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Research Article

Multipoint Layout Planning Method for Multienergy Sources Based on Complex Adaptive System Theory

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Summary. With the continuous expansion of grid-connected power generation from renewable energy sources, such as wind and light, the forms of power sources are more diversified. The coupling and uncertainty of multiple energy sources will cause significant changes in the characteristics of the power system. Problems like the complexity of the power system lack a scientific and complete explanation. This paper comprehensively considers the regional weather conditions, the uncertainty of the output of wind and solar energy sources, and the time and space complementary characteristics of multiple power sources. Based on the theory of complex adaptive systems, a systematic and holistic optimization planning method is studied. Combining the idea of complementarity because of differences, a multipoint layout planning and design method for multienergy power systems is proposed to give full play to the synergistic effects of natural resources, achieve optimal resource allocation, and provide a theoretical basis for improving the consumption of wind and renewable energy. Taking an actual provincial power system in China as an example, through the comparison of production simulation calculations and multiscenario analysis and planning methods, the proposed method can significantly increase the consumption of wind and solar renewable energy.

1. Introduction

In recent years, China's renewable energy development has made remarkable achievements, and China has become the world's largest renewable energy producer and consumer. China's renewable energy will maintain a medium-to-high-speed growth trend [1]. By 2050, the proportion of national renewable energy power generation will reach over 85%, of which wind power and photovoltaic power will account for 63% [2]. The integration of large-scale renewable energy into the grid will be an important aspect of the development of future power systems [3]. In the development of renewable energy, improving the power grid absorption capacity is a key task. Multienergy complementation is an important means to improve the renewable energy absorption capacity. Based on the complementary characteristics of natural energy resources in time and space, to improve the consumption of renewable energy through the layout and coordinated planning of new energy sources, this paper explores the consumption space of wind and solar renewable energy and contributes to the sustainable and healthy development of renewable energy.

Because of the natural characteristics of wind and light, the output of wind power and photovoltaic power has randomness and volatility [4]. Power generation is affected by the geographical environment and climate, and the regional load also has time series characteristics. Reasonable renewable energy installation locations and capacity selection are extremely important [5, 6]. Renewable energy multipoint layout planning is a multivariable, multiconstrained, nonlinear optimization problem that takes into account uncertainty [7]. To characterize uncertain factors like climate, multiscenario analysis methods are widely used in power system planning. The typical scenarios for wind farm output are obtained by clustering the historical wind speed data [8]. Paper [9] divides the annual historical data of wind power and photovoltaic output into four daily scene sample sets in spring, summer, autumn, and winter according to the different seasons and uses a synchronous back generation elimination method to reduce the daily scenes. In the paper, most of the methods of reduction or optimal progressive scene technology are used to generate N_W wind power scenarios, N_{PV} photoelectric power scenarios, and N_L load power scenarios and then obtain the wind-light-load scenarios through permutation and combination. [10]. The essence of multiscenario analysis is to describe the uncertainty of random variables with discrete probability distributions so that the uncertain factors that are difficult to represent using mathematical models are transformed into multiple deterministic scenarios that are easier to solve for processing. Therefore, fundamentally, certain typical scenarios still cannot fully reflect the uncertain characteristics of renewable energy power output. In the multiscenario planning paper, the time series data of wind speed, light, and load are statistically analyzed separately, ignoring the correlation between the time series data and the spatial-temporal complementarity and complex coupling between multiple energy sources.

In recent years, the research on complex system theory has made important progress, which provides a new perspective for analyzing and studying the complex coupling relationship between heterogeneous energy sources, and it helps to grasp the complexity of multienergy power systems as a whole. The complex system theory emphasizes the method of combining holism and reductionism to analyze a system, describing the system with the structure of individuals and their interactions and evolution, taking the overall behavior of the system (such as emergence) as the main research goal and description object, and it discusses the evolutionary dynamics of the system (such as power law and self-organized criticality). The application of the complex system theory to the study of the complex characteristics of large-scale power systems is an important frontier topic in the field of power system research. The paper [11] combines the complex adaptive system with the power system, takes the multitype new energy power supply as the agent, mainly analyzes the complex characteristics of the multienergy power system from the microaspect, and carries out multipoint layout planning and design for each type of power supply to improve the consumption of the new energy. The complex adaptive system theory plays an important role in the research of traditional economic problems. Based on the theory of complex adaptive system, Nicholas and Robert expounded the significance of agent-based simulation to the study of competitive market process and strategy, and they proposed that enterprises should develop enterprise flexibility in many aspects if they want to win in the fierce market competition [12]. Amin and Ballard, based on the theory of complex adaptive system and through the study of power market, concluded that agents (enterprises) can dynamically create market through cooperation and competition. [13]. At the same time, the complex adaptive system theory makes up for the deficiency that the traditional animal and plant theory and cell theory in the field of life science cannot start with many new problems in development. Montemagno et al. introduced the theory of complex adaptive system into bioengineering and proposed the intelligent behavior embedded in aggregates, which made the intelligent treatment enter a new stage [14]. Among the numerous studies on the theory of complex systems, the theory of a complex adaptive system has been accepted to the greatest extent by scholars. The theoretical idea of "adaptability creates complexity" points out the direction for complexity research. The theory of a complex adaptive system has been applied in the financial field [12, 13]and social system field [15–17] and has made great progress.

Therefore, for a multienergy power system, this paper comprehensively considers regional weather conditions, renewable energy power uncertainty, development scale, and other factors based on the theory of a complex adaptive system, combined with the idea of complementarity because of differences, and it proposes a wide area space distribution planning method for renewable energy power supply. Taking the actual power system of a province in China as an example, comparing it with the multiscenario analysis method to verify the effectiveness of the proposed method is of great significance for improving the economic benefits of the multienergy power system. The contributions of this paper are threefold as follows:

(1) There are complex connections among various types of power sources, which will lead to obvious nonlinear characteristics of a multienergy power system. There is little literature on its digital analysis. Taking the actual system as an example, under the condition that other power sources remain unchanged, the position and capacity of a wind turbine are changed, and the new energy consumption data are calculated through production simulation. Based on the production simulation data, the complex characteristics of a multienergy power system are explained.

