1. Fine-grained power consumption data based on load intelligent perception

Non-intrusive load monitoring (NILM) is a load intelligent perception technology. It does not need to install sensors separately for each appliance. The power consumption of each appliance in the total load can be acquired only by collecting and analysing the terminal voltage or total current at the entrance of consumers, providing high-quality and high-definition power data source. As shown in Table 1, the power consumption details of lighting equipment can be obtained through load intelligent perception. Similarly, the power consumption of air conditioners, water heaters, washing machines and other appliances can be obtained.

| Working time   | Power(W) | Electric quantity(kWh×10^{-4}) | Number of operations |
|----------------|----------|--------------------------------|---------------------|
| 19:00-22:37    | 40       | 1446.7                         |                     |
| 20:30-21:04    | 20       | 113.3                          |                     |
| 22:29-22:31    | 20       | 6.67                           | 4                   |
| 22:38-22:42    | 15       | 10.0                           |                     |

As shown in the table above, the user’s electrical activity is bound to have the corresponding electrical operation, which is directly reflected in the power consumption, operation state and use frequency. The total electricity consumption of users directly reflects the frequency of users’ electricity consumption activities, and is closely related to the number of family members and residential area. In this paper, the electricity consumption of each component appliance in the user is selected as the main evaluation factor for the appliance energy efficiency evaluation.

2.2. Electrical behaviour analysis

Combined with practical research, ordinary users usually have more than 10 major appliances involving heating, cooking, lighting and other functions, and the consumption behaviour of different appliances is closely related to the users’ behaviour habits. The daily usage time of each appliance should fluctuate within a certain or several fixed time periods. Because different appliances have different functions, their usage time can be different. When evaluating the energy efficiency of household appliances, users are most concerned about the appliances of low energy utility and the corresponding service time. Therefore, this paper selects the Time-Of-Use (TOU) electricity of each appliance as the main evaluation factor for energy efficiency evaluation.
Table 2. Classification of household appliances.

| Type                | Appliance                                                                 |
|---------------------|---------------------------------------------------------------------------|
| Periodic load       | The refrigerator                                                          |
| Seasonal load       | Air conditioning, electric fan                                             |
| Kitchen load        | Electric cooker, induction cooker, electric oven                           |
| Other loads         | TV, lighting appliances, washing machines, electric water heaters, sweeping robots, computers |

The survey found that different types of appliances have great differences in the range of usage time. For example, kitchen appliances fluctuate during meals, while refrigerators and other cyclical appliances is used throughout the day. Therefore, when considering TOU electricity of each appliance, the time division of different types of appliances is also different. In this paper, we divide household appliances into four categories, as shown in Table 2.

As shown in the table above, periodic load means that this kind of appliances has a fixed period when it works. When considering the optimal energy consumption efficiency of TOU electricity of this kind of load, the time period can be divided into 24 hours in one day. Seasonal load indicates that the working time of this load is seasonal and needs to be divided into different periods according to different seasons. The kitchen load indicates that this type of load is distributed in the kitchen area and its working time is distributed during the user's three meals. Other loads indicate that the working time of this type of load is highly random and needs to be determined based on the specific load.

The optimal energy efficiency of TOU electricity of appliances is the key information when evaluating the energy efficiency of appliances. Through the investigation, it is found that the main appliances that affect users' energy efficiency are air conditioning and water heater, and their electricity consumption accounts for a large proportion in the total amount of users' load electricity consumption. In order to make the horizontal comparison of energy efficiency between the same type of users more meaningful, the optimal TOU electricity of air conditioner and water heater for different types of users is determined. The time division and corresponding electricity consumption are shown in Table 3 and Table 4.

Table 3. Optimal TOU electricity of air conditioner.

| Time           | Electricity (kWh) |
|----------------|-------------------|
| 00:00-12:00    | 0.4               |
| 12:00-18:00    | 1.0               |
| 18:00-24:00    | 1.6               |

Table 4. Optimal TOU electricity of water heater.

| Time           | Electricity (kWh) |
|----------------|-------------------|
| 00:00-8:00     | 0.5               |
| 8:00-16:00     | 0.3               |
| 16:00-24:00    | 1.2               |

3. User deep energy efficiency evaluation

In this paper, we propose a user deep energy efficiency evaluation strategy based on fuzzy comprehensive evaluation, which only needs the TOU electricity of each appliance in the target user to inform the user of the energy efficiency level, such as "high, low " or "high, relatively high, relatively low, low ". It can remind users of low energy efficiency appliances and corresponding working hours, and support the optimization of users' electricity consumption behaviour.
3.1. Basic principle of fuzzy comprehensive evaluation

![Flowchart of fuzzy comprehensive evaluation method.](image)

The key to reasonably rating users' energy efficiency is to make full use of the itemized data of users' appliances. Fuzzy comprehensive evaluation is an evaluation method based on fuzzy mathematics. According to the membership theory in fuzzy mathematics, this method transforms qualitative evaluation into quantitative evaluation. The basic idea of fuzzy theory is to replace belonging or not with the belonging degree. For example, the energy efficiency of users is not just a simple high or low energy efficiency, but classified into different degrees.

