
Research on the Evolution Process of New Distribution Network Forms Considering Low Carbon and Sustainable Development

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Received 07 December 2023; Accepted 16 January 2024

Abstract

To obtain the planning and development status of new distribution networks under the low-carbon and sustainable development goals, research the evolution process of new distribution network forms under the “carbon peak” and “carbon neutrality” goals (dual carbon goals). Firstly, combining the characteristics of high proportion renewable energy, construct a new distribution network morphology evolution system under the “dual carbon target”. Explore the energy pattern and structural form of the current and medium/long-term new distribution network, and obtain the corresponding evolution process. Then, considering the transmission characteristics of the new distribution network under the “dual carbon target”, an evaluation index system is established in three aspects: power supply, distribution, and transmission. And construct an evaluation model for the development form of distribution networks based on SWOT analysis, to evaluate the new development form of distribution networks. Finally, numerical examples were

Distributed Generation & Alternative Energy Journal, Vol. 39_3, 403–424.

doi: 10.13052/dgaej2156-3306.3931

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verified and analyzed using MATLAB simulation software. The method proposed in this article not only intuitively describes the evolution process of the new distribution network morphology, but also obtains the evolution of the new distribution network at different time stages under the “dual carbon target”, as well as the evolution results of the distribution network morphology in terms of carbon emissions and cost investment. The final research results of this article can provide theoretical basis for distribution network planning under the “dual carbon goal”.

Keywords: “Dual carbon goals”, new distribution network, morphological evolution process, evaluation model, renewable energy, structure form.

1 Introduction

With climate change and increasingly severe environmental pollution, cleanliness, low-carbon, and intelligence have gradually become the main strategic directions for the development of power systems. It has become the unified development goal of power enterprises to realize the new energy supply pattern of the power center and ensure the whole power system to realize the energy evolution integrating energy development, transmission, configuration and service [1–3]. At present, China’s industrialization and urbanization are rapidly developing, economic indicators are rapidly increasing, and energy demand is enormous. In addition, coal energy is still the main energy source in the power system field, leading to a phenomenon of high carbon emissions and intensity in China [4–6]. Meanwhile, from a global perspective, the global carbon dioxide emissions in 2022 were approximately 36.07 billion tons, an increase of 1.5% (540 million tons) compared to 2021, an increase of 7.9% (2.64 billion tons) compared to 2020, and an increase of 2.1% (730 million tons) compared to 2019. In terms of decarbonization effectiveness, if the carbon emission intensity of each country is used as a measure, most countries around the world still need to accelerate the decarbonization process. Although in 2021, with the proposal of the Energy Development Cooperation Organization to achieve the “dual carbon goals” of “carbon peaking” and “carbon neutrality” in carbon reduction, the power system sector has gradually launched a new type of distribution network planning with carbon reduction as the goal [7–9]. However, there is still a long way for countries around the world to go in promoting the widespread application of renewable energy in the power system, improving the consumption rate

of renewable energy, improving the economic efficiency of system operation, and reducing carbon emissions.

Under the “dual carbon goals”, clean energy such as hydropower, wind power, and photovoltaic have been widely promoted and applied in the power system. Under the continuous construction and development of various clean energy systems, a high proportion of new energy has become the main feature of the power system. Due to the direct correlation between this feature and the overall morphological structure, planning, and operation mode of the power system [10], all three have undergone changes. The influencing factors of the evolution of the power system mainly include three aspects: public factors, market factors, and technological factors. Yu Fei et al. [11] proposed a low-carbon optimization scheduling model that considers carbon capture and storage technology as well as wind power uncertainty, with the goal of clean and low-carbon development. Liu Juan et al. [12] established a multi flexibility resource planning model for power systems based on low-carbon economy with the goal of source load storage multi flexibility resources. The above studies have only analyzed the development of the power system with the goal of energy conservation and emission reduction. Reference [13] explores the planning of distribution networks under high penetration rates of new energy and proposes a distribution network planning indicator system. In order to improve the calculation accuracy of economic evaluation weight and comprehensive evaluation accuracy of incremental distribution network projects, literature [14] proposed an economic evaluation method of incremental distribution network based on axiology. Zhou Bin et al. [15] proposed a differentiated classification system for distribution networks that covers multiple dimensions, including provinces, cities (counties), urban power supply units, townships, and rural areas, by considering the differences in the development of distribution networks. And an indicator evaluation system has been constructed from the aspects of industrial dominance, commercial trade, and tourism development. Sha Yuheng et al. [16] proposed a precise investment method for distribution networks based on a three-level strategy of region, power grid, and power supply unit, with investment in distribution networks as the research object. Although the above literature has conducted research on distribution network planning, it has not fully considered the application of renewable energy and multimodal energy storage in new distribution networks.