(2) There is little literature to analyze the complex relationship between multiple types of power supplies. In this paper, an agent-oriented modeling method is proposed. Regarding various types of regional power sources as agents, the interaction between the agents is used to characterize the complementary relationship between different power sources in the multienergy power system, so that the system can operate efficiently and stably.

(3) Through the proposed model and solution method, various power supply multipoint layout schemes of the multienergy power system can be obtained, and the installed type and capacity of each node can be determined. By comparing with the methods proposed in previous literature, the utilization efficiency of new energy-generating units has been significantly improved.

The remainder of this paper is organized as follows: Section 2 analyzes the complex coupling relationship in a multienergy power system. Section 3 illustrates the computation method. Section 4 validates the correctness and computation performance. Section 5 provides the conclusion and future work.

2. Analysis of Wind-Solar Coupling Characteristics

With the continuous expansion of the scale of the grid-connected renewable energy power generation, the forms of power sources are diversified, and the coupling and uncertainty of multiple heterogeneous energy resources will cause significant changes in the characteristics of the power system. Taking a simplified power system of a province in China (figure 1) as an example, the complex connection and nonlinear coupling relationship between power sources in a multienergy power system are explained. There are two wind farms in the area, connected to the 2 and 15 nodes. The total installed capacity of the two wind farms is 2050 MW. Under the condition that the total installed capacity of the two nodes is not greater than 2050 MW and the installed capacity and location of other types of power sources remain unchanged, the installed capacity of the wind power of the two nodes is redistributed. The annual consumption of new energy (wind power, photovoltaic, and solar thermal) of the system is shown in Figure 2.

(a) Annual consumption of wind power
(b) Annual consumption of photovoltaic power
(c) Annual new energy electricity abandoned

It can be seen from the figure that with the increase in the total installed capacity of wind power, the annual consumption of wind power also increases. However, when the total installed capacity of wind power is small (the total capacity is less than 500 MW), the annual photovoltaic consumption is significantly lower, and the amount of abandoned new energy power is relatively high. It shows that the connection of wind power has a certain promotion effect on the consumption of photovoltaic energy in the system. Moreover, because of the strong volatility and randomness of new energy sources, when the peak load regulation capacity of the system is insufficient, a single form of new energy is not conducive to consumption.

The new energy consumption will be limited by the transmission section because of the different power access nodes. The new energy curtailment caused by transmission section constraints is shown in Figure 3. It can be seen from the figure that with the increase of the installed wind power capacity at node 2, the abandoned new energy power because of cross-section constraint also increases. The installed capacity of other types of power supply at node 2 is higher, resulting in the limitation of new energy transmission.

With the increase in the total installed capacity of wind power at two nodes, the annual consumption of the new energy of the system also increases, as shown in Figure 4. When the total installed capacity of wind power at two points is equal to 2050 MW, the annual consumption of new energy reaches the maximum.

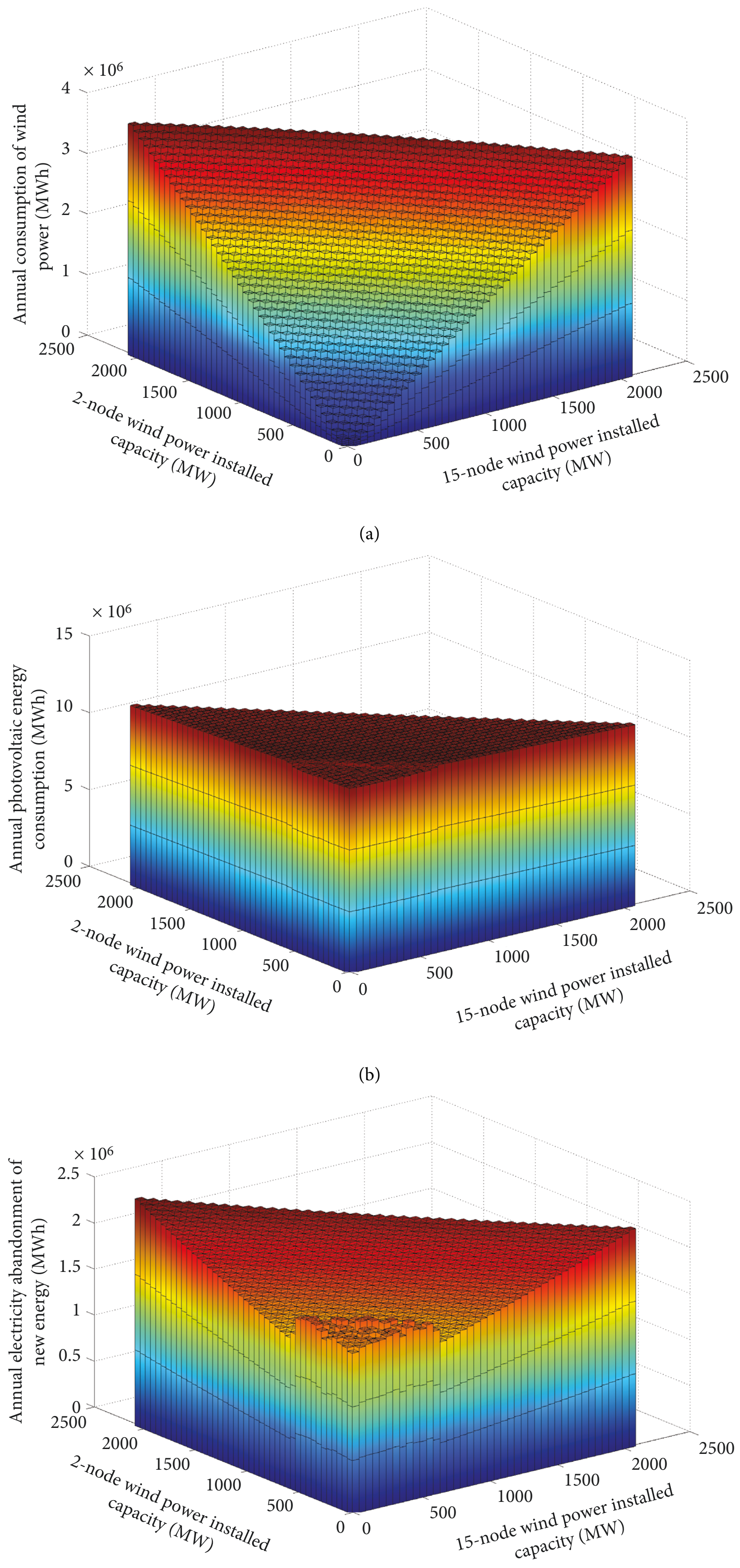
Under the condition that the total installed wind power capacity at the two nodes (2050 MW) remains unchanged, the new energy consumption is shown in Figure 5. It can be seen from the figure that the point with the largest annual consumption of wind power (node 15's installed wind power capacity is 1800 MW, and node 12's installed wind power capacity is 250 MW) is not consistent with the point with the largest annual consumption of new energy (node 15's installed wind power capacity is 1900 MW, and node 2's installed wind power capacity is 150 MW).

