Comprehensive Evaluation of Distributed Energy System Considering Interest Relationships Among Participants

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Abstract. On the ground of evaluating distribute energy systems (DES) effectively and roundly, a comprehensive evaluation model is studied and developed in this paper. Based on the analysis of roles, demands, and interest relationships of four participants of DES—government, DES investment operator, State Grid Company, and users, an evaluation index system is proposed. It covers the factors including energy consuming, environmental protecting, social benefits, economy, system reliability, and users’ satisfaction. Furthermore, an adaptive decision model based on AHP-entropy combined weighting method and Material Element Extension technology is established. Through case study, the feasibility of the evaluation model is testified.

Introduction

Distributed Energy System (DES) refers to an energy system where energies, such as electric power, thermal energy, and cool energy, are produced close to users, typically relying on a number of modular and small-scale technologies \[1\]. DES is believed to be more efficient and environment friendlier than conventional centralized energy system (CES), by concertedly planning, producing, dispatching, and using multiple energies.

However, the lack of a proper and efficient evaluation method for decision making about system planning schemes is a barrier to the development of DES. Over the past few years, there have been some studies about evaluation of energy systems. \[2\] regarded evaluation of residential energy supply system as a multi-criteria decision making problem, and assessed energy systems by employing AHP and PROMETHEE models. \[3\] evaluated environmental and energy performance of CCHP and conventional generation plants by means of life cycle assessment methodology. The above papers show that litter research has been done on comprehensive evaluation of DES, and there has not been any study considering the interest relationship between multiple participants of DES construction and operation.

Motivated by the above reasons, this paper studies and designs a comprehensive evaluation model of DES considering multi interest subjects, by building an index system and establishing a determination model based on Material Element Extension (MEE) model. A case study is implemented to assess some different DESs and verifies the feasibility of the proposed model.

Index System Considering Interest Relationship among Participants

Interest Relationship among Participants

The four main participants of construction and operation of DES are shown below, as well as their roles and interest relationship:

Government: in charge of promoting and supervising DES programs. To achieve the goals of reducing GHG emission, air pollution, and boosting GDP, the government would offer financial support to DES programs, and they collect taxes from DES in return.
DES investment operator: in charge of planning, constructing, and operating DES. They invest in technologies and manpower, and gain profit by selling energy to users.

State Grid: in charge of restructuring the power grid to meet the demand of DES construction, and offering power to DES. In China, the State Grid Company is in monopoly position. DES may cause State Grid income loss due to the decrease of electricity sales volume, but DES could postponing the extension of power network which can save the State Grid Company a lot of money.

Energy users: in charge of purchasing energy and send feedback about user experience.

Index System

Based on the aforementioned analysis, a 3-level index system of DES comprehensive evaluation is proposed and shown in Fig. 1. For the limitation of space, the details of indices is not listed here.

![Index System Diagram](image)

**Evaluation Decision Model**

Matter Element Extension (MEE) is a kind of multi-objective decision method proposed in China in 1980s. The method applies to dealing with the problems with incompatibility among indices, so conflict of interests among participants of DES could be perfectly solved by MEE. Based on MEE, this paper introduces Analytic Hierarchy Process and the Entropy Weight (AHPEW) method for indices weighting.

The detailed analytic process of the AHPEW-MEE method is as follows, as well as shown in Fig. 2.

1. Calculate and get the actual value of indices.
2. Define classical domain and joint domain of every indices. The matter element of evaluation object (planning scheme) can be expressed as:
\[
R_i = [Q, C, X_i] = \begin{bmatrix}
Q_1 & c_1 & x_{i1} \\
& c_2 & x_{i2} \\
& & \vdots \\
& & c_n & x_{in}
\end{bmatrix}
\]
(1)
where \(R_i\) is the matter element of \(i\)th \((i=1, 2, \ldots, m)\) planning scheme or program, \(Q_i\) is the \(i\)th program, \(c_j\) is the \(j\)th \((j=1, 2, \ldots, n)\) index, \(X_i\) is the value set of indices and \(x_{ij}\) is the value of the \(j\)th index in the \(i\)th planning program.