This article is based on the consideration of energy conservation, emission reduction, and economic operation of the distribution network, based on the

“dual carbon goals”, relevant analysis and research have been conducted on the evolution process of the new distribution network morphology. Firstly, based on the inherent characteristics of high proportion renewable energy, a morphological evolution model of the power system driven by high proportion renewable energy was constructed. Analyzed its correlation with the evolution of the distribution network. Then, a structural morphology and evolution model of the distribution network under high proportion renewable energy conditions under the “dual carbon goals” were constructed. Analyzed the evolution process of the new distribution network under the “dual carbon goals”, and evaluated the evolution form. Finally, the effectiveness of the proposed method in this paper was verified through numerical analysis.

2 High Proportion of Renewable Energy Characteristics

The power system has begun to use a large amount of various renewable energy sources, but renewable energy sources such as wind power and photovoltaic have significant randomness and instability. Under the dual carbon goal, the effective utilization and driving of renewable energy are of great significance for achieving the dual carbon goal. Therefore, there is a direct correlation between renewable energy with randomness and the evolution of distribution networks [17–19]. Under the “dual carbon goals”, in the new distribution network, renewable energy with randomness will be used as the main power source, and the complementarity of renewable energy will be ensured through corresponding resource allocation and regulation. Among them, the randomness of renewable energy is directly related to the power supply, and clean power is the core of energy applications. In order to ensure the highly clean power supply mode of the new distribution network, the complementarity between renewable energy sources is applied to achieve flexible planning and operation of the distribution network. At the same time, considering the load generated by the new distribution network, there is significant uncertainty [20]. And the increasing proportion of power supply, energy storage, and load generation and connection of various renewable energy sources has an impact on the interaction and coupling between various energy sources in the distribution network. Therefore, under the “dual carbon goals”, it is necessary to propose effective methods based on the actual operation of the new distribution network to obtain the evolution process of the new distribution network form containing a high proportion of renewable energy.

3 High Evolution System of New Distribution Network Form with High Proportion of Renewable Energy

In order to obtain the evolution process of new distribution network morphology under the “dual carbon goals”, this article constructs a new distribution network morphology evolution system under the “dual carbon goals”. This system includes four parts: the evolution of the energy pattern of the distribution network in the medium and long term under the “dual carbon goals”, the structural form and evolution process of the distribution network, the load characteristics and interactive coupling mechanism of the distribution network, and the evaluation of the development form of the multi temporal distribution network. The four parts of the above evolution system can be referred to as the “two evolution processes”, “one mechanism”, and “one evaluation” of the distribution network. The architecture of the new distribution network morphology evolution system is shown in Figure 1.

In the evolution system of the new distribution network form, the two evolution processes of the distribution network are interrelated. Among them,

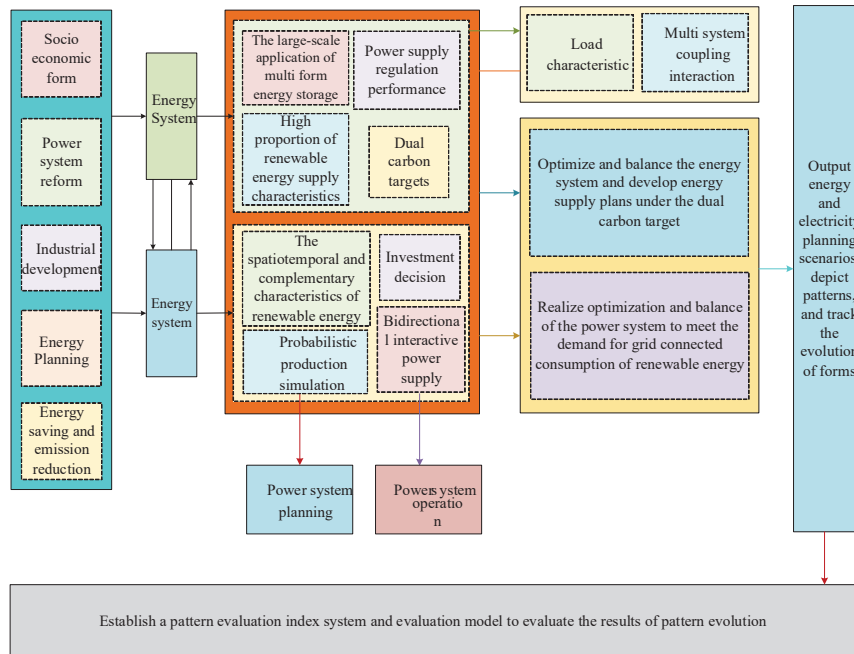


Figure 1 Evolution system of new distribution network morphology under the “dual carbon goals”.