From the above analysis, the complementary characteristics of various heterogeneous energies can promote the consumption of new energy in the system. Different access points have different natural resource conditions and grid section restriction thresholds. Even at the same installed capacity level, different wind turbine access nodes not only affect the wind power consumption but also affect the total new energy consumption. The coupling relationship between new energy sources has very complex nonlinear characteristics.

There is currently a lack of research on the inherent complexity of multienergy power systems. A multienergy power system cannot be understood correctly using the simple addition of its constituent elements. Instead, the complexity of the system must be reproduced with an indivisible overall view, an interconnected organic view, and a dynamic view of each element. This paper focuses on the relationship between new energy sources, combined with the complex adaptive system (CAS) theory, and proposes a multienergy power system power planning model based on agent modeling, which provides a new idea and method for the power planning theory.

3. Planning Model for a Multienergy Power System

3.1. Complex Adaptive System Theory. The complex adaptive system (CAS) was proposed by the Santa Fe Research Institute. The theory includes two aspects: micro and macro [18]. At the microlevel, adaptive and active individuals are simply referred to as agents. An agent exhibits a certain adaptability in interaction with the environment, i.e., to better survive in an objective environment, the behavior rules can be modified according to the effects of the agent's behavior. At the macro level, the system is composed of agents and develops with the interaction between agents and the environment, showing various complex evolution processes, such as differentiation and emergence [19]. A CAS has eight core concepts—the "agent," four characteristics, and three mechanisms around the "agent," namely aggregation, nonlinearity, fluidity, diversity, identification, internal model, and building blocks. The logical relationship is shown in Figure 6. The basic unit in a CAS is called the agent. Identification is an important guiding mechanism during the interaction of the agent, and the agent selects the interactive object in the system through identification. The internal model is the interaction rule between the agents. Because of the existence of the internal model, the agent can make forward-looking judgments about the environment and make adaptive changes to the interactive behavior and its own behavior based on the prejudgment. The interaction between agents is realized and transmitted through "flow." Flow is a continuous and dynamic process, and it has an emergence effect in the flow among the agents. Aggregation



(a)

(b)

(c)

Figure 1: Annual consumption of new energy.

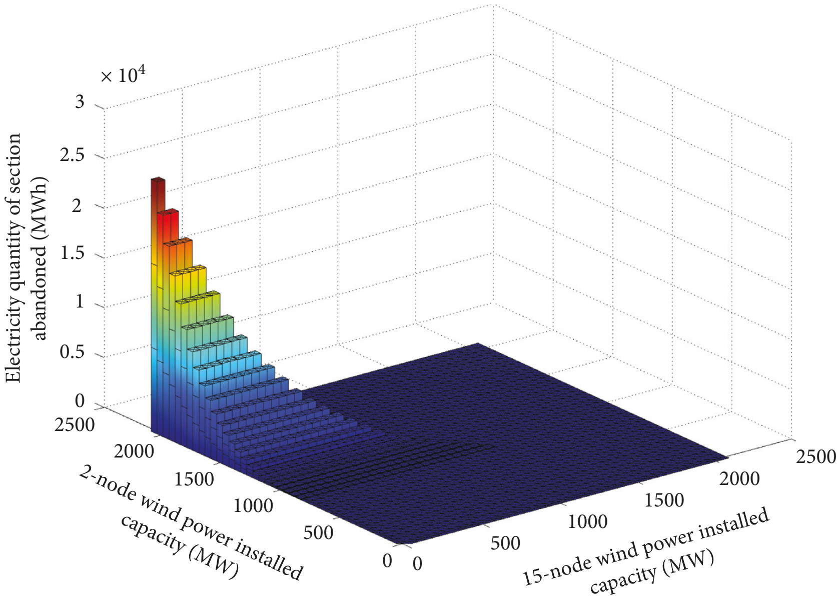


Figure 2: Annual new energy electricity abandonment because of section constraints.

