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Comprehensive Benefit Evaluation of the Wind-PV-ES and Transmission Hybrid Power System Consideration of System Functionality and Proportionality

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Abstract: In the background of decreasing fossil fuels and increasing environmental pollution, the wind-photovoltaic energy storage and transmission hybrid power system (or called the wind-PV-ES and transmission hybrid system) has become a strategic choice to achieve energy sustainability. However, the comprehensive benefit evaluation of such a combined power system is in a relatively blank state in China, which will hinder the reasonable and orderly development of this station. Four parts, the technical performance, economic benefit, ecological impact and social benefit, are considered in this paper, and a multi-angle evaluation index system of the wind-PV-ES and transmission system is designed. The projection pursuit model is used to evaluated system functionality conventionally; relative entropy theory is used to evaluate the system functionality simultaneously; and a comprehensive benefit evaluation model of the technique for order preference by similar to ideal solution (TOPSIS) considering both system functionality and proportionality is constructed. Finally, the national demonstration station of the wind-PV-ES-transmission system is taken as an example to testify to the practicability and validity of the evaluation index system and model.

Keywords: wind-photovoltaic energy storage and transmission hybrid power system; system functionality and proportionality; comprehensive evaluation; projection pursuit model; relative entropy

1. Introduction

Due to the increasingly reduction of fossil fuels and serious environmental pollution, wind power, solar power and other new energy power generation methods have become strategic choices for achieving sustainable energy development in China. However, the safe and stable operation of the power grid has been adversely affected by the randomness and intermittence of new energy sources. The emergence of the wind-photovoltaic energy storage and transmission hybrid power system has effectively alleviated this problem. It is a new type of integrated generation system with wind power generation, photovoltaic power generation, an energy storage system and an intelligent transmission network. Under the coordinated control of the intelligent substation, the system can realize the objectives of power planning tracking, smooth output, peak load shifting and frequency modulation with seven operating modes, which are wind power generation alone, photovoltaic power generation alone, energy storage battery discharge, wind-PV generation, wind-ES generation, PV-ES generation and wind-PV-ES hybrid generation [1]. It has been proven that the wind-PV-ES-transmission hybrid generation modes can weaken the detrimental effect of randomness, intermittence and anti-peak-shaving, promote large-scale new energy integration and achieve energy sustainable development [2].

It is a completely new mode with wind-photovoltaic energy storage and the transmission hybrid power system, large-scale chemical storage and combined operations, and there is little experience to be drawn, so the comprehensive and reasonable evaluation of system performance will provide decision advice for subsequent projects and the application of the new energy power generation system. Currently, there have been more studies of the evaluation of a single new energy power generation both at home and abroad, and the traditional evaluation of new energy power generation mainly focused on the single perspective of economic evaluation [3], risk assessment [4] or social benefit evaluation [5]. With the deepening of the research, many scholars argued that it is necessary to build the evaluation index system of new energy power generation from multiple perspectives of economic benefits, social benefits, environmental benefits, and so on [6,7]. Meanwhile, evaluation methods have been enriched gradually, no longer limited to the analytic hierarchy process [8] and fuzzy comprehensive evaluation [9]. Li et al. [10] constructed the grey-ideal solution model, combining the grey relational analysis and TOPSIS method, to make a comprehensive risk evaluation of a PV project. Mabel et al. [11] evaluated the adequacy of wind power generation systems using the Monte Carlo technique. Deng et al. [12] evaluated the comprehensive benefits of photovoltaic power generation based on the entropy weight method to modify the index weight and the matter-element extension model. There also are a few studies involving the evaluation of a variety of power generation models: Dursun et al. [13] evaluated the battery energy efficiency in a stand-alone hybrid power system, which consists of three power generation systems (PV), a wind turbine and a proton exchange membrane fuel cell (PEMFC). Dong et al. [14] proposed a systematical evaluation model based on the matter-element extension model, from the four dimensions of project management, project benefits, project impact and project sustainability for the wind-PV hybrid project.

Through the review and summary of the related literature, it can be found that there are still some deficiencies in the research on the evaluation of the new energy power system.

(1) At present, the comprehensive benefit evaluation of the wind-PV-ES and transmission power station is still in the state of being relatively blank, and it is still an urgent problem to select the comprehensive evaluation indicators and determine the evaluation method of the hybrid power system.

(2) In China, it is common to use the fuzzy comprehensive evaluation method, the analytic hierarchy process and the matter-element extension method in the evaluation of a new energy power generation project. Admittedly, these methods have certain disadvantages. For example, there are some deficiencies of the fuzzy comprehensive evaluation method in the selection of evaluation factors and the determination of weights. The analytic hierarchy process (AHP) considers more the consistency of the judgement matrix, but less the rationality of the judgment matrix [15]. Additionally, when the index data exceed the section, the correlation function cannot be calculated in the matter-element extension method [16]. Therefore, it is necessary to find a more scientific and effective evaluation method to deal with various and complex indicators of the wind-photovoltaic energy storage and transmission power system.

(3) Generally, when evaluating a new energy power system, only the system functionality is taken into account, but the system proportionality is ignored. More concretely, we tend to care about the value of the index and neglect the coordination between indicators. This will lead to abnormal development by expanding a certain index as a shortcut and hinder the coordinated development of the system. In fact, the system operation itself contains two characteristics of functionality and proportionality [15]; thus, they should not be separated in the actual evaluation work. Aiming at this problem, the literature [17] presented the evaluation model based on the functionality and proportionality of the system, through linear weighting with the functional and proportional evaluation model. Nevertheless, it is easy for information be lost by direct weighting, which cannot reflect the actual development of the evaluation objects.

Based on this, this paper builds a set of the multi-angle evaluation index system of the wind-PV-ES and transmission power system in view of its characteristics, containing an overall investigation from the four aspects of technology, economy and ecology and society. Furthermore, a comprehensive evaluation method considering both system functionality and proportionality has been proposed in this paper. Owing to the diversity and complexity of the evaluation indicators of the hybrid power system, the method firstly applies the projection pursuit method to evaluate the system functionality, which can process and analyze the high dimensional data. Then, the system proportionality is evaluated by the relative entropy model. Finally, TOPSIS is used to get the evaluation results considering system functionality and proportionality, disposing the information loss caused by direct weights. This method can make full use of the existing information and enhance the objectivity of the evaluation result. Moreover, this method is utilized for specific and accurate evaluation analysis of national wind-photovoltaic energy storage and the transmission demonstration power station.

