Energy Efficiency Evaluation Method of Customer-side Integrated Energy System

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Abstract. At present, the integrated energy efficiency evaluation (EEE) system based on subsystems is not yet mature. Combining the characteristics of modularization and decentralization of the integrated energy system (IES), based on the membership function of fuzzy theory and the AHP method, this paper constructs a set of customer-side comprehensive EEE system, which covering all kinds of energy sources including electricity, gas, cooling, heat, water and so on. On this basis, the method of comprehensive energy efficiency evaluation index (EEEI) based on subsystem is summarized which can meet the requirements of breadth and depth of comprehensive EEE and provide decision basis for system design and operation.

1. Introduction
IES has the characteristics of modularization and decentralization. It is an efficient and reliable energy conversion unit arranged around the customer-side [1], which can realize the optimal allocation of resources in various energy systems, give full play to the complementary and synergistic effects of different forms of energy. It can improve the flexibility of system operation and improve the consumption capacity of clean energy and renewable energy, as well as the comprehensive EEE and reliability of the system [2].

Reasonable EEE will promote the rapid development of the comprehensive energy industry, and the research on the comprehensive EEE of the park is also one of the hot directions in this field. Literature [3] constructed the comprehensive EEEI system of the park energy Internet by dividing the park energy internet into supply side, transmission network, demand side, and energy storage, and then measured the park energy internet comprehensive EEE based on fuzzy algorithm. Literature [4] puts forward the evaluation index system that includes economic, policy and other factors, and establishes the hierarchical structure model of operation mode evaluation. The optimal operation mode is selected according to the comprehensive weight, which provides the operation mode reference for the development of the IES of the industrial park. Literature [5] builds the EEE system of the park's IES from the three aspects of safety, economy and environmental protection of the IES. It also introduces the improved projection pursuit grey correlation method, AHP-entropy weight method and other methods that can be used for the EEE of the park's IES.

At present, most of the comprehensive EEE focuses on the system level, and the means to carry out EEE from the perspective of subsystems is not yet mature. Therefore, this paper constructs an EEEI
system of customer-side IES based on distribution, air conditioning, CCHP, PV power generation, energy storage and other subsystems, and uses AHP and membership function to determine the customer-side integrated EEEI.

2. Customer-side comprehensive EEI system

The scientific and standardized construction of evaluation indexes has an important influence on the evaluation results. Based on the principles of systematization, typicality, dynamics, comparability, operability, quantizability and comprehensiveness, and considering the influencing factors of the system, this paper constructs an EEEI system of customer-side IES based on the subsystems of power distribution, air conditioning, cogeneration of cold, heat and power (CCHP), PV power generation, energy storage, etc. EEEI system is shown in Fig.1.

![Figure 1. EE evaluation index system.](image)

2.1. EEEI system of Distribution Subsystem

The transmission of electrical energy depends on the customer's power distribution network. In the transmission process, there will be loss of electrical energy. Transformers and distribution lines play a key role in the distribution network, and their operation directly affects the EEE of the distribution subsystem. Therefore, consider the EEE of the distribution subsystem based on indicators such as the heavy overload time of transformer, transformer comprehensive loss, distribution line loss rate and so on.

2.1.1. Accumulated heavy overload time of transformer.

\[ T_{ls,t} = t_h + t_o \]  

Where \( T_{ls,t} \) is the duration of transformer heavy overload, \( t_h \) is the duration of heavy, and \( t_o \) is the duration of overload.

2.1.2. Transformer comprehensive loss.

\[ SR_t = (W_h - W_l)/W_h \times 100\% \]  

Where \( SR_t \) is the transformer comprehensive loss rate, \( W_h \) and \( W_l \) are the high/low voltage side power during the evaluation period, respectively.
2.1.3. Distribution line loss rate.

\[ SR_l = \frac{(W_s - W_o)}{W_s} \times 100\% \]  

(3)

Where \( SR_l \) is distribution line loss rate, \( W_s \) is the electric quantity at the initial end of the line, and \( W_o \) is the electric quantity at the end of the line (Considering that the customer-side line is short and the branch is short, the line loss rate of distribution lines can also be calculated by using common quantitative value).

2.2. EEEI system of air conditioning system

Air conditioning system mainly consumes electricity or natural gas, and adjusts the air temperature, humidity and so on for users. Refrigeration equipment, chillers, chilled water delivery systems and so on have a significant impact on air conditioning systems. Therefore, consider the EEE of the air conditioning system based on indicators such as energy efficiency ratio (EER) of refrigeration system, chiller operation efficiency, chilled water delivery coefficient, temperature difference, cooling water delivery coefficient, EER of air conditioning terminal, and so on.

