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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 girds. 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 reset 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.

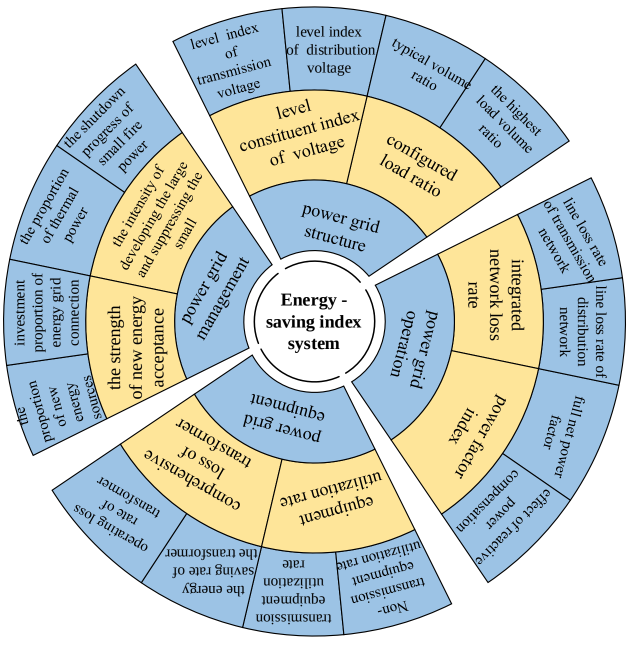

Figure 1. Evaluation index system structure for energy-saving effects.

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:

$$\eta_1 = \sum_{i=1}^{I} V_{Ti} \times \frac{L_{Ti}}{L_{T\Sigma}} \tag{1}$$

where, η_1 is the index of voltage level composition of the transmission grid; I is the number of voltage levels; V_{Ti} is the i-th voltage level of the transmission network; L_{Ti} is the total length of transmission lines of the i-th voltage level; $L_{T\Sigma}$ is the total length of transmission lines for all voltage levels.

- Capacity-load ratio

$$\eta_3 = \frac{K_1 \times K_2}{K_3 \times K_4} \tag{2}$$

$$\eta_4 = \frac{Q_1}{Q_2} \tag{3}$$

where, η_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; η_4 is the maximum capacity-load ratio; Q_1 and Q_2 are the total transformer capacity and maximum system load, respectively [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, σ_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, σ_2 is the overall power factor in power gird; 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, σ_{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; σ_{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

$$\sigma_{12} = \frac{M_1}{M_2} \tag{8}$$

$$\sigma_{13} = \frac{S_{13}}{S_{12}} \tag{9}$$

where, σ_{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； σ_{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

$$\mu_1 = \frac{A_3}{A_2} \tag{10}$$

$$\mu_2 = \frac{A_5}{A_4} \tag{11}$$

where, μ_1 is the operation loss rate of transformers; A_3 is the total power loss of transformers; A_2 is the total transformer power supply; μ_2 is the energy-saving rate of energy-saving transformers; A_5 is the power loss reduced by energy-saving transformers; A_4 is rated capacity of transformers [13].

- Equipment utilization rate

$$\mu_3 = \frac{\sum_T P_j \times t_j}{P_m \times T} \tag{12}$$

$$\mu_4 = \frac{\sum_T t_j}{T} \tag{13}$$

where, μ_3 is the utilization rate of transmission equipment; T is the total assessment time periods; t_i is equipment's j-th investment time; P_i is equipment's j-th input investment power; P_m is equipment's rated power; μ_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 gird, 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.

