Evaluation system for the energy efficiency effects of energy-saving transmission network

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Abstract. The construction of energy-saving transmission network contributes to both economic benefits and greenhouse gas emissions reduction. To reflect the energy-saving effects better, in this paper, a comprehensive evaluation index system and evaluation method for the energy-efficiency effects of energy-saving transmission network are studied. First, an evaluation index system for energy-saving transmission network is established, including indices of energy-saving effects and indices of low-carbon effects. Then, through specific steps of index data preprocessing, index data correlation analysis, index weighting methods, agglomeration model formulation, and comprehensive evaluation results display, the comprehensive evaluation model is formulated. Finally, case study results verified the feasibility and effectiveness of the proposed evaluation index system and assessment method.

1. Introduction
The construction of energy-saving transmission network plays an important role in promoting the development of energy-saving and emission-reduction of the entire society [1,2]. In order to evaluate the energy efficiency performance of energy-saving transmission network, it is necessary to establish a complete set of comprehensive evaluation index system and select proper evaluation methods [3].

Much progress has been made in evaluation index systems and evaluation methods of the energy efficiency of power grids. In [4], a technical and economic comprehensive evaluation index system is established including the network size, the total power loss, the total investment costs, power grid reliability and area sizes. In [5], a comprehensive evaluation system by triangle fuzzy function is created, over 20 quantity and quality indices are included, such as safety, reality, economic, low-cost, social environment and target achievement. In [6], considering smart grid technologies, low-carbon generation technologies, utilization of low-carbon energy and low-carbon power dispatch, corresponding evaluation methods are then proposed to analyze the low-carbon benefits. In [7], on the basis of eliminating the environmental factors, an evaluation system for low-carbon benefits is built in line with the characteristics of the national smart grids.

In this paper, focusing on the energy efficiency effects of energy-saving transmission network, a comprehensive evaluation index system and evaluation methods are studied. The evaluation index system includes both indices of energy-saving effects and indices of low-carbon effects, which better represents the energy efficiency performance of energy-saving transmission network. Then, a
comprehensive evaluation model is formulated, including steps of indicator data pre-processing, indicator data correlation analysis, weights determining in combined methods and so on. The rest of this paper is organized as follows: Section 2 presents the multi-layer index system. Section 3 presents the proposed evaluation method. A case study is shown in Section 4 and Section 5 concludes main work.

2. Evaluation index system for energy efficiency effects of energy-saving transmission network

The energy-saving transmission network can improve the economic benefits and energy efficiency of the power grid, as well as reducing carbon emissions. To reflect these characteristics in the energy-saving transmission network objectively and fairly, the evaluation index system is established from the perspectives of both energy-saving effects and low-carbon effects [8,9].

2.1. Evaluation index system for energy-saving effects

2.1.1. Structure of the energy-saving effects index system

Focusing on energy-saving effects of the energy-saving transmission network, the index system is established reflecting its relevant characteristics and key elements. The evaluation index system structure for energy-saving effects of the energy-saving power grid is shown in figure 1. Four primary indices include power grid structure, power grid operation, power grid management and power grid equipment, which can reflect the benefits of power grid at a certain macroscopic level. Each primary index can be subdivided into two secondary indexes to describe the performance of a particular aspect of the power grid. Further subdivided on the basis of secondary indicators, 16 tertiary indicators can be directly calculated from the actual data of the power grid, which can specifically reflect the performance of the power grid at a certain point.

![Figure 1. Evaluation index system structure for energy-saving effects.](image)

2.1.2. Specific evaluation indices for energy-saving effects

1) Indices set based on grid structure
   - Voltage level composition
     Take the voltage level composition of the transmission network as an example, which can be defined as:
\[ \eta_i = \sum_{i=1}^{I} V_{\eta_i} \times \frac{L_{\eta_i}}{L_{\eta_2}} \]  \tag{1} 

where, \( \eta_i \) is the index of voltage level composition of the transmission grid; \( I \) is the number of voltage levels; \( V_{\eta_i} \) is the \( i \)-th voltage level of the transmission network; \( L_{\eta_i} \) is the total length of transmission lines of the \( i \)-th voltage level; \( L_{\eta_2} \) is the total length of transmission lines for all voltage levels.