2.2.1. EER of refrigeration system. This index is applicable to the case of using electric drive chillers.

\[ EERR = \frac{Q}{\sum N_j} \]  

(4)

where \( EERR \) is the EER of the refrigeration system, \( Q \) is the total cooling heat produced by the air conditioning system, and \( N_j \) is the electrical energy consumption of the main equipment of the refrigeration system during the evaluation period.

2.2.2. Chiller operation efficiency. This index applies to the case of using electric refrigeration and absorption chillers.

\[ COP = \frac{Q}{N_{chiller}} \]  

(5)

Where \( COP \) is the operating efficiency of the chiller, \( N_{chiller} \) is the energy consumption of the chiller. When electric refrigeration is adopted, energy consumption is electric quantity. When absorption chillers are used, the energy consumption is the sum of heating source consumption (calculated by low calorific value) and electricity consumption (converted to primary energy).

2.2.3. Chilled water delivery coefficient.

\[ WTF_{chw} = \frac{Q}{N_{chp}} \]  

(6)

Where \( WTF_{chw} \) is the chilled water delivery coefficient, and \( N_{chp} \) is its total energy consumption.

2.2.4. Temperature difference between chilled water supply and return water.

\[ \Delta t_{chw} = |t_s - t_r| \]  

(7)

Where \( \Delta t_{chw} \) is the temperature difference, \( t_s \) and \( t_r \) are the temperature of chilled water supply port and return port, respectively.
2.2.5. Cooling water delivery coefficient.

\[ W_{TF} = \frac{Q}{N_{cp}} \]  

Where \( W_{TF} \) is the cooling water delivery coefficient, and \( N_{cp} \) is its total energy consumption.

2.2.6. Temperature difference between cooling water supply and return water.

\[ \Delta t_{cw} = |t_s - t_r| \]  

Where \( \Delta t_{cw} \) is temperature difference, \( t_s \) and \( t_r \) are temperature of cooling water supply port and return port.

2.2.7. EER of air conditioning terminal. The air conditioning terminal includes air conditioning unit, new fan group, exhaust fan group, fan coil, etc.

\[ EERt = \frac{Q}{\sum N_t} \]  

Where \( EERt \) is the EER of air conditioning terminal, and \( \sum N_t \) is total energy consumption of terminals.

2.3. EEEI system of CCHP system

Taking the gas-fired internal combustion engine and waste heat/direct combustion lithium bromide absorption air conditioning combined cycle system as an example, the CCHP system mainly consumes gas and provides electricity, cooling and heating to users. Consider the CCHP EEE system based on indicators such as power generation efficiency, cooling and heating efficiency, thermal efficiency of triple production, etc.

2.3.1. Power generation efficiency.

\[ \eta_W = \frac{(W_p \times 3600) \times (V_{g} \times q_g)}{(V_{lbac} \times q_g) + Q_{exh}} \times 100\% \]  

where \( \eta_W \) is power generation efficiency, \( q_g \) is low calorific value of natural gas [6], \( W_p \) is total power generation of triple supply system, and \( V_{g} \) is total gas consumption of internal combustion.

2.3.2. Cooling and heating efficiency. The \( \eta_Q \) is calculated as follows.

\[ \eta_Q = \frac{Q}{(V_{lbac} \times q_g + Q_{exh})} \times 100\% \]  

Where \( V_{lbac} \) is supplementary combustion gas volume, \( Q_{exh} \) is the heat of flue gas absorbed.

2.3.3. Thermal efficiency of triple production. The formula of thermal efficiency \( \eta \) is as follows, where \( Q \) is the total cooling heat generated by the triple supply system.

\[ \eta = \frac{(Q + W_p \times 3600) \times (V_{g} + V_{lbac}) \times q_g}{(V_{g} + V_{lbac})} \times 100\% \]  

2.4. **EEEI system of PV power generation subsystem.**
The PV power generation subsystem uses PV modules to convert solar energy into electrical energy, and the conversion efficiency of the PV modules directly affects the EEE. Therefore, consider the EEE based on indicators such as the conversion rate of PV modules and the comprehensive conversion rate of PV modules.

2.4.1. *Conversion rate of PV modules.* The formula of conversion rate $\mu$ is as follows.

$$\mu = \frac{W_s}{W_p} \times 100\%$$

(14)

2.4.2. *Comprehensive conversion rate of PV modules.* The $\mu_{avg}$ is calculated as follows.

$$\mu_{avg} = \frac{\sum_{i=1}^{n} u(i)}{n}$$

(15)

Where $u(i)$ is corresponding conversion efficiency of PV group, and $n$ is the number of PV modules.