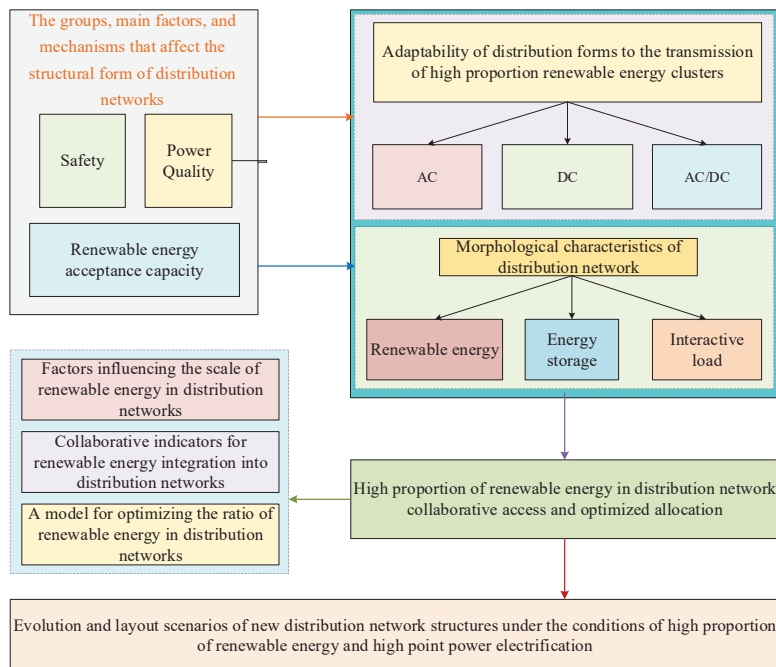


Figure 2 The correlation evolution model of “two evolutionary processes”.

the first evolution process is the evolution of the energy pattern of the distribution network in the medium and long term under the “dual carbon goals”. This process is to complete the medium to long-term matching of the energy pattern of the power grid and its evolution process under the “dual carbon goals”. The second evolution process is the structural form of the distribution network and its evolution process. This process is achieved through a combination of a high proportion of renewable energy and a high degree of power electronics [21]. The structure of the correlation evolution model between the two evolution processes is shown in Figure 2.

The first evolution process of the evolution model in Figure 2 includes various morphological features of the distribution network. To achieve the dual carbon goal, it is necessary to effectively address the multiple randomness generated by the large amount of access from renewable energy in the distribution network [22], and on this basis, complete the characterization of the evolution of the distribution network pattern. At the same time, the core of the second evolution process is the adaptability of renewable energy cluster transportation.

4 High Evaluation Model of Distribution Network Development Form Based on Swot Analysis

4.1 Evaluation Index System

Under the “dual carbon goals”, the evaluation of the development form of the distribution network is to achieve the prediction of the maximum consumption of renewable energy, and then coordinate the optimal operation of various energy sources based on the prediction results. Evaluation indicators are the foundation for building an evaluation model, so this article first constructs an evaluation indicator system with low-carbon operation of the distribution network as the core. The evaluation system has Completeness, pertinence, scientificity and accessibility. Not only can it comprehensively reflect the low-carbon goals of various links in the evolution process of the distribution network [23], but it can also preserve the operational characteristics of the distribution network itself and ensure the minimization of redundancy in indicators.

This article combines the transmission characteristics of the new distribution network and establishes an indicator system from three aspects: power supply, distribution, and transmission. This includes four primary indicators: low-carbon power supply, low loss network, peak shifting and valley filling, and terminal energy conservation and emission reduction. The four types of primary indicators also include eight secondary indicators: the proportion of renewable energy installed capacity to total installed capacity, the proportion of renewable energy generation to total power generation, capacity to load ratio, voltage qualification rate, renewable energy investment cost, the proportion of production and storage capacity, load control ratio, and intelligent information equipment collection rate. The forms of each indicator in the evaluation indicator system are shown in Figure 3.