2. The Comprehensive Benefit Index System of the Wind-PV-ES-Transmission Hybrid Power System

The wind-PV-ES and transmission hybrid generation system has exploited and utilized a variety of new energy technology and equipment. Accordingly, it plays an important role in the stable operation of the combined system and friendly grid connection of new energy power to evaluate the technical performance level reasonably. While ensuring the level of technical performance of the system, the economic benefit is also considered as an essential part of the assessment, as well as an important guarantee to the orderly development of the hybrid system. The construction of the wind-PV-ES and transmission generation system not only influences the operation of the power grid, but also has a certain impact on the ecological environment and social environment in the surroundings. As a result, the four aspects of the technical performance, economic benefit, ecological impact and social benefit are all included in the comprehensive evaluation of the combined generation system.

Considering the subjective and objective factors that affect the sustainable development of the combined system, as well as the actual characteristics of wind-PV-ES and the transmission system in China, the factors influencing the comprehensive benefit of the system are identified by the Delphi method [18], and a complete evaluation has been designed with an overall target, four sub-targets and sixteen indicators. The comprehensive benefit evaluation index system of wind-photovoltaic energy storage and transmission hybrid power generation is displayed in Figure 1.

(1) The wind-photovoltaic energy storage and transmission hybrid power generation system applies multifariously advanced technologies, such as energy storage technology, wind and light power prediction technique and intelligent scheduling technology, so the key point of technical evaluation is whether the various technologies meet the relevant standard. It includes the four indexes of the probability of system instability, electrical power quality, energy storage efficiency and capacity of peak load shifting to evaluate the technical performance of the wind-photovoltaic energy storage and transmission power plant.

The probability of system instability reflects the system risk, and it is the quantification of the reliability level of the wind-photovoltaic energy storage and transmission system.

Electrical power quality is an important index to measure the impact of the grid, which is determined by the voltage, frequency and waveform quality of the power system after paralleling in the grid.

Energy storage efficiency is an important parameter of the energy storage battery, directly affecting the total energy storage cost. Inefficiency will increase the cost of effective energy output, as only a part of the energy storage capacity can be used.

The capacity of peak load shifting refers to the ability of improving peak load shifting and reducing the startup and shutdown times, as well as the output of peaking units in the power grid after the wind-photovoltaic energy storage and transmission system is connected to the grid.

(2) In view of the characteristics of the wind-photovoltaic energy storage and transmission hybrid system, the economic benefit evaluation investigates the profitability, solvency, sustainability and the

life-cycle economic benefit after the project has been put into operation, containing the internal rate of return, payback period, asset-liability ratio and return on equity.

The internal rate of return (IRR) is a discount rate that the sum of the present value of annual net cash flow is zero in the whole calculation period, and when the internal rate of return is greater than the minimum attractive rate of return, the project is worth the investment.

The payback period refers to the time from the start of construction to the recovery of the total investment of the whole project, the shorter the payback period, the stronger the profitability of the project.

The asset-liability ratio is the proportion of total liabilities in all assets. The higher the asset-liability ratio, the greater the risk of debt repayment.

Return on equity is the ratio of the net profit to the average total assets in a certain period. The higher return on equity indicates the better benefit of the project and the stronger ability to operate continuously.

(3) The ecological benefit refers to the impact on the local environment during the construction and operation of the wind-PV-ES and transmission project. Actually, the influence of the wind and photovoltaic power station on the ecological environment is extremely significant and positive. Ecological benefit mainly includes energy-savings benefit, mitigation benefit, influence of energy structure adjustment and impacts on soil and vegetation.

The energy-savings benefit means the degree of resource conservation in the operation of the wind-photovoltaic energy storage and transmission power station. Compared to the traditional thermal power stations, the new energy station does not consume fossil resources, like coal, saving considerable coal. Therefore, it is appropriate to use the coal saving amount to measure the energy-savings benefit of this power station.

The mitigation benefit refers to the saving on the emission cost of pollutants from the wind-photovoltaic energy storage and transmission station. As we all know, traditional thermal power produces a large amount of SO_2, NO_2, fly ash and other pollutants. Additionally, the disposal and remediation costs of pollutants are too ruinous to estimate. On the contrary, the wind-photovoltaic complementary station hardly produces pollutants [19]. Thus, the emission cost is used to measure the mitigation benefit of the wind-photovoltaic energy storage and transmission power station in this paper.

Nowadays, energy consumption in China is dominated by coal, and the utilization rate is low. Additionally, the coal-dominated energy structure has faced a double dilemma of economic growth and environmental protection. Nevertheless, the wind-photovoltaic energy storage and transmission system improves the proportion of new energy in the traditional power grid through using clean energy and enormously promotes the adjustment of the energy structure.

There will be a certain impact on soil and vegetation in the process of the construction and operation of the wind-photovoltaic station. Excavation and roads construction will cause damage to vegetation during the wind turbine construction process, and solar power generation will keep the land under solar panels from accepting sunshine, which has effects on the growth of animals and plants.

(4) The construction of the wind-photovoltaic energy storage and transmission power station brings a huge investment to the local area, provides new jobs, improves the local employment rate and promotes local economic development; correspondingly, the tax revenue is increased, and the quality of life is improved, as well as people's spiritual life. The social benefit is comprised of employment benefit, regional economic benefit, effect on life quality of residents and public support. The employment benefit is measured by direct employment benefit, namely the product of direct employment and regional annual average wage.