- **Capacity-load ratio**
  \[ \eta_3 = \frac{K_i \times K_2}{K_3 \times K_4} \]  \tag{2} 

\[ \eta_4 = \frac{Q_1}{Q_2} \]  \tag{3} 

where, \( \eta_3 \) is typical day capacity-load ratio; \( K_1, K_2, K_3 \) and \( K_4 \) are the load dispersion coefficient, reserve coefficient, average power factor and transformer operation rate, respectively; \( \eta_4 \) is the maximum capacity-load ratio; \( Q_1 \) and \( Q_2 \) are the total transformer capacity and maximum system load, respectively \[ \text{[10]} \].

2) **Indices set based on power grid operation**

- **Overall power line loss rate**
  \[ \sigma_1 = \frac{S_1 - S_2}{S_1} \]  \tag{4} 

where, \( \sigma_1 \) is the overall line loss rate in transmission network; \( S_1 \) is the total power transmitted in transmission network; \( S_2 \) is the power supplied to end-users through transmission network.

- **Overall power factor**
  \[ \sigma_2 = \frac{P}{|S|} \]  \tag{5} 

where, \( \sigma_2 \) is the overall power factor in power grid; \( P \) is the active power and \( |S| \) is the apparent power.

3) **Indices set based on power grid management**

- **The effect of shutting down small capacity thermal power plants policy**
  \[ \sigma_{10} = \frac{S_9}{S_{10}} \]  \tag{6} 

\[ \sigma_{11} = \frac{S_{11}}{S_{12}} \]  \tag{7} 

where, \( \sigma_{10} \) is the progress of shutting down small thermal plants; \( S_9 \) is the capacity of small thermal plants that are shut down under the policy; \( S_{10} \) is the total capacity of small thermal plants before implementing the policy; \( \sigma_{11} \) is the proportion of small thermal plants among all generations; \( S_{11} \) and \( S_{12} \) are the capacity of remaining small thermal plants and the total installed capacity in power grid, respectively.
Absorptivity of renewable energy generations

\[ \sigma_{12} = \frac{M_1}{M_2} \] (8)

\[ \sigma_{13} = \frac{S_{13}}{S_{12}} \] (9)

where, \( \sigma_{12} \) is the proportion of grid-connected renewable energy generation investment; \( M_1 \) and \( M_2 \) are respectively the investment of renewable energy integration facilities and total investment in grid construction; \( \sigma_{13} \) is the proportion of renewable energy generation; \( S_{13} \) and \( S_{12} \) are respectively the total installed capacity of renewable energy generations and the total installed capacity of generations in the entire power grid [11,12].

4) Indices set based on transmission network equipment

- Overall power loss of transformers

\[ \mu_1 = \frac{A_1}{A_2} \] (10)

\[ \mu_2 = \frac{A_1}{A_4} \] (11)

where, \( \mu_1 \) is the operation loss rate of transformers; \( A_1 \) is the total power loss of transformers; \( A_2 \) is the total transformer power supply; \( \mu_2 \) is the energy-saving rate of energy-saving transformers; \( A_1 \) is the power loss reduced by energy-saving transformers; \( A_4 \) is rated capacity of transformers [13].

- Equipment utilization rate

\[ \mu_3 = \frac{\sum P_j \times t_j}{P_m \times T} \] (12)

\[ \mu_4 = \frac{\sum t_j}{T} \] (13)

where, \( \mu_3 \) is the utilization rate of transmission equipment; \( T \) is the total assessment time periods; \( t_j \) is equipment's \( j \)-th investment time; \( P_j \) is equipment's \( j \)-th input investment power; \( P_m \) is equipment's rated power; \( \mu_4 \) is the utilization of non-transmission equipment.

2.2. Evaluation index system for low-carbon effects

2.2.1. Structure of the low-carbon effects index system. With the advance of low-carbon development concept, the low-carbon effects of energy-saving transmission network should also be paid attention to. Considering this, a comprehensive evaluation index system for the low-carbon effects of energy-saving transmission network is established. The structure of the evaluation index system is shown in figure 2. Six primary indices can reflect the low-carbon benefits of the power grid at a certain macro-level, including the characteristics of low-carbon power, energy efficiency index, low carbonization index of enterprises, low carbonization characteristics of power grid, conventional power and effect of power grid on the utilization of low-carbon power sources. Primary indices can be
subdivided into sixteen secondary indices to describe the low-carbon performance of a particular aspect of the power grid. On the basis of secondary indices, further subdivided tertiary indices can reflect the low-carbon performance of the power grid at a specific point.