4.2 Evaluation Model

Under the “dual carbon goals” evaluation index system proposed in this article, a distribution network development form evaluation model is constructed based on the SWOT analysis method to evaluate the new distribution network development form. The model evaluation process is shown in Figure 4, and the specific steps are as follows:

(1) Standard cloud for determining new distribution network form indicators. Based on the actual development of the new distribution network under the “dual carbon goals”, the development forms of the new distribution network

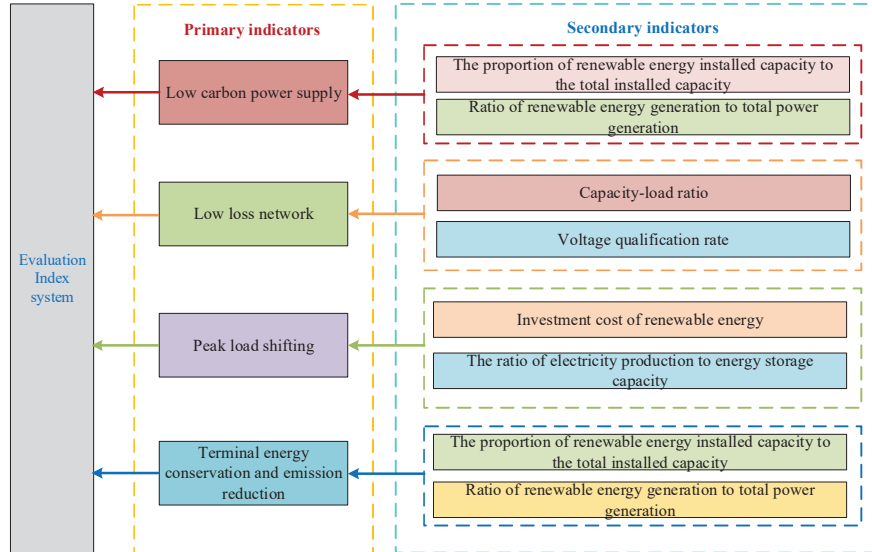


Figure 3 Evaluation index system for distribution network under “dual carbon goals”.

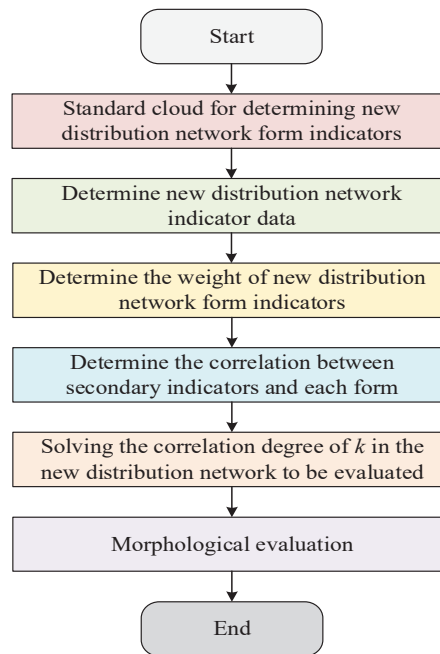


Figure 4 Model evaluation flowchart.

will be divided and processed to form different forms [24]. There are a total of 5 forms, including beginner, low-level, intermediate, advanced, and demonstration. Based on the relevant standard clouds of various forms of the distribution network, compare the evaluation index data of the distribution network in a horizontal manner. On the premise of ensuring that the set quantity values correspond to the indicator system [25], the range of quantity values in five forms is set as $[C_{\min}, C_{\max}]$ based on the properties and implementation of each indicator. Among them, C_{\min} and C_{\max} represent the maximum and minimum values of the quantity value, respectively.

In this article, $[C_{\min}, C_{\max}]$ is processed through transformation to form a cloud model, and the digital feature expectation, entropy, and superentropy of the model are represented by E_x , E_n and H_e , respectively [26]. The expression formulas for E_x , E_n and H_e are shown in Equations (1), (2), and (3) respectively

$$E_x = (c_{\min} + c_{\max})/2 \tag{1}$$

$$E_n = (c_{\min} - c_{\max})/6 \tag{2}$$

$$H_e = s \tag{3}$$

(2) Determine new distribution network indicator data. Determine the quantitative and qualitative indicators in the indicator system. And complete the determination of new distribution network indicator data based on relevant data queries and expert scoring [27].