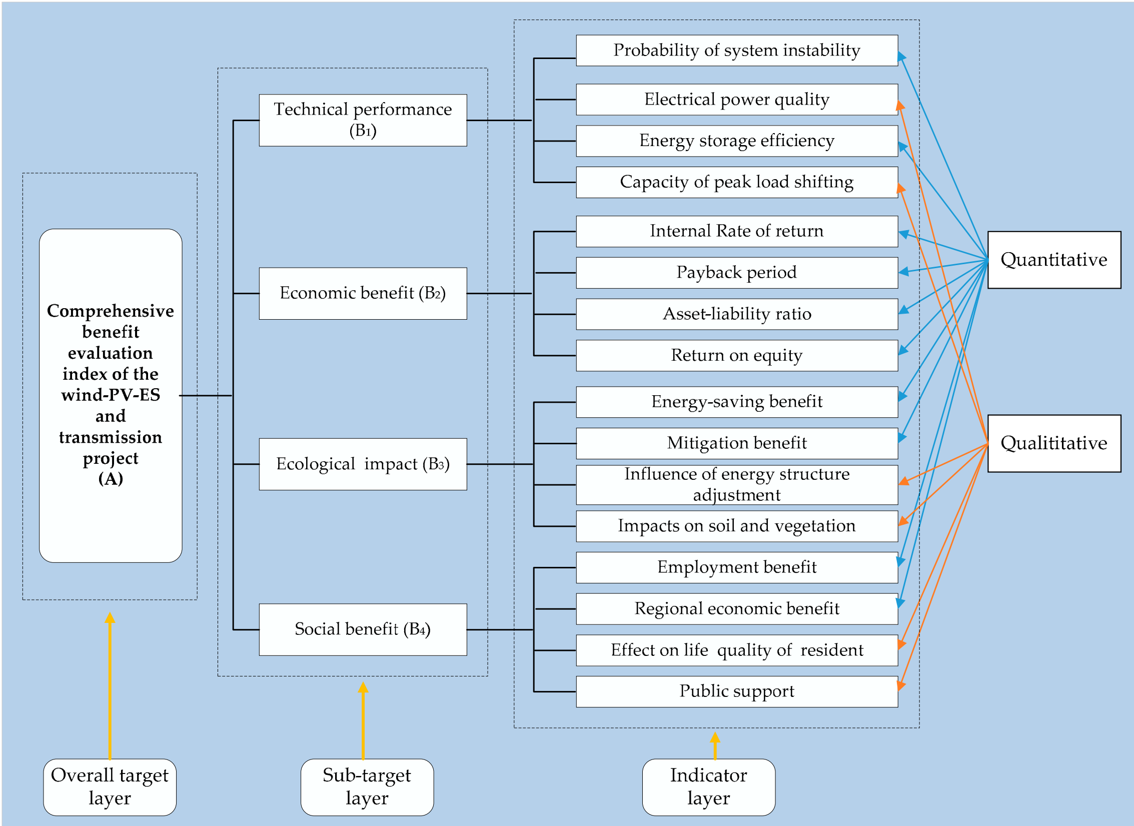

Figure 1. Comprehensive evaluation index system of the wind-PV-ES and transmission project.

3. Comprehensive Evaluation Model of the TOPSIS Consideration of Functionality and Proportionality

3.1. Evaluation Model

3.1.1. Functionality Evaluation Based on the Projection Pursuit Model

The projection pursuit evaluation model, an exploratory data analysis method, is directly driven by the data. This method can eliminate the interference of the variables irrelevant to the data structure and characteristics. Furthermore, it can successfully project the high-dimensional data of a non-normal distribution onto one-dimensional space, then analyze the data structure in the low dimensional space, so as to determine the contribution of each evaluation index to the evaluation target. The projection value is obtained through the best projection direction and the linear projection of the evaluation index [20]. Comprehensive evaluation of the functionality of the hybrid power system is a complex nonlinear problem influenced by a multidimensional factor, and the projection pursuit evaluation model is built by the following steps [21]:

Step 1: Determination of the index value. Generally, the qualitative index is fuzzy and difficult to quantity, so the expert scoring method is used to evaluate the qualitative indices, except the effect on the life quality of residents and public support; these two indicators will be obtained through the questionnaire method [22]. The properties of indices are shown in Table 1. The qualitative indices are divided into excellent, good, common and bad according to the performance, and the score division is shown in Table 2. The average expert scores are taken as the value of the index. In addition, the quantitative indicators are mainly obtained from the specific operation center of the wind-PV-ES and transmission hybrid power system.

Step 2: Index data preprocessing. Evaluating: The index n of objects m and the original matrix are set up as follows:

$$X = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix} \quad (1)$$

Table 1. The number and property of the evaluation indices.

Index Name	Index Number	Index Property
Probability of system instability	x_{11}	Quantitative
Electrical power quality	x_{12}	Qualitative
Energy storage efficiency	x_{13}	Quantitative
Capacity of peak load shifting	x_{14}	Qualitative
Internal rate of return	x_{21}	Quantitative
Payback period	x_{22}	Quantitative
Asset-liability ratio	x_{23}	Quantitative
Return on equity	x_{24}	Quantitative
Energy-savings benefit	x_{31}	Quantitative
Mitigation benefit	x_{32}	Quantitative
Influence of energy structure adjustment	x_{33}	Qualitative
Impacts on soil and vegetation	x_{34}	Qualitative
Employment benefit	x_{41}	Quantitative
Regional economic benefit	x_{42}	Quantitative
Effect on life quality of resident	x_{43}	Qualitative
Public support	x_{44}	Qualitative

Table 2. The rating criteria of the qualitative index level.

Index Level	Excellent	Good	Average	Bad
Rating interval	80–100	60–80	40–60	0–40

In order to provide index consistency and eliminate the dimensionality, the extreme value standardization method for the maximal index is shown in Equation (2), and for minimal index is shown in Equation (3).

$$\text{For the maximal index } x_{ij}^* = \frac{x_{ij} - m_j}{M_j - m_j} \quad (2)$$

$$\text{For the minimal index } x_{ij}^* = \frac{M_j - x_{ij}}{M_j - m_j} \quad (3)$$

where M_j and m_j are the maximum and minimum of the index, respectively.

Step 3: Construction of the projection index function $f(w)$. The projection pursuit model is to synthesize the m dimensional data x_{ij} into a one-dimensional projection value z_i in the projection direction of $w_j = (w_1, w_2, \cdots, w_n)$.

$$z_i = \sum_{j=1}^{n} w_j x_{ij}^* \ (i = 1, 2, \cdots, m) \quad (4)$$

where w_j is the unit vector, and it is required for the projection value z_i to extract variation information in x_{ij}^* as large as possible, so the spread characteristics must be that the local projection point should be as dense as possible, preferably condensed into several point groups, and the projection point groups should be dispersed as much as possible on the whole. Therefore, the function of projection indexes can be expressed as:

$$f(w) = S_z D_z \quad (5)$$

In the formulae, S_z and D_z are the standard deviation and the local density of the projection value z_i, respectively.

$$S_z = \sqrt{\frac{\sum_{i=1}^{m} [z_i - E(z)]^2}{m-1}} \quad (6)$$

$$D_z = \sum_{i=1}^{m} \sum_{j=1}^{n} (R - r_{ij}) U(R - r_{ij}) \quad (7)$$

where $E(z)$ is the average value of the z_i and R is the window radius of the local density. r_{ij} is the distance between the objects, and $r_{ij} = |z(i) - z(j)|$. $U(h)$ is the unit step function; if $R < r_{ij}$, then $U(R - r_{ij}) = 0$; otherwise, $U(R - r_{ij}) = 1$.