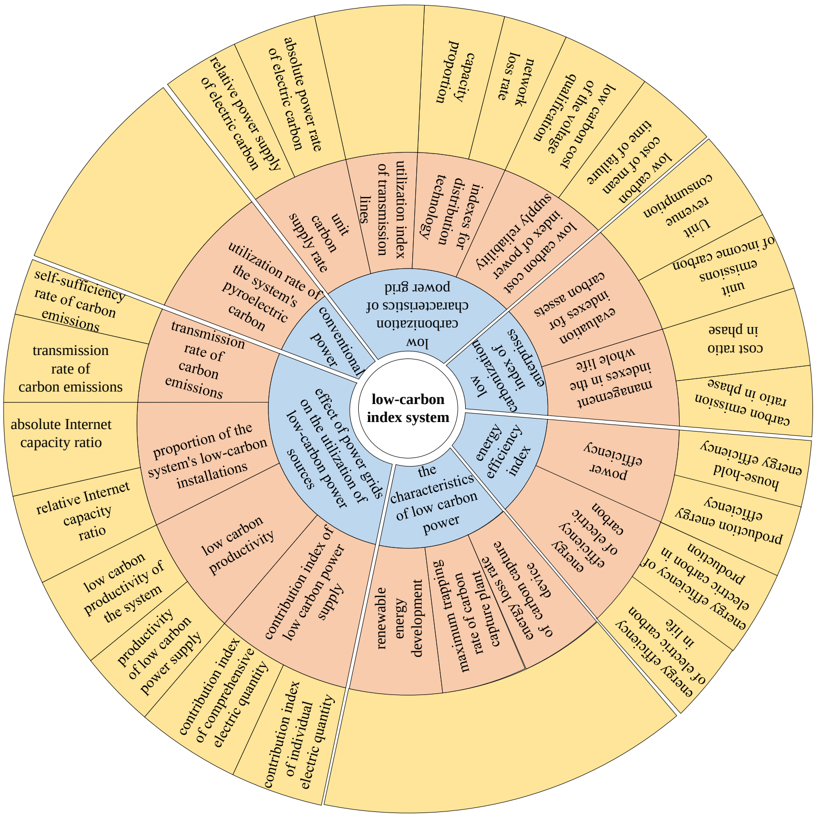

Figure 2. Evaluation index system structure for low-carbon effects.

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 γ_{CCS} can be expressed as:

$$\gamma_{CCS} = (1 - \frac{Emi_C}{fuel_C}) \times 100\% \tag{14}$$

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 gird can be expressed as:

$$\eta_{CE} = \frac{S_t}{Emi_{Ct}} \tag{15}$$

where, η_{CE} is the carbon utilization; S_t is the power generation from thermal power plants; Emi_{Ct} 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

$$\zeta_C = \left(\frac{\sum P_e \times \sigma s_{Ce}}{q_S \times \sigma s_C} + 1\right)^{-1} \times 100\% \tag{16}$$

$$\zeta_W = \frac{\sum P_w \times \sigma s_{CW}}{q_S \times \sigma s_C} \times 100\% \tag{17}$$

where, ζ_C and ζ_W are the inner and external carbon emission rates, respectively; P_e is the electricity exchange; q_S is the total electric energy production; σs_{Ce} is carbon intensity of electricity exchange; σs_C is the total carbon emission intensity of power grid; P_w is the electricity delivered outside; σs_{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:

$$\eta'_{net} = \frac{S_{LCl-net}}{S_{12}} \tag{18}$$

where, η'_{net} is the absolute grid-integration rate of low-carbon power source *l;* $S_{LCl-net}$ is the grid-integration capacity of low-carbon power source *l*.

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:

$$\eta''_C = \frac{E_{in}}{E_{net} \times \sigma S_{inC} + Out_{SF_6}} \tag{19}$$

where, η''_C is the absolute power supply rate of unit carbon in the power grid; E_{in} is total power supply; E_{net} is the grid-integration power; σS_{inC} is carbon emission intensity of electricity consumption; Out_{SF_6} is the equivalent SF_6 emissions.

- The transmission line utilization index

$$\eta_{line} = \frac{P_{line\_av}}{P_{line\_\max}} \times \frac{load_{\max}}{P_{net\_av}} \tag{20}$$

where, η_{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.

$$\eta_{aPEC} = \frac{\eta_{PE}}{C_{PEC}} \tag{21}$$

$$\eta_{rPEC} = \frac{\eta_{PE}}{C_{PEC}} \times \mu_{EE} \tag{22}$$

where, η_{aPEC} and η_{rPEC} are the absolute and relative carbon energy efficiency during electricity production, respectively; η_{PE} is the electricity consumption efficiency; C_{PEC} is the carbon intensity of electricity consumption; μ_{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.

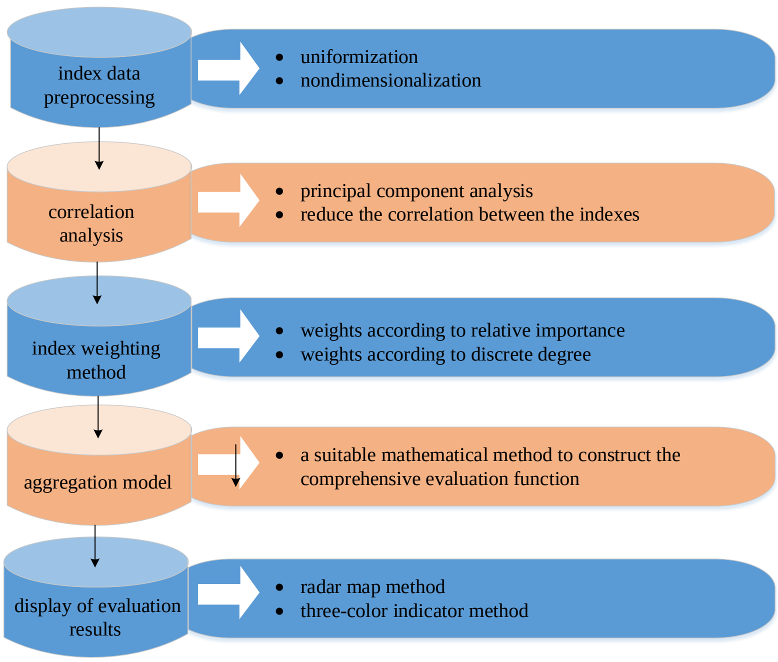

Figure 3. Steps of comprehensive evaluation methods.