2.5. **EEEI system of energy storage subsystem.**
Taking the energy storage power station as an example, starting from the factors that affect the energy storage system, consider the EEE of the energy storage subsystem based on indicators such as comprehensive efficiency, energy storage loss rate, electricity consumption rate, and substation distribution loss rate, etc.

2.5.1. *Comprehensive efficiency of energy storage power station.* The $\eta_{EESS}$ is calculated as follows.

$$\eta_{EESS} = \frac{E_{on}}{E_{off}} \times 100\%$$

(16)

Where $E_{on}$ and $E_{off}$ are its on grid power and off grid power of the energy storage power station.

2.5.2. *Energy storage loss rate of power station.*

$$R_{ES} = \frac{\sum E_C - \sum E_D}{E_{off}} \times 100\%$$

(17)

Where $R_{ES}$ is energy storage loss rate, $\sum E_C$ and $\sum E_D$ are total charge and discharge amount of each unit.

2.5.3. *Comprehensive efficiency of energy storage power station.*

$$R_S = \frac{\sum E_S}{E_{off}} \times 100\%$$

(18)

Where $R_S$ is the station power consumption rate, $\sum E_S$ is the total station power consumption.

2.5.4. *Comprehensive efficiency of energy storage power station.* The $R_i$ is calculated as follows.

$$R_i = \frac{E_{off} - \sum E_S - \sum E_C + \sum E_D - E_{on}}{E_{off}} \times 100\% = 1 - \eta_{EESS} - R_{ES} - R_S$$

(19)
3. Customer-side comprehensive EEE method

AHP is a decision analysis method that combines qualitative and quantitative solutions to solve multi-objective complex problems. The EEEI system of customer-side IES includes multiple subsystems, with many evaluation objectives and high complexity. Therefore, we use AHP to carry out the customer-side comprehensive EEE.

3.1. Comprehensive EEE model.

Taking the comprehensive EEEI as the evaluation goal, the customer-side IES power distribution, air conditioning, CCHP, PV power generation, energy storage and other influencing factors are integrated to build the customer-side comprehensive EEE model. The comprehensive EEE model is shown in Fig.2.

Figure 2. Comprehensive EEE model.

The EEEI of the customer-side IES and subsystem is divided into three levels, which is expressed as the evaluation set: \( Q = \{ Q_{\text{high}}, Q_{\text{medium}}, Q_{\text{low}} \} \).

3.2. Comprehensive EEE model.

First, the evaluation indicators of the five subsystems are constructed into five subsets of influencing factors and a customer-side integrated EE impact set: distribution system subset \( C_1 = (P_1, P_2, P_3) \), air conditioning system subset \( C_2 = (P_4, P_5, P_6, P_7, P_8, P_9, P_{10}) \), CCHP system subset \( C_3 = (P_{11}, P_{12}, P_{13}) \), ...
PV power generation system subset $C_4 = (P_{14}, P_{15})$, energy storage system production subset $C_5 = (P_{16}, P_{17}, P_{18}, P_{19})$, customer-side integrated EE set $O = (C_1, C_2, C_3, C_4, C_5)$. On this basis, the weight vector is obtained, which is recorded as $W = (w_1, w_2, \ldots, w_n)$.

According to the fuzzy statistical method, the membership of each individual index can be obtained. Then considered the relationship between the membership degree of each EEEI, we can derive the single indicator evaluation matrix $R$. Last, according to the principle of normalization and maximum membership, the EEEI of the customer-side IES can be finally determined.

| Table 1. Relationship between the membership degree of each EEEI. |
|-----------------|-----------------|
| Index Item      | Membership Degree |
|-----------------|------------------|
| High EEEI       | 0.8~1.0          |
| Medium EEEI     | 0.7~0.8          |
| Low EEEI        | Below 0.7        |

4. Conclusion

From the perspective of energy subsystem, this paper constructs a customer-side integrated EEEI system based on power distribution, air conditioning, CCHP, PV power generation, energy storage and other subsystems. By using AHP and membership function, the energy efficiency level method of customer-side IES based on energy subsystem is proposed. This method comprehensively considers the importance and weight values of each subsystem evaluation index, and obtains a comprehensive energy efficiency level, which provides EEE management decision support for operational managers and achieves energy conservation, cost reduction and efficiency increase.

Acknowledgments

This work was financially supported by the fund of NARI Technology Co., Ltd. (No. 524608200058)

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