Step 4: Optimization of the projection index function. When the index value is given, the projection index function $f(w)$ only changes with the projection direction w. Different projection directions reflect the different characteristics of the data structure, and the best projection direction w^* is the direction that exposes the characteristic structure of high dimensional data to the greatest amount possible, so it can be estimated by solving the problem of maximizing the function of projection indexes.

$$\text{Maximizing objective function } Max : f(w) = S_z D_z \quad (8)$$

$$\text{Constraint condition } \sum_{j}^{n} (w_j)^2 = 1 \quad (9)$$

This is a complex nonlinear optimization problem with w_j as the optimization variables. In this paper, the objective function is optimized by the real coding-based accelerating genetic algorithm (RAGA) [23].

RAGA is a general adaptive global optimization method formed by simulating the genetics and evolution of biology in the natural environment [24]. The algorithm for optimizing the projection direction based on RAGA is shown as follows:

(1) In n-dimensional space, select m groups of random numbers $b_i (i = 1, 2, ..., n)$ in the interval [0, 1] as the optimization code according to the population size, and each group of coding corresponds to a projection direction.

(2) The unit vector is set to $w_i = -1 + 2b_i$, $(i = 1, 2, ..., n)$; then, calculate the projection index function $f(w)$.

(3) In accordance with the principle of increasing the projection index, select m codes, the projection indexes of which are large, through the operations of selection, crossover and mutation; after that, go back to Step (2) for the next optimal cycle, then repeat it until the end.

(4) The steps above constitute the standard genetic algorithm (SGA), but SGA cannot guarantee global convergence. At this time, the new initial variable interval is replaced by the variable interval of the excellent individuals emerging from the first and second or the third and fourth evolutionary iterations; then, return back to Step (1) to rerun SGA. The interval of excellent individuals will be gradually reduced, and the distance to the optimum point gets closer. The algorithm runs until the optimization function value of the optimal individual is less than a certain set value or the algorithm reaches a predetermined time, and the best individual in the current population is the result of RAGA.

Step (5): Putting the best projection direction w^* obtained by Step (4) into Equation (4) to gain the projection value z_i, the larger the projection value, the higher the comprehensive evaluation value of the system functionality.

3.1.2. Proportionality Evaluation Based on Relative Entropy

The concept of entropy was first derived from thermodynamics, which is the degree of deviation from the equilibrium state of an isolated physical system. Later, Shannon introduced it into information theory to express the uncertainty, stability and information of the system [25]. In general, the entropy is always related to the relevant factors and the state of the system. The size of the entropy can reflect the degree of deviation from the equilibrium state; the smaller the entropy, the greater the degree of deviation. Accordingly, the entropy is used to describe the proportionality of the system in this paper.

On the basis of the definition and principle of entropy, there may be q types of states in the system, and the occurrence probability of each state is $P_t(t = 1, 2, ..., q)$, so the entropy can be calculated by Equation (10).

$$S_i = -\sum_{t=1}^{q} (P_t \log P_t),\ i = 1, 2, ..., m \tag{10}$$

As is shown in Equation (10), these are the following properties of the entropy.

(1) Additivity: the system entropy is equal to the sum of the entropy of each state.

(2) Non-negativity: according to the nature of probability $P_t \in [0, 1](t = 1, 2, ..., q)$, the system entropy is non-negative.

(3) Extremum property: when the system state probability is an equal probability, namely $P_t = \frac{1}{q}(t = 1, 2, ..., q)$, the system entropy reaches maximum.

$$S_i(P_1, P_2, ..., P_t) \leq S(\frac{1}{q}, \frac{1}{q}, ..., \frac{1}{q}) = \log(q),\ i = 1, 2, ..., m \tag{11}$$

(4) Independence: the system entropy is independent of the order of the probability P_t.

Consequently, the system proportionality evaluation can be define as follows.

The entropy of the evaluation index n of objects m is:

$$S_i = -\sum_{j=1}^{n} \left(\frac{x_{ij}}{\sum\limits_{j=1}^{n} x_{ij}} \log(\frac{x_{ij}}{\sum\limits_{j=1}^{n} x_{ij}}) \right),\ (i = 1, 2, ..., m) \tag{12}$$

As can be seen from the extremum property of entropy, the much closer the index values, the higher the entropy and the more coordinated the system. When the index values are equal, the maximal entropy $S_{\max} = \log(q)$, and the relative entropy is defined as:

$$S_i^* = \frac{S_i}{S_{\max}},\ i = 1, 2, ..., m \tag{13}$$

As we can see from Equation (13), $S_i^* \in [0, 1]$, the larger the value of S_i^*, the closer the index values and the more proportional the system, so it is reasonable to use the relative entropy S_i^* to measure the system proportionality quantitatively.

3.1.3. Evaluation Model of TOPSIS Consideration of Both Functionality and Proportionality

The technique for order preference by similarity to ideal solution (TOPSIS) was first proposed by Hwang and Yoon in 1981 [26], and the idea was derived from the decision problem of multivariate statistical analysis [27]. The specific steps of TOPSIS to comprehensively evaluate the wind-PV-ES and transmission power system are as follows.