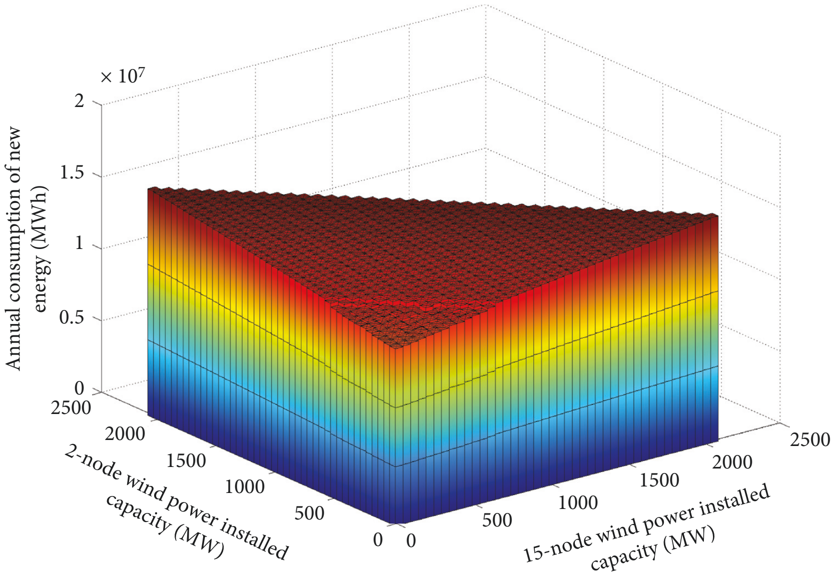


Figure 3: Annual consumption of new energy.

is the characteristic of the relationship between agents, including the interactive relationship between the agents. The interaction between the agents is mostly nonlinear, and the whole is not equal to the environment. The interaction and continuous adaptation of the agents to the environment led to the development and evolution of the agents in different directions, finally forming differentiation and resulting in system diversity. Building blocks encapsulate the contents and rules of the next level as a whole, and participating in the interaction of higher-level systems facilitates the study of the law of interaction between higher-level systems.

3.2. Complexity of a Multienergy Power System. At present, the theory of complex adaptive systems is mostly used in the fields of economic management, social systems, and life sciences. A multienergy power system is also a typical complex adaptive system: a multienergy power system is composed of power sources with various forms of power generation, such as wind power, photovoltaics, hydropower, thermal power, solar thermal power, and storage. The cooperative relationship between these energy sources can adapt to the environment and coordinate the development of other agents in a more efficient and comprehensive way.

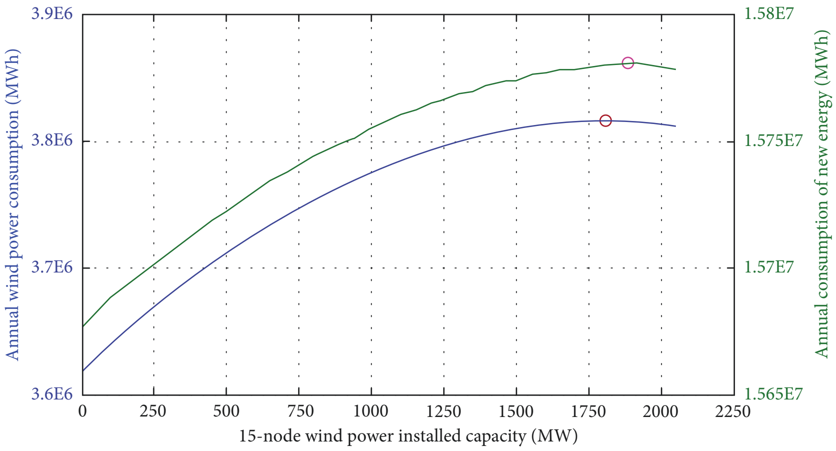


Figure 4: Change in annual consumption new energy.

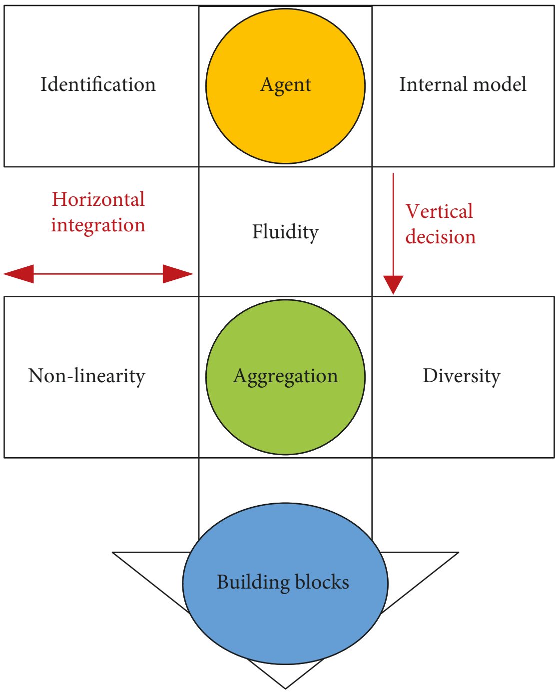


Figure 5: Feature logic diagram.

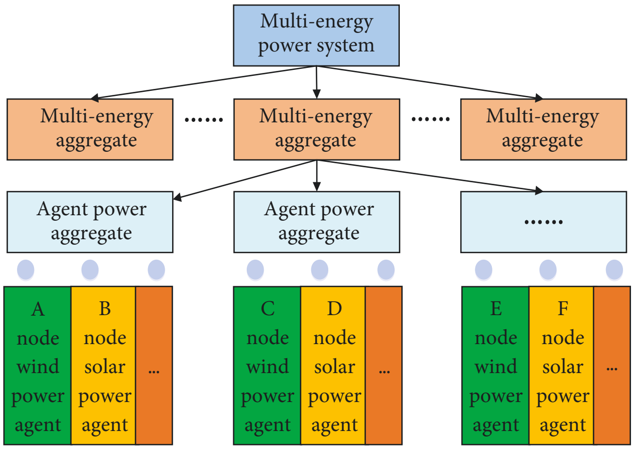


Figure 6: Multienergy power system.