(3) Determine the weight of new distribution network form indicators. The combination weighting method of fast Delphi method and entropy weight method is used in the article to determine the indicator weight, and the combination weight calculation is shown in formula (4)

$$w_j = k_1 p_j + k_2 q_j \tag{4}$$

In the formula, k_1 and k_2 are the preference coefficients of the two methods for determining the corresponding weights. w_j is the combined weight. p_j and q_j are the weights obtained by solving two weight determination methods for indicator j , $j = 1, 2, \dots, 14$. The weight calculation formula for the entropy weight method is

$$p_{ij} = b_{ij} / \sum_{i=1}^n b_{ij} \tag{5}$$

$$E_j = \left(\sum_{i=1}^n p_{ij} \ln p_{ij} \right) / \ln n \quad (6)$$

$$q_j = (1 - E_j) / \sum_{j=1}^M (1 - E_j) \quad (7)$$

In the formula, n is the number of corresponding schemes, and M is the number of corresponding indicators. b_{ij} is the pre standardized data, and p_{ij} is the post standardized data. The information entropy of indicator j is represented by E_j .

(4) Determine the correlation between secondary indicators and each form. In the case of normal distribution characteristics, in order to obtain the correlation degree of j in form k , it needs to be completed according to the digital characteristics. This feature data belongs to the indicator standard cloud. In the case of differential forms, the calculation formula for correlation degree is

$$\mu^k(x_{ji}) = \exp\left(-\frac{(x_{ji} - E_x)^2}{2y_i^2}\right) \quad (8)$$

Among them

$$y_i = R_N(E_N, H_e) \quad (9)$$

In the formula, x_{ji} is the value of indicator j in the i -th time. $k = 1, 2, 3, 4, 5$. $R_N(\cdot)$ is a normal random function.

(5) Solving the correlation degree of k in the new distribution network to be evaluated. The calculation formula for the correlation degree of k in the new distribution network is

$$Z_k = \sum_{j=1}^M w_j \mu^k(x_j) \quad (10)$$

(6) Morphological evaluation. Determine the level of membership and maximize it. Based on the principle of having the highest degree of membership, complete the judgment and analysis of the process of morphological evolution on the basis of determining the level.

5 Example Analysis

To verify the relevant application effects of the proposed method in the evolution process of new distribution network morphology under the “dual carbon

goals”. This article takes a typical urban distribution network in a certain region of China as the re-search object, and selects the 2020, 2021, 2022, and current operating data of the typical urban distribution network as the basic experimental samples. Combining the method proposed in the article, a numerical example analysis is conducted on the morphological evolution process of the research object in MATLAB simulation software. This article will take the capacity to load ratio as an example to demonstrate the form of the capacity to load ratio standard cloud (demonstration form [2.11,0.04,0.61], advanced form [2.01,0.04,0.61], intermediate form [1.81,0.04,0.61], low-level form [1.61,0.04,0.61], primary form [1.41,0.04,0.61].), and all other secondary indicators will be treated similarly.

Based on current data, obtain the planning indicators for the dual carbon scenario of the research object in the mid-term (2024–2028) and long-term (2029–2039) planning stages. And analyze the morphological evolution process of the research object under the “dual carbon goals”.

Solve the subjective and objective weights of each indicator layer, and compare the subjective and objective weight values to determine the importance of each indicator. The results of planning indicators and their weights within the three time periods are shown in Tables 1, 2 and 3. At the same time, calculate the combined weights of each secondary indicator in three

Table 1 Current planning indicators and weight calculation results

Primary Indicators	Secondary Indicators	Subjective Weight	Objective Weight
Low carbon power supply 0.5432	A: The proportion of renewable energy installed capacity to the total installed capacity 0.4910	0.3858	0.1861
	B: Distributed power consumption rate 0.5090	0.2743	0.0717
Low loss network 0.0912	C: Capacity-load ratio 0.5667	0.0620	0.0958
	D: voltage qualification rate 0.4333	0.0139	0.0712
Load shifting 0.0335	E: Investment cost of renewable energy 0.4117	0.0470	0.0867
	F: The proportion of distributed energy production and storage capacity 0.5883	0.0906	0.0975
Terminal energy conservation and emission reduction 0.3321	G: Load control ratio 0.7112	0.1057	0.1017
	H: Collection rate of intelligent information equipment 0.2888	0.0207	0.2893