Mark estimation scales set as \(T = \{T_k \} (k=1, 2, \ldots, p)\). Classical domain is expressed as:
\[
R_0 = [T_k, C, V_k] = \begin{bmatrix}
k & c_1 & (a_{1k}, b_{1k}) \\
& c_2 & (a_{2k}, b_{2k}) \\
& & \vdots \\
& & c_n & (a_{nk}, b_{nk})
\end{bmatrix}
\]
(2)
where \(R_0\) is the classical domain of the \(k\)th estimation scale, \(V_k\) is the data range of index within the \(k\)th scale, \(V_k = <a_{jk}, b_{jk}>\), \(j=1, 2, \ldots, n\), \(a_{jk}\), \(b_{jk}\) are respectively the minimum and maximum boundary value of the \(j\)th index in the \(k\)th scale.

Joint domain is expressed as:
\[
R_p = [Q, C, V_p] = \begin{bmatrix}
k & c_1 & <a_{1p}, b_{1p}> \\
& c_2 & <a_{2p}, b_{2p}> \\
& & \vdots \\
& & c_n & <a_{np}, b_{np}>
\end{bmatrix}
\]
(3)
where \(R_p\) is joint domain, \(V_p\) is the data range of index of all scales, \(V_p = <a_{jp}, b_{jp}>\), \(a_{jp}\), \(b_{jp}\) are respectively the acceptable minimum and maximum boundary value of the \(j\)th index.

![Figure 2. Evaluation process of AHPEW-MEE method.](image)

1. Calculate actual value of indices
2. Define classical domain and joint domain of every indices
3. Standardize indices values
4. Weight indices
   - AHP weighting
   - Entropy weighting
   - Comprehensive weight
5. Build comprehensive correlation model
6. Calculate comprehensive evaluation value

(1) To eliminate the influence of different dimensions of indices, in this paper, the min-max normalization method is employed for standardization: For “cost type” indices, \(r_{ij} = (x_{ij}^{\text{max}} - x_{ij})/(x_{ij}^{\text{max}} - x_{ij}^{\text{min}})\); for “benefit type” indices, \(r_{ij} = (x_{ij}^{\text{min}} - x_{ij})/(x_{ij}^{\max} - x_{ij}^{\text{min}})\), where \(r_{ij}\) is the normalized value, \(x_{ij}\) is the actual value, \(x_{ij}^{\text{min}}\) and \(x_{ij}^{\text{max}}\) are the minimum and maximum value of the \(j\)th index.

(2) Weight indices by AHPEW method. AHP is a kind of subjective weighting method depending on experts’ experience, while EW is an objective weighting method based on information entropy theory. The two methods are combined to weighting in this paper so that they can complement each other. The weight of the \(j\)th index is:
where \( \omega_j \) is AHP weight, \( \omega_j \) is entropy weight; to take both subjective and objective weight into consideration, \( \alpha = 0.5 \).

The correlation of the \( j \)th index of \( Q_i \) to the \( k \)th scale is as below:

\[
K_{ik}(v_j) = \begin{cases} 
\rho(r_{j\in V_{ik}}) & r_{j\in V_{ik}} \notin [a_{j\beta}, b_{j\beta}] \\
\rho(r_{j\in V_{ik}}) - \rho(r_{j\in V_{ik}}) / G_{j\beta} & r_{j\in V_{ik}} \in [a_{j\beta}, b_{j\beta}]
\end{cases}
\]

\[
\rho(r_{j\in V_{ik}}) = \rho(r_{j}, (a_{j\beta}, b_{j\beta})) = \frac{r_j - a_{j\beta} + b_{j\beta}}{2} - \frac{b_{j\beta} - a_{j\beta}}{2}
\]

\[
G_{j\beta} = b_{j\beta} - a_{j\beta}
\]

where \( K_{ik}(v_j) \) is correlation of \( j \)th index to \( k \)th scale, \( \rho \) refers to distance, \( G \) means the width of domain and the comprehensive correlation is:

\[
K'_i(Q) = \sum_{j=1}^n \omega_j K_{ik}(v_j)
\]

where \( K'_i(Q) \) is the weighted correlation. Compare all the correlation values, and the bigger the correlation, the nearer to the corresponding scale.

(4) Calculate comprehensive evaluation value

\[
\bar{K}'_i(Q) = \frac{K'_i(Q) - \min K'_i(Q)}{\max K'_i(Q) - \min K'_i(Q)}
\]

\[
k^*_i = \frac{\sum_{i=1}^n k_i \times \bar{K}'_i(Q)}{\sum_{i=1}^n \bar{K}'_i(Q)}
\]

where \( k^*_i \) is the comprehensive evaluation value of \( Q_i \).