Step 1: Setting up the standardized decision matrix. The system functionality z_i and system proportionality S_i^* both are positive indicates, and S_i^* is between zero and one, so it only needs to normalize z_i through Equation (14).

$$z_i^* = \frac{z_i}{\sum\limits_{i}^{m} z_i},\ i = 1, 2, ..., m \tag{14}$$

Consequently, the standardized decision matrix P is described as:

$$P = \begin{bmatrix} z_1^* & z_2^* & \cdots & z_m^* \\ S_1^* & S_2^* & \cdots & S_m^* \end{bmatrix} \quad (15)$$

Step 2: Determination of ideal solution. The preferred object is better in both functionality and proportionality, that is the positive ideal point y^+ is the maximum of each evaluation value, and the negative ideal point y^- is the minimum. Besides, S_i^* and z_i^* both are between zero and one, so the positive and negative ideal points are shown in Equation (15).

$$\begin{aligned} y^+ &= (1, 1) \\ y^- &= (0, 0) \end{aligned} \quad (16)$$

Step 3: Calculating the distances between decision matrix and the positive and negative ideal point, separately.

$$\begin{aligned} d_i^+ &= \sqrt{\left(S_i^* - 1\right)^2 + \left(z_i^* - 1\right)^2} \\ d_i^- &= \sqrt{\left(S_i^* - 0\right)^2 + \left(z_i^* - 0\right)^2} \end{aligned} \quad (17)$$

where $i = 1, 2..., m$.

Step 4: Obtaining the relative closeness degree of each object. The optimal solution is the closest to the positive ideal point, while the farthest from the negative ideal point. Accordingly, the relative closeness D_i^* is expressed as Formula (17).

$$D_i^* = \frac{d_i^-}{d_i^+ + d_i^-},\ i = 1, 2, ..., m \quad (18)$$

Step 5: Ranking by the relative closeness D_i^*. The greater the D_i^*, the better the corresponding object.

3.2. Evaluation Step

Based on the above analysis, the comprehensive evaluation steps of the wind-PV-ES and transmission hybrid system taking into account system functionality and proportionality are as follows:

Step 1: Determination of the original index matrix and pre-processing the index.

Step 2. Constructing the projection index functions and using RAGA to optimize the projection function to obtain the best projection directions.

Step 3. Taking the best projection direction into Equation (5) to get the final projection value, which is the result of functionality evaluation.

Step 4. Calculating the entropy of each object according to Equation (12).

Step 5. Obtaining the relative entropy of each object according to Equation (13), namely the result of the system proportionality evaluation.

Step 6. Normalizing the evaluation results to obtain the evaluation decision matrix, which takes into account both system functionality and proportionality.

Step 7. Calculating the distance between the decision matrix and the positive and negative ideal points.

Step 8. Calculating the relative closeness degree of each object.

Step 9. Further sorting the results of the comprehensive evaluation according to the principle of the closeness degree.

The evaluation procedure is shown in Figure 2.

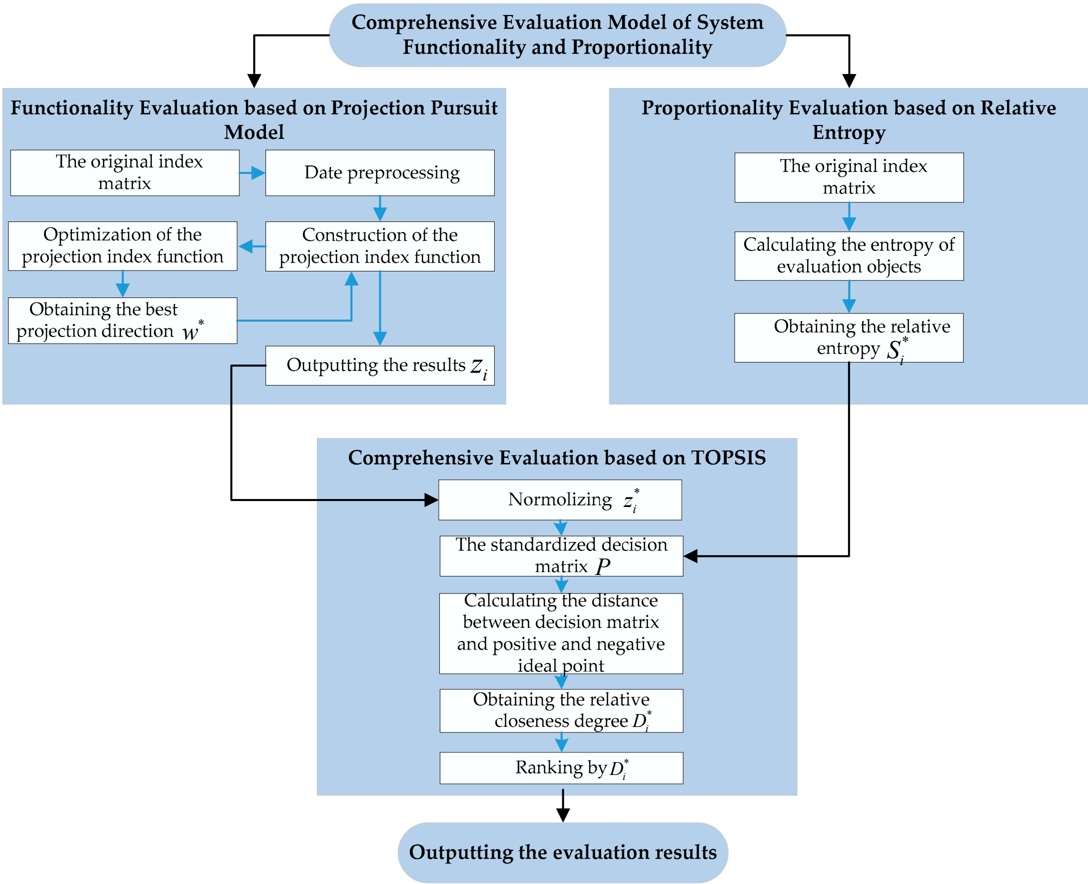

Figure 2. Comprehensive evaluation model of system functionality and proportionality.

4. Empirical Research

4.1. Project Introduction

The national demonstration project of the wind-PV-ES and transmission hybrid system is located in Zhangjiakou, which is rich in the wind and solar resources; the annual effective wind energy reserve is up to 1436 kWh/m^2; the annual effective wind speed time is 5200–7200 h; and the annual average illumination period is 2898 h. However, the local load demand is so small that most of the power must be transmitted to the load center by high voltage. The first phase of the national demonstration project has been put into operation in December 2011. The construction projects contain 98.5 thousand kilowatts of wind power, 40 thousand kilowatts of photovoltaic power, 20 thousand kilowatts of energy storage and a 220-kilovolt intelligent substation [28]. The first phase project has cost in total 3.3 billion yuan, in which one billion yuan was invested in the wind power plant, and the photovoltaic and energy storage system cost 2.3 billion yuan. The initial internal rate of return is 7%, and the payback period is 13 years.