Table 2 Medium term planning indicators and weight calculation results

Primary Indicators	Secondary Indicators	Subjective Weight	Objective Weight
Low carbon power supply 0.5504	A: The proportion of renewable energy installed capacity to the total installed capacity 0.4888	0.3851	0.185
	B: Distributed power consumption rate 0.5112	0.2754	0.072
Low loss network 0.0859	C: Capacity-load ratio 0.5556	0.0616	0.094
	D: voltage qualification rate 0.4444	0.0142	0.072
Load shifting 0.0381	E: Investment cost of renewable energy 0.3968	0.0462	0.084
	F: The proportion of distributed energy production and storage capacity 0.6032	0.093	0.1
Terminal energy conservation and emission reduction 0.3256	G: Load control ratio 0.6846	0.1018	0.098
	H: Collection rate of intelligent information equipment 0.3154	0.0227	0.295

Table 3 Long term planning indicators and weight calculation results

Primary Indicators	Secondary Indicators	Subjective Weight	Objective Weight
Low carbon power supply 0.5665	A: The proportion of renewable energy installed capacity to the total installed capacity 0.4776	0.3787	0.1807
	B: Distributed power consumption rate 0.5224	0.2809	0.0727
Low loss network 0.0734	C: Capacity-load ratio 0.5478	0.0610	0.0927
	D: voltage qualification rate 0.4522	0.0145	0.0726
Load shifting 0.0406	E: Investment cost of renewable energy 0.3767	0.0438	0.0797
	F: The proportion of distributed energy production and storage capacity 0.6223	0.0961	0.1033
Terminal energy conservation and emission reduction 0.3195	G: Load control ratio 0.6639	0.1008	0.0951
	H: Collection rate of intelligent information equipment 0.3361	0.0242	0.3032

time periods according to formula (4). The combined weight values of each secondary indicator within the three time periods are shown in Figure 5, the value and proportion of secondary indicators in each stage is shown in Figure 6.

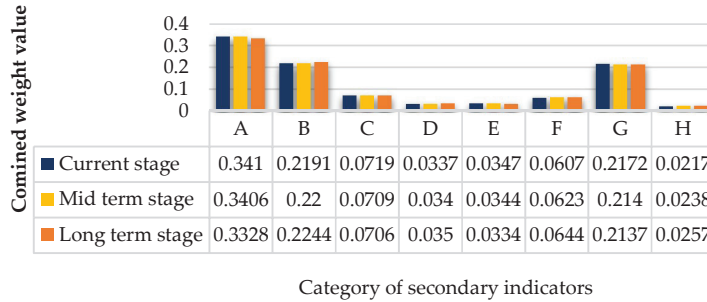


Figure 5 The combined weight values of each secondary indicator within three time periods.

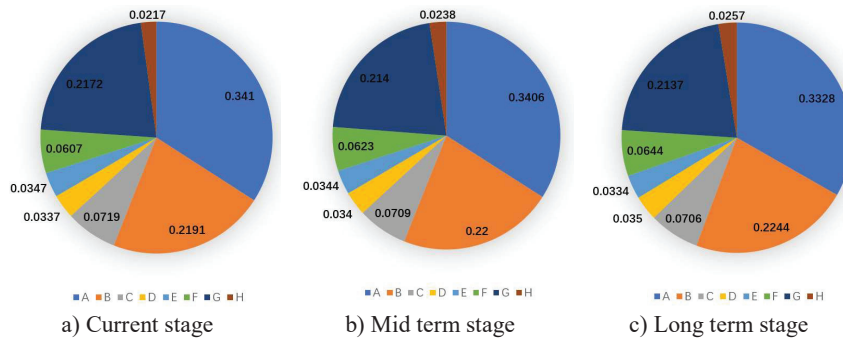


Figure 6 Value and proportion of secondary indicators in each stage.

According to the subjective, objective, and combined weight results in Tables 1–3, Figures 5 and 6, it can be seen that there are significant differences in the weight results of the indicators, and the degree of influence of each indicator in the model varies. The combination weight value of the two secondary indicators in the first level low-carbon power supply is the highest, which will directly affect the achievement of the “dual carbon goals”. At the same time, it indirectly reflects that in the evolution process of the new distribution network form, the dual carbon goal can be achieved by improving the consumption rate and installed capacity of renewable energy.

Obtain the correlation degree of various indicators under different forms, and based on this, obtain the comprehensive correlation degree of each development form of the new distribution network in three time stages, as shown in Figure 7.