3.2. Index data pre-processing

3.2.1. Uniformization of indices. For negative indicators:

$$x^* = \frac{1}{x}(x > 0) \tag{23}$$

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

For moderate indicators:

$$x^* = \begin{cases} 1.0 - \dfrac{q_1 - x}{\max\{q_1 - m, M - q_2\}} & ,x < q_1 \\ 1.0 & ,x \in [q_1, q_2] \\ 1.0 - \dfrac{x - q_2}{\max\{q_1 - m, M - q_2\}} & ,x > q_2 \end{cases} \tag{24}$$

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

$$x_{ij}^* = \frac{x_{ij} - m_j}{M_j - m_j} \tag{25}$$

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:

$$X = \left(X_{ij}\right)_{m\times n} \qquad i = 1, 2, \cdots, m; j = 1, 2, \cdots, n \tag{26}$$

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:

$$R_{ij} = \frac{\sum_{k=1}^{m}\left(X_{ki} - \overline{X}_i\right)\left(X_{kj} - \overline{X}_j\right)}{\sqrt{\sum_{k=1}^{m}\left(X_{ki} - \overline{X}_i\right)^2 \sum_{k=1}^{m}\left(X_{kj} - \overline{X}_j\right)^2}} \tag{27}$$

3) Step 3

Calculate the eigenvalues λ_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,…,n). The contribution rate of principal component Z_i is:

$$W_i = \frac{\lambda_i}{\sum_{k=1}^{n}\lambda_k} \tag{28}$$

And the cumulative contribution rate is:

$$W_{i\Sigma} = \frac{\sum_{k=1}^{i} \lambda_i}{\sum_{k=1}^{n} \lambda_k} \tag{29}$$

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:

$$Z_i = \begin{bmatrix} l_{11} & l_{12} & \cdots & l_{1n} \\ l_{21} & l_{22} & \cdots & l_{2n} \\ \vdots & \vdots & & \vdots \\ l_{n1} & l_{n2} & \cdots & l_{nn} \end{bmatrix} \begin{bmatrix} X_{i1} \\ X_{i2} \\ \\ X_{in} \end{bmatrix} \tag{30}$$

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:

$$\omega_j = k_1 p_j + k_2 q_j \tag{31}$$

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.

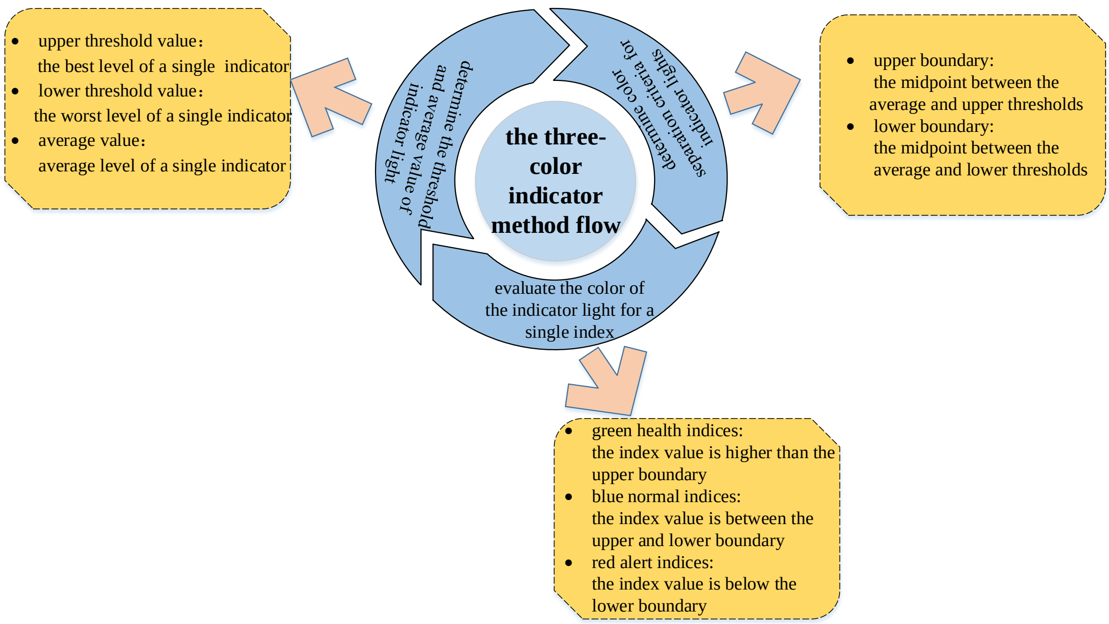

Figure 4. The three-color indicator method for individual evaluation.