Figure 2. Evaluation index system structure for low-carbon effects.

2.2.2. Specific evaluation indices for low-carbon effects

1) Proportion of low-carbon power sources
Proportion of low-carbon power sources of the power grid includes renewable energy development, maximum capture rate of carbon capture power plants and energy consumption rate of carbon capture devices.

The maximum capture rate of carbon capture power plants $\gamma_{CCS}$ can be expressed as:

$$\gamma_{CCS} = (1 - \frac{Emi_{C}}{fuel_{C}}) \times 100\%$$  \hspace{1cm} (14)

where, $Emi_{C}$ is actual carbon emissions; $fuel_{C}$ is carbon emissions associated with fuel consumption.

2) Performance of traditional generations
Carbon utilization of thermal power plants in the power grid can be expressed as:

$$\eta_{CE} = \frac{S_{t}}{Emi_{C}}$$  \hspace{1cm} (15)

where, $\eta_{CE}$ is the carbon utilization; $S_{t}$ is the power generation from thermal power plants; $Emi_{C}$ is corresponding carbon emissions from thermal power plants [14].

3) Utilization of low-carbon power sources
The utilization of low-carbon power sources in energy-saving power grid consist of the transmission rate of carbon emissions from power grid, the proportion of low-carbon installed capacity, the low-carbon productivity and the contribution index of the low-carbon power sources.

- The transmission rate of carbon emissions from power grid

\[ \zeta_c = \left( \frac{\sum P_e \times \sigma_s C_e}{q_s \times \sigma_s C_C} + 1 \right) \times 100\% \] (16)

\[ \zeta_w = \frac{\sum P_w \times \sigma_s C_{CW}}{q_s \times \sigma_s C_C} \times 100\% \] (17)

where, \( \zeta_c \) and \( \zeta_w \) are the inner and external carbon emission rates, respectively; \( P_e \) is the electricity exchange; \( q_s \) is the total electric energy production; \( \sigma_s C_e \) is carbon intensity of electricity exchange; \( \sigma_s C_C \) is the total carbon emission intensity of power grid; \( P_w \) is the electricity delivered outside; \( \sigma_s C_{CW} \) is the carbon intensity of electricity delivered outside.

- The grid-integration rate of low-carbon power sources

The grid-integration rate of low-carbon power sources contains absolute rate and the relative rate of low-carbon power sources. Take the absolute grid-integration rate as an example, which can be defined as:

\[ \eta_{net} = \frac{S_{LCL-net}}{S_{12}} \] (18)

where, \( \eta_{net} \) is the absolute grid-integration rate of low-carbon power source \( i \); \( S_{LCL-net} \) is the grid-integration capacity of low-carbon power source \( i \).

4) Low carbonization characteristics of the power grid

The low carbonization characteristics of the power grid includes power supply rate of unit carbon, transmission line utilization index, low carbon distribution technology indicators and low carbon cost index of power supply reliability.

- Power supply rate of unit carbon

Take the absolute power supply rate of unit carbon in the power grid as an example, which can be defined as:

\[ \eta_{C} = \frac{E_m}{E_{net} \times \sigma S_{int} + Out_{SF_e}} \] (19)

where, \( \eta_{C} \) is the absolute power supply rate of unit carbon in the power grid; \( E_m \) is total power supply; \( E_{net} \) is the grid-integration power; \( \sigma S_{int} \) is carbon emission intensity of electricity consumption; \( Out_{SF_e} \) is the equivalent \( SF_e \) emissions.

- The transmission line utilization index

\[ \eta_{line} = \frac{P_{line,av}}{P_{line, max}} \times \frac{load_{max}}{P_{net, av}} \] (20)

where, \( \eta_{line} \) is transmission line utilization index; \( P_{line,av} \) and \( P_{line, max} \) are average and maximum power of the target line, respectively; \( load_{max} \) and \( P_{net, av} \) are the maximum load and average power of the entire network, respectively.