In the demonstration station, the wind power system has adopted a diversity of wind turbines, with the large-scale application of the 2-MW doubly-fed induction generator and the 2.5-MW direct-drive wind turbine, the first utilization of the 3-MW direct-drive wind turbine and the 1-MW vertical axis wind turbine at the same time. The PV system has mainly used polysilicon components and is equipped with two kinds of large capacity inverters of 500 kW and 630 kW. Moreover, the energy storage station has installed the 14-MW lithium iron phosphate battery, the 2-MW all-vanadium redox flow battery and other chemical energy storage batteries. The wind turbines, photovoltaic arrays and energy storage are respectively connected to the 35-kV bus through the step-up transformers and then connected to the smart grid by the 220-kV intelligent substation.

Currently, the system has already realized six operating modes, which are wind power generation alone, photovoltaic power generation alone, wind-PV generation, wind-ES generation, PV-ES generation and wind-PV-ES hybrid generation. For example, when the wind power and PV system both have output, but the synthetic output cannot meet the grid-connected requirements, then the energy storage system needs to participate in the adjustment. In this case, the system operates in combination with wind, PV and energy storage. Through panoramic monitoring and intelligent optimization of the wind farm, the photovoltaic power plant, energy storage system and substation by the combined generation control system, based on the light forecasting module, scheduling module and wind energy predicting module, the system realizes the power planning tracking, smooth output, peak load shifting and frequency modulation by seamlessly switching between the six operating modes.

4.2. Example Analysis

In this paper, the comprehensive benefit of this demonstration project is investigated based on the TOPSIS method considering both system functionality and proportionality from 2011 to 2015. The qualitative indicators are quantitated by the panel composed of experts from the production and technology department, the operation and maintenance department, the combined generation monitoring center and a specialist in the field of electric power technology and economy, according to the scoring criteria in Section 3.1.1. The quantitative date of samples is obtained from the statistics of power station construction and operation. On that basis, the main procedures of the comprehensive benefit evaluation of the national demonstration project are as follows.

Step 1. According to the extreme value standardization method above, the maximum of the index is the transform to one, and the minimum is the transform to zero. Thus, the original matrix is preprocessed to get the standardized matrix X^*, where objects $n = 4$ and indicators $m = 16$.

$$X^* = \begin{bmatrix} 1.0000 & 0.0000 & 0.0000 & \ldots & 0.0000 \\ 0.5000 & 0.3333 & 0.2222 & \ldots & 0.2308 \\ 0.2546 & 0.8000 & 0.8889 & \ldots & 0.6923 \\ 0.0000 & 1.0000 & 1.0000 & \ldots & 1.0000 \end{bmatrix} \tag{19}$$

Step 2. Construct the projection index function $f(w)$, and use MATLAB to compile the program of projection pursuit optimized by the real coding-based accelerating genetic algorithm (RAGA-PP). Aiming at finding the optimal value of the projection index function more quickly, the parameters are set as follows: population size $N = 400$, cross-probability $pc = 0.8$, mutation probability $pm = 0.6$, maximum iteration number Gmax = 100 and the acceleration = 20 times. On this basis, the projection functions of the total target and four sub-target are optimized, respectively, and the optimal projection direction for total target A is shown in Formula (20).

$$\begin{aligned} w_A^* = \; & (0.1323, 0.1004, 0.0421, 0.0346, 0.1157, 0.0933, 0.0464, 0.0447, \\ & 0.0624, 0.0618, 0.0232, 0.0341, 0.0855, 0.0543, 0.0258, 0.0436) \end{aligned} \tag{20}$$

The optimal projection direction for four sub-targets is displayed in Formula (21).

$$\begin{aligned} w_{B_1}^* &= (0.3543, 0.2870, 0.2085, 0.1501) \\ w_{B_2}^* &= (0.2852, 0.2548, 0.2304, 0.2296) \\ w_{B_3}^* &= (0.3236, 0.3214, 0.1728, 0.1823) \\ w_{B_4}^* &= (0.3687, 0.3247, 0.1618, 0.1447) \end{aligned} \tag{21}$$

The size of the optimal projection direction of each component essentially reflects the impact of each index on the evaluation objective; the larger the value of the corresponding index, the greater the degree of influence. Accordingly, the system instability probability has the greatest influence on the comprehensive benefit of the wind-PV-ES-transmission power station, followed by the internal rate of return, power quality, payback period, energy-savings benefit and emission mitigation benefit. In addition, system instability probability, internal rate of return, energy-savings benefit and employment benefit are the most important factors in the functional evaluation of the technical performance, economic benefit, ecological impact and social benefit, separately. Therefore, we should pay more attention to these important factors throughout the construction and operation process in similar projects in the future. The impact values of all indicators are shown in Figure 3.

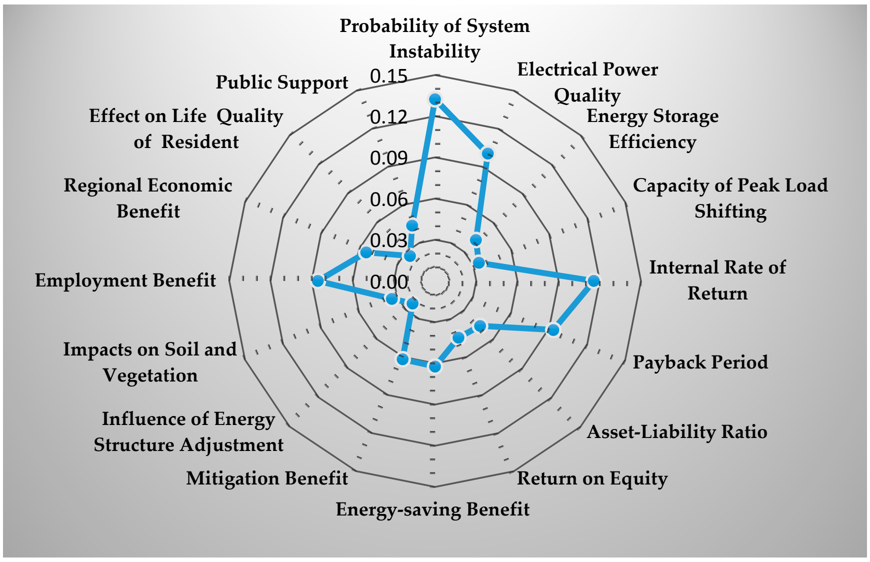

Figure 3. Radar chart of the indicators' impact values.