Following Holland's theoretical framework of a CAS, using the core concepts of a CAS, the "agent" and the seven basic concepts (four characteristics and three mechanisms) surrounding the "agent" are used to analyze the characteristics and mechanisms of a multienergy power system as a CAS and deeply analyze the complexity and adaptability of the multienergy power system.

3.2.1. Agent.

The basic unit in a CAS is called the agent. The agent has its own initiative, goals, and internal structure. The adaptability of the agent is reflected in its ability to perceive external information stimuli and adjust its own behavior through learning. The agent is the inevitable starting point for studying the law of system evolution using a complex system [19].

In a multienergy power system, various power sources are the adaptive agents. Different locations, different types, and different capacities of power sources interact with each other. The environment of each agent is not only determined by the natural environment, such as wind and light resources, but also provided by other agents through the interconnection of the power grid. At the same time, each agent also participates in the process of providing an environment for other agents.

3.2.2. Aggregation.

An agent has aggregation characteristics. Aggregation is the characteristic of the relationship between agents. After the agents as the basic units gather, the interaction between them will form a large-scale complex system, and the aggregate can also be used as the basic unit to form a larger-scale complex system. It is often a turning point for changes in the macroscopic nature of the system. Therefore, aggregation includes the interactive relationship between agents.

There are multiple forms of aggregation in a multienergy power system: a single type of power is gathered to form a large-capacity gathering site. Different types of power are sent out in a bundled form through aggregation. At the system level, the power sources of various types and capacities use the network as a carrier, and aggregation on the time scale ensures the real-time source-load balance of the multienergy power system. These complex aggregation agents formed by the aggregation effect determine the scale and complexity of the development of a multienergy power system.

3.2.3. *Nonlinearity.*

The theory of complex adaptive systems states that most of the interactions between the agents are nonlinear relationships, and the whole is not equal to the simple accumulation of individual parts. An agent does not have a simple, passive, and one-way causal relationship but an active mutual adaptation relationship. This initiative and adaptability of the agent creates the complexity of the system.

As a CAS, a multienergy power system is not equal to the simple sum of all the parts of the power source. There are many factors that affect power generation. The impact of these factors on the power generation system is not independent but interactively linked, and the output fluctuation of any power generation agent will have an impact on the output of other power generation agents. The power generation agents adapt to each other in a nonlinear environment and develop together.

3.2.4. *Fluidity.*

Complex adaptive systems emphasize the role of "flow." As a characteristic, the transmission channel and speed between the agents directly affect the evolution of the system, i.e., the interaction between agents is realized and transmitted through "flow." Since the interaction between the agents is nonlinear, "flow" triggers a chain reaction. The flow between agents produces an emergent effect, presenting a continuous and dynamic process.

In a multienergy power system, the agents are connected through energy flow, information flow, and capital flow. Power flow is a typical factor flow in a multienergy power system. The power flow varies with time, and each power supply agent will adjust its capacity with or without adaptation to achieve the most efficient state.

3.2.5. *Diversity.*

Diversity is caused by the adaptation of subjects to environmental changes. In the process of interaction and continuous adaptation, the differences between subjects will develop and expand, leading to the development and evolution of subjects in different directions, maintaining a stable state in a certain environment, and finally forming differentiation, resulting in the diversity of the system.

The adaptability of a multienergy power system is also a process of differentiation, resulting in the complexity of its structure and the diversity of its morphological performance. A power supply agent not only survives in the natural environment but also exists in the environment created by other agents. The completion of each adaptation process opens up possibilities for the next adaptation, thus maintaining the continuous renewal of the multienergy power system.

3.2.6. *Identification.*

In the process of subject interaction, identification is an important guiding mechanism. An agent chooses an interactive agent in the system through identification. By identifying the characteristics of each agent, the interaction between agents can be effectively promoted. In the process of interaction, new identification is generated, which provides the system with new coupling and aggregation possibilities.

In a multienergy power system, how the power supply agent realizes its own advantages is a prerequisite for the coordinated and complementary operation and development of the entire system. The identification of the agents of different types of power supply are their timing output characteristics. For example, the wind power output is "low at midday and high at night," while the photovoltaic output is "high at midday and low at night." Different types of power sources have different timing output characteristics, and differentiated directional signs play an extremely important role in the complementary and coordinated development of multisource power systems.

3.2.7. *Building Block.*

The concept of system building blocks provides convenience for analyzing the hierarchical problems of complex systems. The content and rules of the next level are "encapsulate," temporarily ignoring its internal details, and they participate in the interaction of higher-level systems as a whole, which is convenient for studying the rules of interaction between higher-level systems.

Using the concept of system building blocks to encapsulate the subsystems, it is convenient to study the operating rules of the system and the interaction between the subsystems in various regions at the system level to scientifically analyze the complementary operation mechanism of a multienergy power system and the interaction mechanism between the subsystems of each region.

3.2.8. *Internal Model.*

The internal model in the CAS theory defines the interaction rules between agents or system building blocks. For a given agent in a system, once the possible stimulus range is specified and the possible response set is estimated, the rules of the agent can be determined. Because of the existence of the internal model, an agent can make forward-looking judgments about the environment and make adaptive changes to the interaction behavior and its own behavior based on the prediction.

Internal models are widely used in the planning of multienergy power systems. An internal model is a guidance tool for current behavior using the prediction of some expected future state, which is often a constraint condition in the modeling process. According to the feedback information from the internal model, each agent adjusts its own capacity to adapt to changes in the environment.

Based on the above eight important concepts and combined with the theory of complex adaptive systems, this paper proposes a multipoint layout planning method for multienergy power systems, which considers complementarity.