5) Energy efficiency and low-carbon indicator

Take the carbon energy efficiency during electricity production as an example.
\[ \eta_{aPEC} = \frac{\eta_{PE}}{C_{PEC}} \]  

\[ \eta_{rPEC} = \frac{\eta_{PE}}{C_{PEC} \times \mu_{EE}} \]

where, \( \eta_{aPEC} \) and \( \eta_{rPEC} \) are the absolute and relative carbon energy efficiency during electricity production, respectively; \( \eta_{PE} \) is the electricity consumption efficiency; \( C_{PEC} \) is the carbon intensity of electricity consumption; \( \mu_{EE} \) is the proportion of electricity among all types of terminal energy consumption.

3. Comprehensive evaluation model and evaluation methods

3.1. Evaluation process

The specific steps of comprehensive evaluation methods for the effects of energy-saving power grid is shown in figure 3.

![Figure 3](image-url)  

**Figure 3.** Steps of comprehensive evaluation methods.

3.2. Index data pre-processing

3.2.1. Uniformization of indices. For negative indicators:

\[ x^* = \frac{1}{x} \quad (x > 0) \]  

where, \( M \) is the allowable or maximum upper bound of index \( x \).

For moderate indicators:
\[
x^* = \begin{cases} 
1.0 - \frac{q_1 - x}{\max \{q_1 - m, M - q_2\}}, & x < q_1 \\
1.0, & x \in [q_1, q_2] \\
1.0 - \frac{x - q_2}{\max \{q_1 - m, M - q_2\}}, & x > q_2 
\end{cases}
\]  

(24)

where, \([q_1, q_2]\) is the best stable interval of index \(x_j\); \(M\) and \(m\) are respectively the allowable upper and lower limits of index \(m\).

### 3.2.2. Nondimensionalization of indices

\[
x^*_{ij} = \frac{x_{ij} - m_j}{M_j - m_j}
\]

(25)

where, \(M_j\) and \(m_j\) are respectively the maximum and minimum value of index sample \(x_j\).

### 3.3. Index data correlation analysis

The specific steps of index data correlation analysis are as follows:

1) **Step 1**
   
   Suppose there are \(n\) secondary indicators under a certain level of indicators, and there are \(m\) data samples for each secondary indicator, which all have been standardized. The sample matrix is:
   
   \(X = (X_{ij})_{m \times n}\)
   
   \(i = 1, 2, \ldots, m; \ j = 1, 2, \ldots, n\)
   
   (26)
   
   where, \(X_{ij}\) indicates the \(i\)-th data sample of the \(j\)-th index.

2) **Step 2**
   
   Calculate the covariance matrix \(R\) of data sample. Among them, \(R_{ij}(i,j=1,2,\ldots,n)\) is the correlation coefficients between index variables \(X_i\) and \(X_j\); \(R\) is a real symmetric matrix (\(R_{ij} = R_{ji}\)). \(R_{ij}\) can be calculated as:
   
   \[
   R_{ij} = \frac{\sum_{k=1}^{m}(X_{kj} - \bar{X}_j)(X_{ij} - \bar{X}_i)}{\sqrt{\sum_{k=1}^{m}(X_{kj} - \bar{X}_j)^2} \sum_{k=1}^{m}(X_{ij} - \bar{X}_i)^2}
   \]
   
   (27)

3) **Step 3**
   
   Calculate the eigenvalues \(\lambda_i\) of the covariance matrix \(R\) and arrange them in order from large to small. Then calculate corresponding feature vector \(l_i (i=1,2,\ldots,n)\). The contribution rate of principal component \(Z_i\) is:
   
   \[
   W_i = \frac{\lambda_i}{\sum_{k=1}^{n} \lambda_k}
   \]
   
   (28)

And the cumulative contribution rate is:
\[ W_\Sigma = \frac{\sum_{i=1}^{n} \lambda_i}{\sum_{i=1}^{n} \lambda_i} \]  
(29)

4) Step 4
Find out the sample data value corresponding to the main component. The sample values of each component of \( i \)-th data sample is:

\[ Z_i = \begin{bmatrix} l_{11} & l_{12} & \cdots & l_{1n} \\ l_{21} & l_{22} & \cdots & l_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ l_{n1} & l_{n2} & \cdots & l_{nn} \end{bmatrix} \begin{bmatrix} X_{1i} \\ X_{2i} \\ \vdots \\ X_{ni} \end{bmatrix} \]  
(30)

3.4. Index weighting method
The G-1 method and the entropy method are used to obtain the weight coefficient \( p_j \) based on the relative importance of the indices and the weight coefficient \( q_j \) based on the degree of data dispersion. Then the comprehensive weight can be obtained, which is:

\[ \omega_j = k_1 p_j + k_2 q_j \]  
(31)

where, \( k_1 \) and \( k_2 \) are undetermined constants, which satisfy \( k_1>0, k_2>0 \) and \( k_1+k_2=1 \).