According to the simulation results in Figure 7, it can be seen that comparing the results in Figure 7 with the standard cloud results in various states can reveal. In the current time stage, the new distribution network is in its

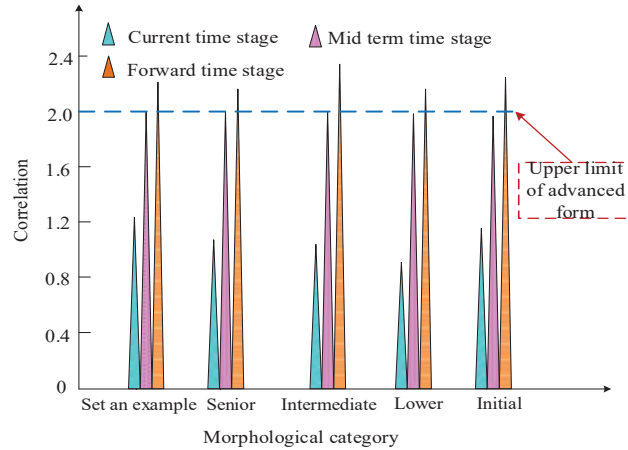


Figure 7 Comprehensive correlation degree results of new distribution network development forms.

primary form. During the mid-term period, it is at the upper limit of advanced form and close to the demonstration form. In the long-term period, achieve demonstration form. This result intuitively indicates that under the “dual carbon goals”, the method proposed in this paper can clearly and intuitively describe the evolution process of the new distribution network morphology. Different stages of time present different morphological development results, possessing the function of morphological evolution.

According to the simulation results in Figure 8, it can be seen that as the time period extends, the various indicators of the dual carbon planning for the new distribution network have significantly improved. The planning indicators for the medium and long term are significantly better than those for the current time stage. It indicates that under the “dual carbon goals”, the form of the new distribution network will undergo different evolution within different time stages, and the evolution results meet the development needs of the “dual carbon goals”.

To intuitively demonstrate the application of this method in the evolution process of new distribution network morphology. Using the achievement level of the “dual carbon goals” as the measurement standard, obtain the evolution results of carbon emissions of the research object at different time stages, as shown in Figure 9.

According to the simulation results in Figure 9, it can be seen that during the three time periods, the total carbon emissions showed a downward trend,

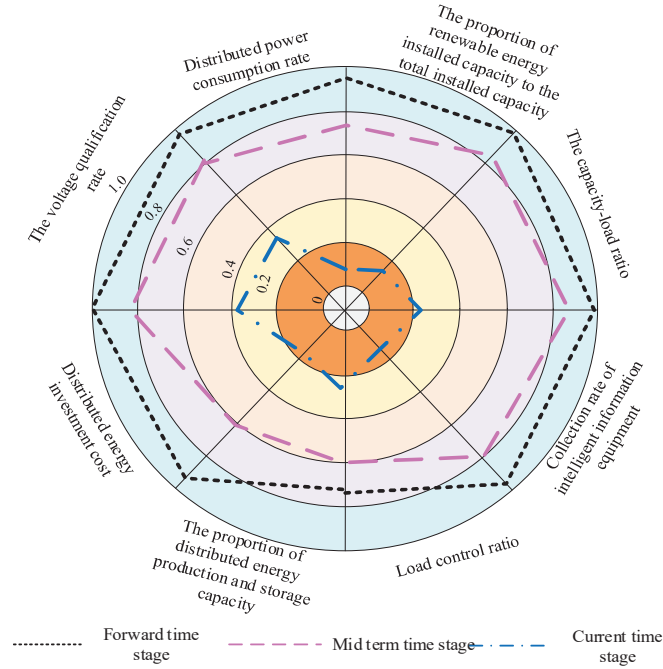


Figure 8 Distribution network form membership results.

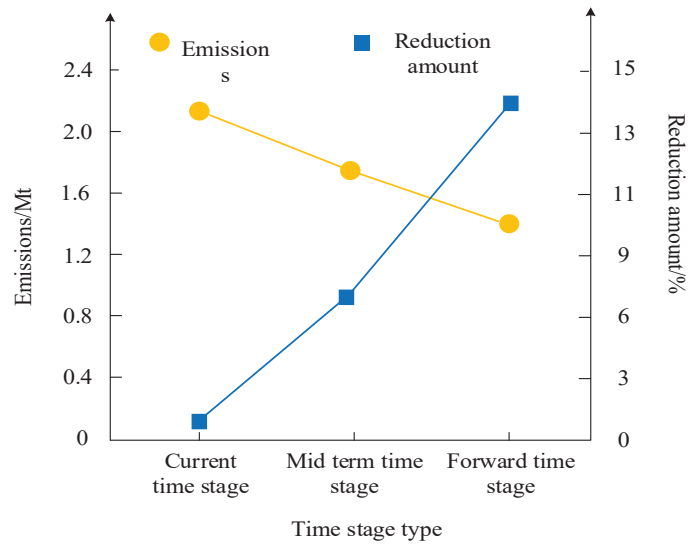


Figure 9 Evolutionary results of carbon emissions.