Step 3. The optimal projection values of each target layer are calculated according to Equation (4), and the results are shown in Table 3. Besides, the projection value scatter diagram of each target layer is shown in Figure 4.

Table 3. Optimal projection value of each target layer.

Year	Technical Performance	Economic Benefit	Ecological Impact	Social Benefit	System Functional Comprehensive Benefit	
	z_{B_1}	z_{B_2}	z_{B_3}	z_{B_4}	z_A	Rank
2012	0.4065	0.7765	0.6911	0.8894	0.9674	4
2013	0.7488	0.9022	0.8140	0.9493	1.3275	3
2014	0.8945	0.9664	0.8983	1.0317	1.8292	2
2015	1.1683	1.0254	0.9382	1.0582	2.5765	1

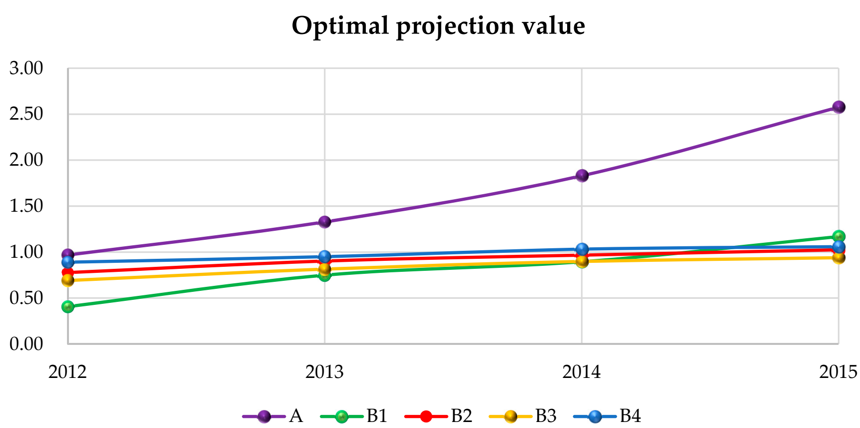

Figure 4. Optimal projection value of each target layer in 2012–2015.

The projection pursuit model not only can integratedly evaluate the functionality of the demonstration station, but also can individually compare each aspect of the evaluation index system, in order to find out the difference in each part and to provide references for decision makers. Table 3 shows the benefit levels of the hybrid power station in the technical, economic, ecological and social aspects during 2012–2015, and the larger the projection value, the better the benefit level. Additionally, the results have demonstrated that during the period from 2012 to 2015, the technical, economic, ecological and social benefits of the combined system have been increasing gradually; the technical performance level has enhanced the quickest, especially.

Step 4. The entropy values S of each year are determined by Equation (12).

$$S = (0.4334, 0.4651, 0.4936, 0.5001) \quad (22)$$

Step 5. According to Equation (13), the relative entropy values of each evaluation year are obtained, which are the evaluation results of the system proportionality, as well.

$$S_x = (0.7199, 0.7725, 0.8199, 0.8306) \quad (23)$$

Obviously, the relative entropy has been increased gradually, so the system coordination of the wind-PV-ES and transmission power station is getting better and better from 2012 to 2015.

After normalization of the functional evaluation values z_A, the evaluation decision matrix P is obtained, taking into account both system functionality and proportionality.

$$P = \begin{bmatrix} 0.1444 & 0.1981 & 0.2730 & 0.3845 \\ 0.7199 & 0.7725 & 0.8199 & 0.8306 \end{bmatrix} \quad (24)$$

Step 6. Calculate the distance between the decision matrix and the positive and negative ideal points, and the results are as follows.

$$\begin{aligned} d^+ &= (0.9003, 0.8335, 0.7490, 0.6384) \\ d^- &= (0.7342, 0.7975, 0.8641, 0.9153) \end{aligned} \quad (25)$$

Step 7. Calculate the relative closeness of each year further.

$$D^* = (0.4492, 0.4890, 0.5357, 0.5891) \quad (26)$$

The results of the calculation above are summarized in Table 4. The change of the functional and coordinated evaluation values of each year are shown in Figure 5, and the change of the closeness degree of each year is shown in Figure 6.

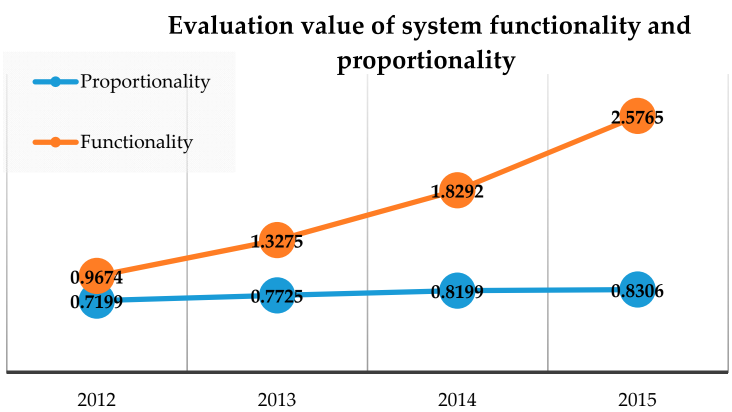

Figure 5. Trend chart of system functionality and proportionality in 2012–2015.

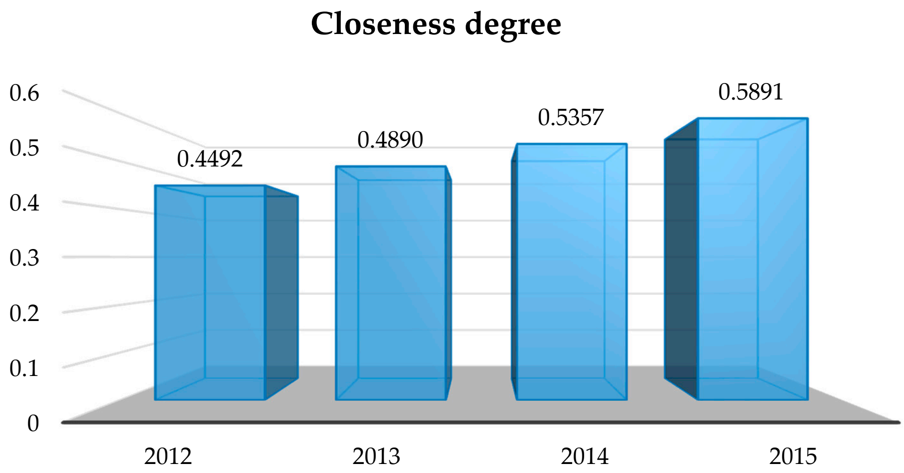

Figure 6. Trend chart of relative closeness degree in 2012–2015.