3.3. Power Planning Model. A multienergy power system is also a CAS: a multienergy power system is composed of various forms of power sources (similar to Tetris, which has different shapes and achieves goals through mutual combination), and the various forms of power sources cooperate with each other and coordinate with each other. The coordination relationship between various energies adapts to the coordinated development of the power system and the natural resource environment with other agents in a more efficient and comprehensive manner. A multienergy power system architecture is shown in Figure 7.

Since the installation power capacity is a continuously changing value, the unit capacity equipment is selected as the agent (i.e., the installation capacity is a multiple of the unit capacity, expressed in terms of the number of pieces of installed equipment). As a result, planning conforms to the actual project, and the continuity problem is transformed into a discrete problem, which effectively improves the calculation efficiency.

The agent power supply model is divided into the following two aspects: (1)The internal rules of the agent power supply. The basic behavior pattern of an agent follows the "stimulus-response" model. An agent obtains the stimulus information about the external environment through a detector, combines the credit allocation mechanism and the rule library, transmits the execution instructions to the effector according to the specific situation, and finally changes its own behavior through the effector, thereby affecting the environment.

An agent receives different pieces of information generated by environmental changes and changes its structure and behavior to adapt to the environment. At the same time, the environment is constantly evolving because of changes in the agents. The learning process of an agent is embodied in rule discovery and rule library update, and "continuous learning" and "experience accumulation" predict future changes to maintain the survival and development of the agent. Figure 8 describes the agent learning process.

The internal rules reflect the learning ability of the agents and the adaptability to the environment and determine the location of the access node and the behavior of gathering with other agents. According to the analysis in Section 1, when the location of the power source changes, the amount of renewable energy consumption presents a nonlinear change characteristic. An agent's objective function value (related to system operation indicators) cannot be directly derived from the planning scheme and must be calculated in conjunction with production simulation. Sequential production simulation is closer to the operation of the actual power grid and can reflect the network constraints between the various subsystems and the characteristics of wind power and photovoltaic output, so that a multenergy power system can be analyzed in detail.

The interactive behaviour of the agent. In a CAS, intricate relationships, such as collaboration and competition, will occur among the agents. In a multienergy power system, complementary characteristics are typical interactions between power sources. Since the power generation, power supply, and electricity consumption of the power system are completed at the same time, the complementary characteristic should be the concept of complementarity defined on the time scale. The volatility of renewable energy power is a relative indicator, i.e., the closeness of the power output to the load curve.

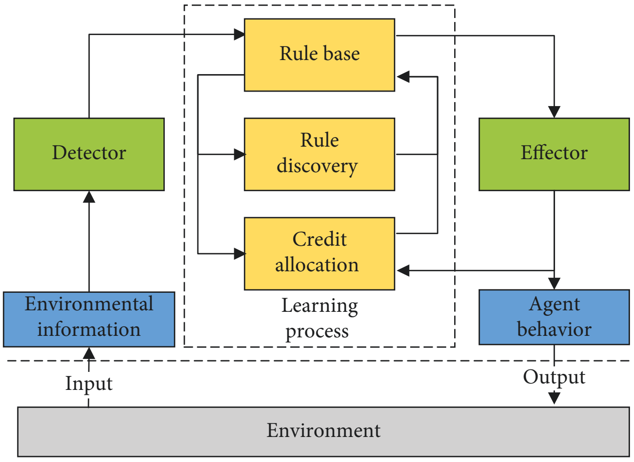


Figure 7: Schematic diagram of the adaptive agent learning process.

In a CAS, differentiated identification is a mechanism by which an agent generally exists behind another agent to identify, select, and gather each other (similar to Tetris, different blocks have different borders and shapes). The identification of different types of power sources is their timing output characteristics, and the differentiated oriented identification plays an extremely important role in the complementary and coordinated development of multi-source power systems. The interaction process of the agent is shown in Figure 9.

Based on the above analysis, the statistical output characteristics of all types of power sources at 24 hours in a year constitute the feature tag sequence.

$$\Psi_k = \left[\varphi^k_{1,n}, \varphi^k_{2,n} \cdots \varphi^k_{24,n}\right], \tag{1}$$

$$\varphi^k_{i,n} = \frac{\sum_{t=1}^{8760} P^k_{t,n}}{\max\left(\sum_{t=1}^{8760} P^k_{t,n}\right)} \begin{cases} t = d^* 24 + i \\ d = 0, 1 \cdots 364 \end{cases}, \tag{2}$$

The sequence of agent feature identification is a real number between [0,1]. The tag of an agent is related to its timing output characteristics. This value represents the characteristics of the agent, such as wind power output characteristics, that are high at night and low at noon and photovoltaic output characteristics that are high at noon and low at night. Because of the difference of the location, node, and natural resources of an agent, with the development of the evolution process, the time series output of the agent will also change through the calculation of sequential production simulation. Therefore, the tags of agents under different spatiotemporal conditions have the characteristics of time-variability and diversity, which provide the data basis for the diverse cooperation among the agents.

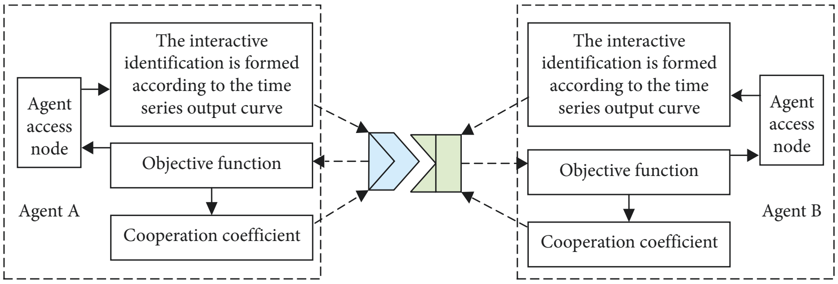


FIGURE 8: Schematic diagram of the power agent interaction process.