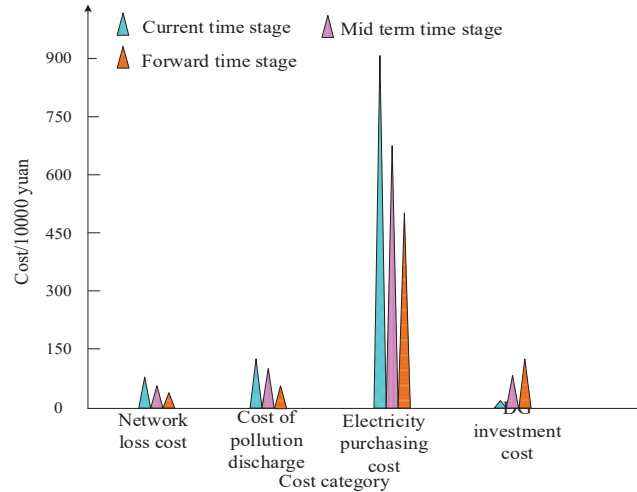


Figure 10 Evolution results of cost forms for new distribution networks.

while the carbon reduction showed a significant upward trend. The results indicate that the method proposed in this article can obtain the evolution process of the “dual carbon goals” morphology of the new distribution network. And the evolution results meet the development standards of the dual carbon goal, showing a positive state.

To further verify the application effect of the proposed method in the evolution process of new distribution network morphology. Using the cost of the distribution network as the evolution content, obtain the cost evolution results over three time periods, as shown in Figure 10.

According to the test results in Figure 10, it can be seen that the cost morphology evolution of the new distribution network has undergone varying degrees of changes over the three time periods. The costs of network loss, pollution discharge, and electricity purchase all show a downward trend, indicating that energy loss and consumption have decreased to varying degrees at different time stages. And the cost result in the forward time stage is about half of the cost in the current time stage, with a decrease of about 50%. The investment cost of (distributed energy) DG shows an increasing trend over time, but the reduction rate of the other three costs depends on the increase of DG. Therefore, compared to the reduction of other costs, the increase in DG still aligns with the development of the “dual carbon goals”. Ultimately, it indicates that the method proposed in this paper can capture the evolution process of the cost morphology of the new distribution network and derive the results of the evolution trend.

6 Conclusions

In order to obtain the planning and development status of the new distribution network under the “dual carbon goals”, this article conducted a study on the evolution process of the new distribution network morphology under the “dual carbon goals”. Firstly, a new distribution network morphology evolution system under the “dual carbon goals” has been constructed. Then, an indicator system was established in three aspects: power supply, distribution, and transmission, and a distribution network development form evaluation model based on SWOT analysis was constructed. Finally, the effectiveness of the proposed method in this paper was verified through numerical analysis, and the following conclusions were drawn:

- (1) The method proposed in this article can effectively capture the evolution process of distribution networks in various forms and aspects at different time stages under the “dual carbon goals”. And the evolution results show that the evolution direction of the distribution network morphology conforms to the dual carbon goal planning.
- (2) Through the analysis in this article, it can be concluded that in the evolution process of the new distribution network form, measures such as improving the consumption rate of renewable energy, installing capacity of renewable energy, and effectively controlling the load proportion in the distribution network can accelerate the achievement of the dual carbon goal.
- (3) With the extension of the time period, the results of various indicators of the dual carbon planning for the new distribution network have significantly improved. And the mid-term and long-term planning indicator results are significantly better than the current time stage indicator planning results. It indicates that under the “dual carbon goals”, the form of the new distribution network will undergo different evolution within different time stages, and the evolution results meet the development needs of the “dual carbon goals”.

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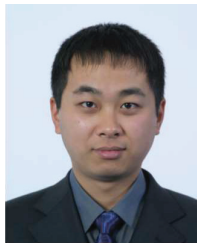
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