The process of the fuzzy comprehensive evaluation method is shown in Figure 1. The fuzzy comprehensive evaluation factors refer to the main factors affecting the subject. We suppose there are \( n \) evaluation factors, recorded as \( U=\{u_1,u_2,...,u_n\} \). For example, the main factors affecting clothing are style, brand, colour, material and so on. Then, we design and determine the comment set. There are \( m \) possible comment sets recorded as \( V=\{v_1,v_2,...,v_m\} \), such as good, average, poor. And considering the different status and role of various factors, it is measured by the weight vector \( A=\{a_1,a_2,...,a_n\} \). Finally, we evaluate the degree to which each factor of a thing belongs to each comment, and establish a fuzzy evaluation matrix \( R \). The key is to set up a reasonable membership function and calculate the total evaluation based on an appropriate fuzzy synthesis operator \( B = A \circ R \), normalize \( B \), and then make a judgment according to the maximum membership principle. The fuzzy operators are shown in the following formula, as:

\[
A \circ R = (b_1,b_2,...,b_n) \\
R = (r_{ij})_{m \times n}, r_{ij} \in [0,1] \\
b_j = \sum_{i=1}^{n} (a_i \wedge r_{ij}), j = 1,2,...,m
\]

Where, \( A=\{a_1,a_2,...,a_n\} \), \( \sum_{i=1}^{n} a_i = 1, a_i \geq 0 \). \( b_j \) is the evaluation function.

3.2. Membership function

A scientific and reasonable membership function is the basis for applying fuzzy theory to accurately and quantitatively describe fuzzy concepts. At present, the common membership functions include triangular, trapezoidal and Gaussian membership functions.

In this paper, we take the electricity data as the key factor to measuring the users' energy efficiency, combined with the characteristics of the energy efficiency analysis problem, and the trapezoidal membership function is adopted. If the optimal interval of a certain index or evaluation factor is \([7, 12]\), the index value falling within the interval is optimal. For 6.4, it is not desired to be directly classified as “non-optimal”, but there is a transition. There is \(6.4 - 6 = (7 - 6) = 0.4\) about 6.4 in \([6, 7]\), and the degree of belonging to the optimal interval \([7, 12]\) is 0.4.

3.3. Household energy efficiency evaluation model based on fuzzy comprehensive evaluation

To sum up, we construct a household energy efficiency evaluation model based on two-layer fuzzy comprehensive evaluation. Based on the optimal TOU electricity of appliances obtained from the survey
(as shown in Table 3 and Table 4), we use a single-layer fuzzy comprehensive evaluation for the target appliances, and then use a two-layer fuzzy comprehensive evaluation to realize based on the appliance energy efficiency evaluation. Combined with the above, the main appliances that affect household electrical energy efficiency are air conditioners and water heaters. We use the TOU electricity information of air conditioners and water heaters obtained by load intelligent perception to construct a fuzzy comprehensive evaluation factor set.

According to the user's energy efficiency grade, we set a reasonable evaluation set, as shown in the following formula:

\[ V = \{ v_1, v_2, v_3 \} \]  

In this formula, \( V \) represents the comment set; \( v_1 \) means high energy efficiency; \( v_2 \) represents general energy efficiency; \( v_3 \) indicates low energy efficiency.

We can design the weight vector of the first layer according to the power consumption proportion of air conditioner and water heater, as shown in the following formula:

\[ A_i = (a_1, a_2, a_3) \]  

\[ a_i = \frac{W_i}{W_i + W_2 + W_3} \]  

Where, \( A_i \) is the weight vector of the air conditioner in the first layer; \( W_i \) represents its TOU electricity.

In the same way, the weight vector of the water heater in the first layer is \( A_2 = (a_4, a_5, a_6) \).