Table 4. Comprehensive evaluation results.

Year	Functionality	Proportionality	Relative Closeness Degree	Rank
2012	0.9674	0.7199	0.4605	4
2013	1.3275	0.7725	0.4881	3
2014	1.8292	0.8199	0.5322	2
2015	2.5765	0.8306	0.5785	1

Step 8. Evaluation results analysis:

Seen from the comprehensive benefit evaluation results above, the basis for the principle of the greater the relative closeness degree, the best corresponding scheme, the comprehensive benefit of the national demonstration project is 2015 > 2014 > 2013 > 2012. From the specific perspective of system functional and proportional evaluation results, the technology, economic, ecological and social benefits of the wind-PV-ES-transmission system have been all increased year by year since 2012, and the development of various indicators of the system has become more balanced, which indicates that the level of system coordination has become increasingly better.

The generation and dispatching mode of the wind-PV-ES and transmission system and the large-scale and multi-type energy storage are new technologies in the world, so there is less experience from which to learn. In accordance with the actual situation, it has faced high investment, lack of technical reserves, system instability, low energy conversion efficiency and many other difficulties in the early production of the combined power plant in 2012, the worst benefit and the poorest coordination in all evaluation years.

After five years of hard research and practice, the combined control and scheduling system and energy storage integration technology have been continuously developed. The energy storage station has covered five types of electrochemical batteries, including lithium iron phosphate battery, all-vanadium redox flow battery, etc., nearly 300 thousand batteries, which has realized uninterrupted participation in hybrid generation all day and switched between smooth fluctuation and peak load shifting operation mode, flexibly. Moreover, the energy efficiency is greater than 86%; the power output deviation is less than 1.5%; and the power quality is close to the conventional power. Meanwhile, economic benefit and ecological benefit have been rapidly increased during 2014–2015. The station output more than 1.13 billion kWh green power from in 2014 to 2015 [29], twice the power generation in 2012–2013, and the trend of power generation from 2012 to 2015 is displayed in Figure 7. Compared to the international general power generation, the hybrid power system has saved 390 thousand tons of standard coal and reduced 840 thousand tons of carbon dioxide emissions.

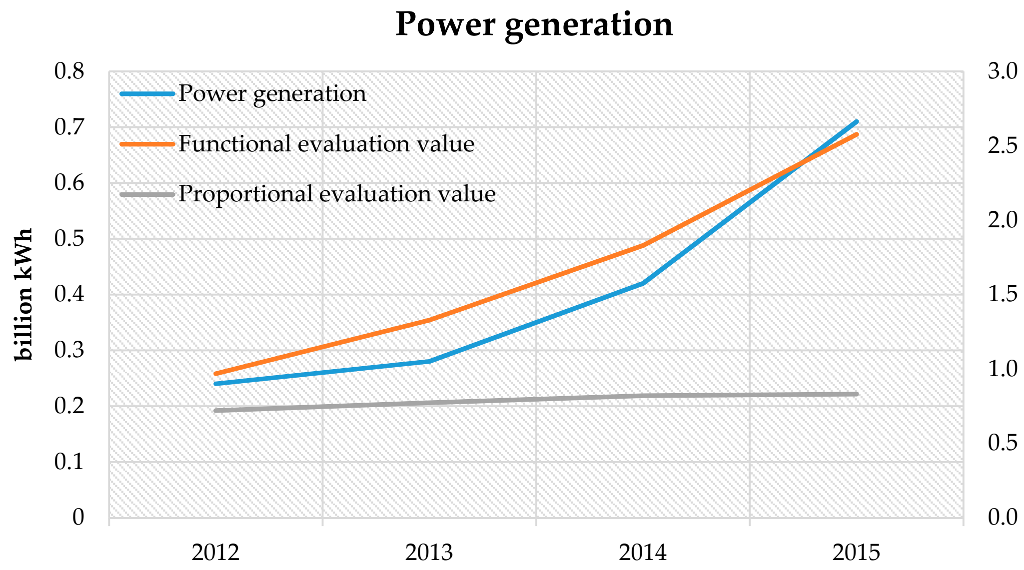

Figure 7. Trend chart of power generation in 2012–2015.

The project has confirmed the feasibility of battery energy storage technology and proven that wind-PV-ES-transmission hybrid generation can weaken the detrimental effect of randomness, intermittence and promote large-scale new energy integration, providing stable support to the new energy integration. Because of the remarkable effect of the demonstration of the first-stage project, the second-stage has been put into operation at the end of 2015, which includes 400 thousand kilowatts of wind power, 60 thousand kilowatts of photovoltaic power and 50 thousand kilowatts of energy storage, with a total investment of nearly six billion yuan [29]. The second-stage project will further explore the complementary advantages of wind and sunlight resources and detect the control mode combined the wind-PV-ES-transmission system with pumped storage, to build a world-class demonstration and research platform successfully.

5. Conclusions

The paper has made a comprehensive benefit evaluation of the wind-photovoltaic energy storage and transmission hybrid power generation system. Firstly, we construct a multi-angle evaluation index system to examine the comprehensive benefit of the hybrid system from the four aspects of technology, economy and ecology and society. Then, the evaluation model of TOPSIS considering both system functionality and proportionality has been put forward in the paper. Since the projection pursuit evaluation model cannot reflect the proportionality of the system, this paper has proposed the concept of relative entropy to describe the coordination of the system quantitatively. In order to avoid information loss caused by direct line weighting the results of functionality and proportionality evaluation, the TOPSIS method has been adopted to assess the comprehensive benefit of the wind-PV-ES and transmission system. Finally, the paper put the index system and comprehensive evaluation model into the context of empirical research, combined with the engineering data of national wind-photovoltaic energy storage and the transmission demonstration project. The results have demonstrated that the comprehensive benefits of the power system have been increased gradually in 2012-2015, and the development has been obtaining more and more coordination, which is consistent with the actual situation, and indicates a certain significance for reference and promotion.

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