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

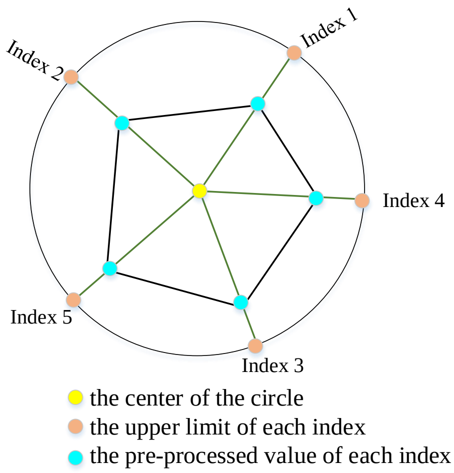

Figure 5. The radar map for comprehensive evaluation of multiple indicators.

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.

Table 1. Partial data from the 2014-2018 system planning of Yunan Province.

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.

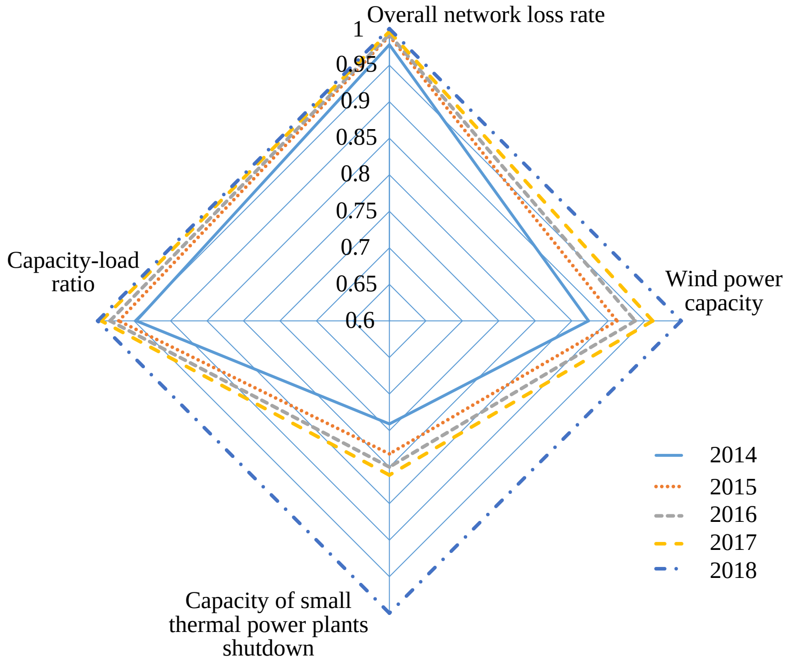

Figure 6. Energy-saving and low-carbon effects of the power grid.

Table 2. Weights of indices.

Indices	Weights of 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 Yunan 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

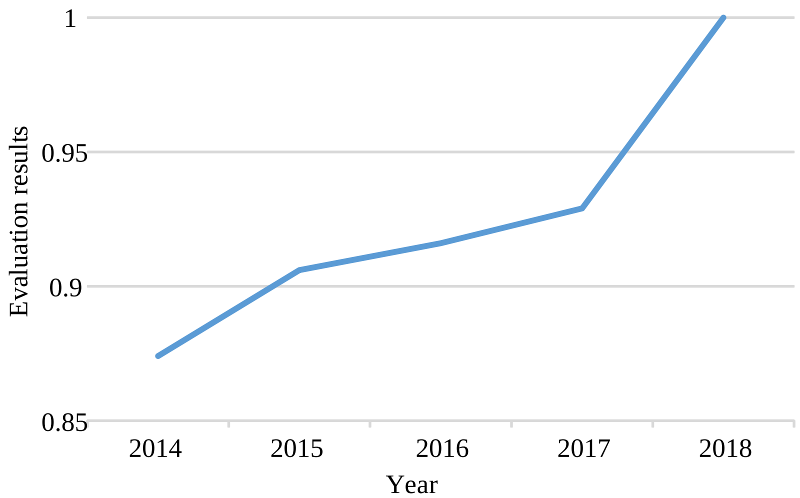

Figure 7. Change of energy-saving and low-carbon effects in different years.

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.

Acknowledgment

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