Based on the optimal TOU electricity of appliances obtained above, combined with the trapezoidal membership function and the index data table, we can design and determine the membership function of each factor to the comment set. The index data is shown in Table 5.

| comment set | TOU electricity |
|-------------|-----------------|
| \( v_1 \)   | Below \( a \)   |
| \( v_2 \)   | \( a \) to \( 1.4a \) |
| \( v_3 \)   | Above \( 1.4a \) |

As shown in the above table, \( a \) represents the optimal TOU electricity of the appliance. The membership function \( r_i \) of the TOU electricity \( u \) to \( V_1 \) is shown in the following formula:

\[ r_1 = \begin{cases} 
1 & u < a \\
1.4a - u & a \leq u \leq 1.4a \\
0.4a & u > 1.4a 
\end{cases}, \quad r_2 = \begin{cases} 
\frac{u - 0.8a}{0.2a} & 0.8a < u < a \\
1 & a \leq u \leq 1.4a \\
\frac{1.6a - u}{0.2a} & 1.4a < u < 1.6a \\
0 & 1.6a \leq u \leq 1.4a 
\end{cases}, \quad r_3 = \begin{cases} 
0 & u < a \\
\frac{u - a}{0.4a} & a \leq u \leq 1.4a \\
1 & u > 1.4a 
\end{cases} \]

Where, \( u \) is the actual TOU electricity of the appliance in the target user; \( r_i \) indicates the degree of membership of the appliance to the comment \( V_1 \) under the TOU electricity. The membership function \( r_2 \) of the TOU electricity \( u \) to \( V_2 \) and the membership function \( r_3 \) of the TOU electricity \( u \) to \( V_3 \) are shown in the following equations:

Using the optimal energy efficiency TOU electricity and actual TOU electricity of the target user's air conditioner and water heater, combined with the membership function, the first layer of fuzzy evaluation matrix can be obtained respectively. \( R_1 \) and \( R_2 \) are fuzzy evaluation matrices of air conditioner and water heater respectively. Then using the fuzzy operator \( A \circ R \) can obtain the first-level energy efficiency evaluation vector of the main appliances that affect the energy efficiency of users. \( B_1 \) and \( B_2 \) are the evaluation vectors of air conditioner and water heater respectively.
We can combine the first-level evaluation results to form a second-level evaluation matrix \( B \). In the same way, according to the proportion of electricity consumption of air conditioner and water heater, the second layer of weight vector \( A \) is designed.

\[
A = \left( a_1, a_8 \right)
\]

\[
a_i = \frac{W_i + W_2 + W_3}{W_1 + W_2 + W_3 + Q_1 + Q_2 + Q_3}, \quad a_i = \frac{Q_i + Q_2 + Q_3}{W_1 + W_2 + W_3 + Q_1 + Q_2 + Q_3}
\]

Where, \( Q \) represents the time-sharing power of the water heater within the user's load.

We still use the same fuzzy operator to obtain the second-level comprehensive evaluation result, and then obtain the final energy efficiency rating of the target user according to the maximum membership.

4. Example analysis

We test the proposed method in three households. Based on the sub-item data of appliances obtained by load intelligence perception, we evaluate the power consumption efficiency of the target households. The user information is shown in the following table.

| Table 6. User information list |
|-------------------------------|
| Name          | User 1 | User 2 | User 3 |
| Population    | 1      | 3      | 5      |
| Air conditioner| 00:00-12:00 | 1.1   | 1.2   | 2.8   |
| TOU electricity (summer)/kWh | 12:00-18:00 | 1.6   | 2.4   | 3.0   |
| Water heater  | 00:00-8:00    | 0.6   | 0.7   | 1.2   |
| TOU electricity/kWh | 8:00-16:00 | 0.6   | 1.0   | 1.1   |
|                  | 16:00-24:00  | 1.6   | 0.2   | 3.5   |

4.1. Construct energy efficiency factor set and comment set

In this paper, the fuzzy comprehensive evaluation factors set of electric energy efficiency mainly consists of the TOU electricity of air conditioning and water heater. Taking user 1 as an example, the evaluation factor set is shown in the following formula:

\[
U_i = \{1.1,1.6,2.0\}, \quad U_2 = \{0.6,0.6,1.6\}
\]

Where, \( U \) represents the fuzzy comprehensive evaluation factor set; \( U_1 \) represents the air conditioning evaluation factor set; \( U_2 \) represents the evaluation factor set of water heater.

Similarly, user 2 evaluation factor set is as follows:

\[
U_i = \{1.2,2.4,2.5\}, \quad U_2 = \{0.7,1.0,1.3\}
\]

User 3 evaluation factor set is as follows:

\[
U_i = \{2.8,3.0,5.3\}, \quad U_2 = \{1.2,1.1,3.5\}
\]

The comment set of the above target users is set as \( V = \{0,1,2\} \), which is used to represent low energy efficiency, general energy efficiency and high energy efficiency respectively.