3.5. The display of comprehensive evaluation results

3.5.1. Three-color indicator method for individual evaluation. The flow chart of the three-color indicator method for individual evaluation is shown in figure 4.

3.5.2. Radar map method for comprehensive evaluation. The radar map for comprehensive evaluation
of multiple indicators is shown in figure 5.

![Figure 5](image)

**Figure 5.** The radar map for comprehensive evaluation of multiple indicators.

4. **Case study**
Take data from the 2014-2018 energy-saving and low-carbon system planning schedule of Yunnan Province, China as an example. Relevant data is shown in table 1.

| Year | Overall network loss rate/(%) | Capacity of wind power /[10 MW] | Capacity-load ratio | Capacity of small thermal power shutdown/[MW] | Maximum load/[10 MW] |
|------|-------------------------------|-------------------------------|--------------------|-----------------------------------------------|---------------------|
| 2014 | 5.96                          | 590                           | 2.34               | 440                                           | 9300                |
| 2015 | 5.83                          | 660                           | 2.29               | 270                                           | 10000               |
| 2016 | 5.88                          | 722                           | 2.25               | 0                                             | 10700               |
| 2017 | 5.87                          | 791                           | 2.23               | 0                                             | 11300               |
| 2018 | 5.86                          | 866                           | 2.21               | 2185                                          | 11900               |

According to the evaluation results, a radar map showing the low-carbon development of power grid in each year can be obtained, as depicted in figure 6.

From figure 6, during the period of 2014-2018, a steady increase in proportion of wind power capacity and the configured capacity-load ratio can be seen, indicating improvement in utilization of low-carbon energy and equipment utilization efficiency. The overall network loss rate in each year is relatively stable.

Take $k_1$=0.9 and $k_2$=0.1, and the comprehensive weights of the four indices are obtained, as shown in table 2.
Figure 6. Energy-saving and low-carbon effects of the power grid.

Table 2. Weights of indices.

| Indices                                      | Subjective weighting | Objective weighting | Comprehensive weighting |
|----------------------------------------------|----------------------|---------------------|-------------------------|
| Overall network loss rate                   | 0.339                | 0.004               | 0.305                   |
| Proportion of wind power capacity           | 0.242                | 0.155               | 0.233                   |
| Index of small thermal power pants shutdown| 0.220                | 0.813               | 0.279                   |
| Capacity-load ratio                         | 0.200                | 0.028               | 0.183                   |

The comprehensive evaluation results of the energy-saving and low-carbon effects of Yunnan Province power grid in year 2014 - 2018 are shown in table 3 and figure 7.

According to figure 7, the energy-saving and low-carbon effect increases year by year, especially from year 2017 to 2018, which shows the largest increase. Compared with the radar map in figure 6, we can figure out that the reason behind the remarkable increase lies in the shutdown of a large number of small thermal power plants in 2018.

Table 3. Comprehensive evaluation results in year 2014 - 2018.

| Year | Comprehensive evaluation results | Extended to 0-1 range |
|------|---------------------------------|-----------------------|
| 2014 | 0.189                           | 0.874                 |
| 2015 | 0.196                           | 0.906                 |
| 2016 | 0.198                           | 0.916                 |
| 2017 | 0.201                           | 0.929                 |
| 2018 | 0.216                           | 1.000                 |
5. Conclusions
In this paper, an index system for the energy-saving and low-carbon effects of the energy-saving power grid is established and an evaluation model and method are put forward. The low-carbon and energy-saving effect of the power grid planning scheme in Yunnan Province in 2014-2018 is taken as an example, and the case study results demonstrated that, combining the energy-saving effect index system with the low-carbon benefit index system, the established comprehensive evaluation index system reflects key elements of the energy-saving power grid. Meanwhile, the proposed display method can present evaluation results in a more intuitionistic way.

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