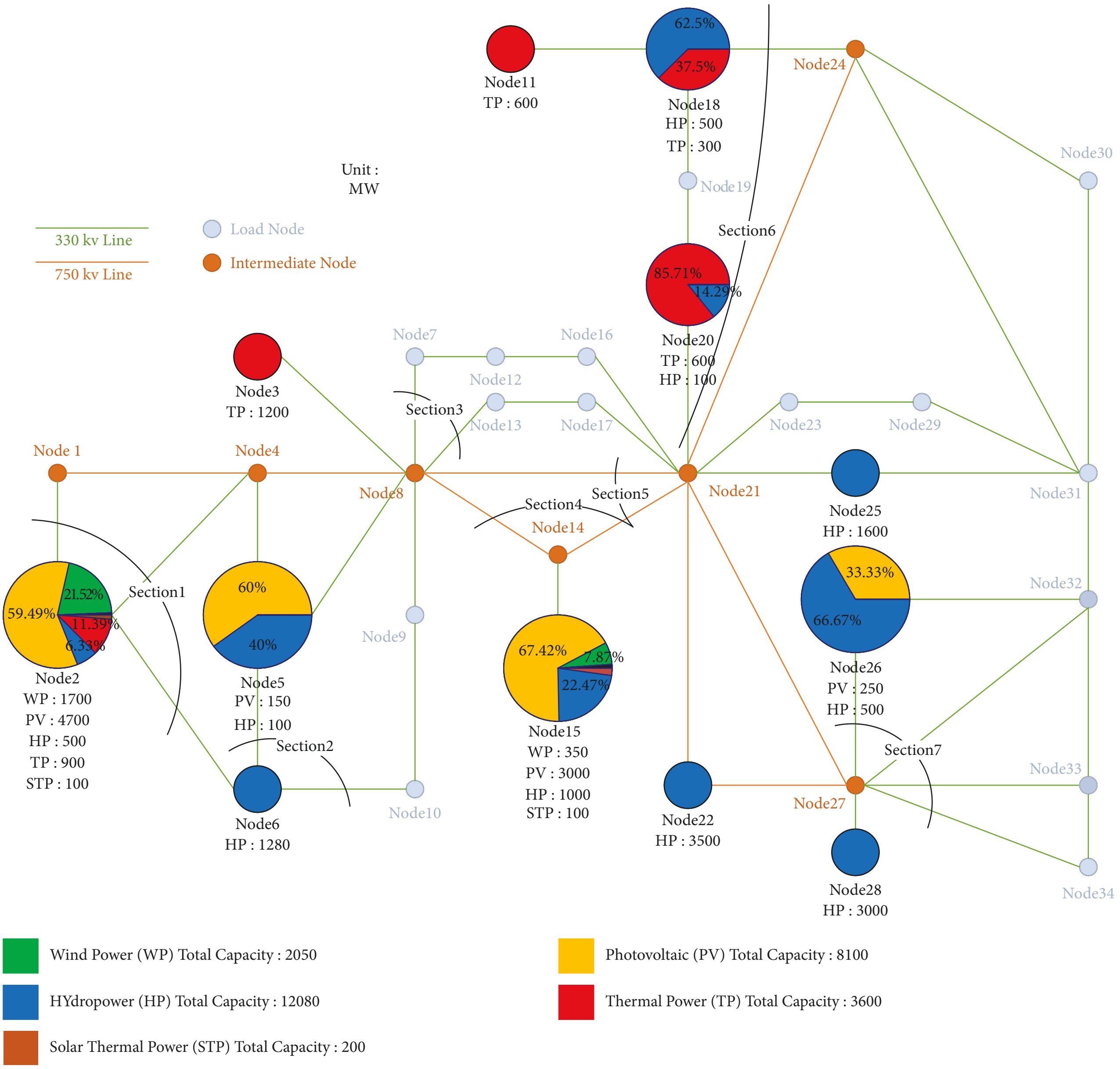


FIGURE 9: Power system structure diagram.

Similar to the tag process of the agent, the load tag is established ($\Psi_{loa\ d} = [\varphi_1^{\text{load}}, \varphi_2^{\text{load}} \cdots \varphi_{24}^{\text{load}}]$). Since the load does not change in the planning level year, its tag array is relatively fixed. The matching degree can be obtained by comparing the tags of the agent and load.

$$\eta_n^{k,\text{load}} = \sum_{j=1}^{24} \left| \varphi_{j,n}^{k} - \varphi_j^{\text{load}} \right|, \tag{3}$$

It can be seen from the above formula that the smaller the matching degree, the smaller the volatility and the better the complementarity. The cooperation mechanism among agents is determined as follows:

$$\begin{cases} \eta_n^{k,\text{load}} \geq \eta_n^{k,l,\text{load}} \\ \eta_n^{l,\text{load}} \geq \eta_n^{k,l,\text{load}} \end{cases}, \tag{4}$$

If $\begin{cases} \eta_n^{k,load} \geq \eta_n^{k,l,load} \\ \eta_n^{l,load} \leq \eta_n^{k,l,load} \end{cases}$ or $\begin{cases} \eta_n^{k,load} \leq \eta_n^{k,l,load} \\ \eta_n^{l,load} \geq \eta_n^{k,l,load} \end{cases}$ is satisfied, agent k and agent l cooperate with each other with a certain probability of forming a unified agent. In addition, when an agent's consumption decreases, if the other agent's consumption increases and the increase value is greater than the decrease value, the two agents will also aggregate.