4.2. Construct Fuzzy Evaluation Matrix

Based on Table 4 and Table 5, the weight vector of the first layer of air conditioning and water heater for user 1 expressed as \( A_1 = (0.14, 0.33, 0.53) \) and \( A_2 = (0.25, 0.15, 0.6) \); user 2’s first layer air conditioning weight vector \( A_1 = (0.15, 0.38, 0.47) \) and the first layer water heater weight vector \( A_2 = (0.28, 0.22, 0.5) \); user 3’s first layer air conditioning weight vector \( A_1 = (0.18, 0.3, 0.52) \) and the first layer water heater weight vector \( A_2 = (0.23, 0.2, 0.57) \).
Combined with the membership function, according to the optimal energy efficiency TOU electricity, the first layer fuzzy evaluation matrix of the target users can be obtained. User 1’s air conditioning fuzzy evaluation matrix $R_1$ and water heater fuzzy evaluation matrix $R_2$ are shown as follows:

$$
R_1 = \begin{bmatrix} 1 & 0 & 0 \\ 0.63 & 1 & 0.38 \end{bmatrix}, \quad R_2 = \begin{bmatrix} 0.5 & 1 & 0.5 \\ 0.83 & 1 & 0.16 \end{bmatrix}
$$

User 2’s air conditioning fuzzy evaluation matrix $R_1$ and water heater fuzzy evaluation matrix $R_2$ are shown as follows:

$$
R_1 = \begin{bmatrix} 0.23 & 1 & 0.77 \\ 0 & 0.61 & 1 \end{bmatrix}, \quad R_2 = \begin{bmatrix} 0 & 0 & 1 \\ 0 & 0.15 & 1 \end{bmatrix}
$$

Using the above fuzzy vector and matrix can get the first layer evaluation vector of the target users. The evaluation vector of air conditioning and water heater in User 1 are shown as follow:

$$
\begin{bmatrix} 0.8039 \\ 0.5300 \\ 0.2714 \end{bmatrix}, \quad \begin{bmatrix} 0.7300 \\ 0.8500 \\ 0.2210 \end{bmatrix}
$$

The evaluation vector of air conditioning and water heater in User 2 are shown as follow:

$$
\begin{bmatrix} 0.0345 \\ 0.4523 \\ 0.9655 \end{bmatrix}, \quad \begin{bmatrix} 0.0616 \\ 0.2200 \\ 0.9384 \end{bmatrix}
$$

The evaluation vector of User 3 are shown as follow:

$$
\begin{bmatrix} 0.2508 \\ 0.8140 \\ 0.7608 \end{bmatrix}, \quad \begin{bmatrix} 0.0399 \\ 0.7527 \\ 0.9010 \end{bmatrix}
$$

The second layer of weight vector $A$ is designed, according to the proportion of each TOU electricity of air conditioning and water heater. Because of the different types of target users, user 1’s second layer weight vector $A = (0.6 \ 0.4)$; user 2’s second layer weight vector $A = (0.64 \ 0.36)$; user 3’s second layer weight vector $A = (0.62 \ 0.38)$.

User 1’s second evaluation matrix $R$ are shown as follow:

$$
\begin{bmatrix} 0.8039 & 0.5300 & 0.2714 \\ 0.7300 & 0.8500 & 0.2210 \end{bmatrix}
$$

User 2’s second evaluation matrix $R$ are shown as follow:

$$
\begin{bmatrix} 0.0345 & 0.4523 & 0.9655 \\ 0.0616 & 0.2200 & 0.9384 \end{bmatrix}
$$

User 3’s second evaluation matrix $R$ are shown as follow:

$$
\begin{bmatrix} 0.2508 & 0.6160 & 0.7608 \\ 0.0399 & 0.7527 & 0.9010 \end{bmatrix}
$$

4.3. Fuzzy comprehension evaluation

Using the above fuzzy operators to get the comprehensive judgement of the target users respectively. User 1’s result $B = [0.7743 \ 0.6580 \ 0.2512]$, User 2’s result $B = [0.0443 \ 0.3687 \ 0.9557]$, User 3’s result $B = [0.1707 \ 0.7983 \ 0.8141]$. According to the principle of maximum membership degree and the result of household energy efficiency evaluation based on fuzzy comprehensive evaluation, user 1 is low energy efficiency, user 2 and user 3 are both high energy efficiency. Then the electrical energy efficiency in the target users’ load can be obtained according to the first layer evaluation results based on the evaluation of appliances. User 1’s air conditioning is low energy efficiency and water heater is average energy efficiency. User 2’s air conditioning and water heater are both high energy efficiency. User 3’s air conditioning is average energy efficiency and water heater is high energy efficiency.
5. Conclusion
We propose a user deep energy evaluation method based on the fuzzy comprehension evaluation. Considering the appliance consumption behaviour, this paper analyses the user's electricity consumption behaviour via the itemized appliance data from load intelligent perception. The first layer fuzzy evaluation accomplishes the evaluation of the electricity consumption of component appliances, and the second layer fuzzy evaluation gives the comprehensive evaluation of the electricity consumption of target users and shows energy efficiency results of specific appliances, which is significant for guiding the power demand-side saving and management. The paper makes different evaluation index for different types of users while evaluating their energy efficiency, which makes the method more robust.

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