Case Study

There are three DES planning programs (S1, S2, S3) for an industry zone in north China. The details of the programs as well as reference system are shown in Table 1.

| System | Structure |
|--------|-----------|
| CES    | Power grid, gas boiler, electric cooler |
| S1     | Power grid, wind turbine, gas turbine, waste heating boiler, absorption cooler, electric cooler, electric boiler, battery |
| S2     | Power grid, wind turbine, PV, gas turbine, waste heat boiler, absorption cooler, electric cooler, electric boiler, battery |
| S3     | Power grid, wind turbine, PV, gas boiler, waste heat boiler, absorption cooler, electric cooler, battery |
Based on the data of systems, values of all quantitative indices of the four systems are calculated firstly. The qualitative indices are transferred to quantitative evaluation by employing fuzzy evaluation method \[4-5\]. Define 4 comment sets—“poor”, “medium”, “good”, and “excellent”, which scores are \([0,2), [2,5), [5,8), [8,10)\], and then build membership function to determine the scores of every qualitative index. Four classes are defined: \(k=1,2,3,4\), the bigger the number, the higher the score. Table 2 shows the final evaluation results of the four systems.

\[
\text{Table 2. Final comprehensive evaluation results.}
\]

| Program | CES  | S1   | S2   | S3   |
|---------|------|------|------|------|
| Score   | 1.4073 | 2.7042 | 3.0576 | 2.6711 |

From this table, we can see that S2 gets the highest rank. S3 scores less than S2 but slightly exceed S1. All the three DES systems overmatch CES in a high degree, which demonstrates DES’s superiority over CES. DES utilize more renewable energy and consume less grid power than CES, therefore DES exerts much better than CES in terms of energy \((F_1)\) and environment \((F_2)\), but much worse on State Grid Company’s income \((I_{19})\). Although CES doesn’t have to renovate for DES’s construction, it has critical need for expansion in the long term due to the sustainable growth of electric loads, which cost much more on lands and equipment, hence it spends more money on renovation \((I_{18})\) than DES, and also destroy more ecological environment \((I_8)\). DES takes advantage of complementarity of multiple energies, so the reliability of DES is also better than CES \((F_9)\). In terms of users’ satisfaction with service \((F_{10})\), as DES investment operator needs to improve its competitiveness in the market all the time (different with the State Grid Company’s monopoly status), it tends to try harder to provide better service to users.

In the aspect of \(I_1\), \(I_2\) and \(F_2\), S2 and S3 (WT+PV) show better performance than S1 (only WT), which is because the natural complementarity of wind and solar energy makes S2 and S3 consume less gas power and grid power. For the same reason, S1 makes more fluctuation of exchanging power \((F_8)\) between DES and the main grid, and exerts marginally worse on reliability \((F_9)\). The subsidy of wind power is much less than that of solar power in China, so S1 gets less allowance than the other two programs, leading to longer investment payoff period \((I_{12})\), less total income \((I_{14})\), and larger Roi \((I_{15})\). Wind power shows “anti-peak regulation” character, since it generate more during valley period of electric load, for example, during night. At night, the demand of electric is low, but not of heat. Conventional CCHP plants works in “fixing power based on heat” mode, which cause high wind power abandoning rate during night. But in S1 and S2, electric boilers plays an important role in consuming wind energy. They transfer superfluous wind power to heat, so the whole system can reach higher thermoelectric rate and consume less gas. Therefore, S1 and S2 (with EB) works better than S3 (without EB) in the aspect of \(I_3\). But the investment and o&m costs of EC are expensive, so S3 behaves not so well in economy respect.

\section*{Summary}

In this paper, a comprehensive evaluation model of DES is studied and proposed. An index system, considering the interest relationship between four participants of DES, is built. The index system contains three hierarchies and covers factors including energy, environment, society, economy, reliability, and satisfaction. A determination model based on AHP-entropy weighting method and Material Element Evaluation model is developed and applied. Through case study of an industry zone in China, the following conclusions could be deduced:

1. The multi-participant comprehensive index system in this paper can reflect interest demands, and evaluate DES roundly.
2. The AHPEW-MEE decision model can achieve efficient evaluation, and is easy for comparison.
3. A DES designer should take fully consideration in complementarity among multiple energies, and allocate equipment scientifically.
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