3.4. Various Types of Power Output Models.

3.4. Various Types of Power Output Models. The output power of a turbine is closely related to the wind speed. The wind speed generally follows a *Weibull* distribution, and its probability density function is expressed as follows:

$$f(v) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} \exp\left[-\left(\frac{v}{c}\right)^{k}\right], \tag{5}$$

The relationship between the turbine output power $P_{\text{win},t}$ and wind speed is as follows:

$$P_{\text{win},t} = \begin{cases} 0 v \leq v_{ci}, v > v_{co} \\ \dfrac{v - v_{ci}}{v_N - v_{ci}} P_{\text{win},N} v_{ci} < v \leq v_N, \\ , P_{\text{win},N} v_N < v \leq v_{co} \end{cases} \tag{6}$$

The light intensity γ obeys a beta distribution in a certain period, and the probability density function $f(\gamma)$ is as folllows:

$$f(\gamma) = \frac{\Gamma(\alpha + \beta)}{\Gamma(\alpha)\Gamma(\beta)} \gamma^{\alpha-1} (1 - \gamma)^{\beta-1}, \tag{7}$$

The relationship between photovoltaic power $P_{pv,t}$ and light intensity is as follows:

$$P_{pv,t} = \begin{cases} P_{\text{PV,N}} \gamma > \gamma_{\text{N}} \\ P_{\text{PV N}} \dfrac{\gamma}{\gamma_{\text{N}}} \gamma \leq \gamma_{\text{N}} \end{cases}, \tag{8}$$

The output power of hydropower $P_{hy\ d,t}$ meets the following constraints:

$$\begin{cases} P_{\text{hyd, min}} \leq P_{hy\ d,t} \leq P_{\text{hyd,max}} \\ P_{\text{hyd,down}} \leq P_{\text{hyd,downmax}} \\ P_{\text{hyd,up}} \leq P_{\text{hyd,upma}x} \end{cases}, \tag{9}$$

The output power of thermal power $P_{the,t}$ meets the following constraints:

$$\begin{cases} P_{\text{the, min}} \leq P_{\text{the,t}} \leq P_{\text{the,max}} \\ P_{\text{the,down}} \leq P_{\text{the,downmax}} \\ P_{\text{the,up}} \leq P_{\text{the,upmax}} \end{cases}, \tag{10}$$

The relationship between the output power of solar thermal power $P_{stp,t}$ and light intensity is as follows:

$$P_{stp,t} = \begin{cases} \eta_{p,e} P_{stp,N} \gamma > \gamma_N \\ \eta_{p,e} P_{stp\ N} \dfrac{\gamma}{\gamma_N} \gamma \leq \gamma_N \end{cases}, \tag{11}$$

Solar thermal power stations generate electricity through steam turbine units. Hence, they have operation constraints similar to those of conventional steam turbine units. In addition, the charging/discharging power of the energy storage tank of a solarthermal power station can be continuously adjusted within a limited range, however, charging/discharging cannot be carried out simultaneously.

$$\begin{cases} 0 \leq P_{\text{stp,sto,in}} = \eta_{p,h} P_{\text{stp}\ N} \dfrac{\gamma}{\gamma_N} \leq P_{\text{hea,sto,in}}^{\max} \\ 0 \leq P_{\text{stp,sto,out}} = \eta_{h,e} P_{\text{stp}\ N} \dfrac{\gamma}{\gamma_N} \leq P_{\text{hea,sto,out}}^{\max} \\ P_{\text{stp,sto,out}} \times P_{\text{stp,sto,in}} = 0 \end{cases}, \tag{12}$$

At the microlevel, two agents gather to form a unified agent. At the macro level, new energy sources are complementary and coordinated. The form of an agent can be expressed as follows:

$$H = \sum_{m_{\text{type}}} \sum_{i=1}^{n} h_{m_{\text{type}},i}, \tag{13}$$

3.5. Objective Function.

3.5. Objective Function. Each agent takes the maximum consumption of new energy as the objective function.

$$\max Q_H = \sum_{m_{\text{type}}} \sum_{i=1}^{n} Q_{h_{m_{\text{type}},i}}, \tag{14}$$

Each agent connects with the other agents through the identification mechanism, establishes the cooperation and aggregation relationship, and determines the access node with the goal of maximizing the consumption of new energy. Because of the nonlinear relationship between the agents, when the position of any agent changes, it will not only affect the current agent output but also affect the output of other agent. As all agents choose the node location with the same goal, the new energy consumption of the whole system gradually increases and finally converges dynamically to the maximum value.

3.6. Constraints

3.6.1. Power Flow Constraint. To simplify the calculation, the DC power flow calculation method is adopted.

$$P = B\theta, \tag{15}$$

By calculating the DC power flow, the active power flow direction of each line at all times can be obtained, which provides a calculation basis for the multipoint layout planning and design of power sources.

3.6.2. Climbing Constraints. The power system needs to maintain power balance at all times, which needs to be adjusted by flexible power sources.

$$\begin{cases} \Delta P_{i,\mathrm{up}}^{t} \leq P_{i,\mathrm{the,maxup}}^{t} + P_{i,\mathrm{hyd,maxup}}^{t} + P_{i,\mathrm{stp,maxup}}^{t} \\ \Delta P_{i,up}^{t+1} \leq P_{i,\mathrm{the,maxup}}^{t+1} + P_{i,\mathrm{hyd,maxup}}^{t+1} + P_{i,\mathrm{stp,maxup}}^{t+1} \end{cases}, \tag{16}$$

$$\begin{cases} \Delta P_{i,do\ wn}^{t} \leq P_{i,\mathrm{the,\ max\ down}}^{t} + P_{i,\mathrm{hyd,maxdown}}^{t} + P_{i,\mathrm{stp,maxdown}}^{t} \\ \Delta P_{i,do\ wn}^{t+1} \leq P_{i,\mathrm{the,\ max\ down}}^{t+1} + P_{i,\mathrm{hyd,maxdown}}^{t+1} + P_{i,\mathrm{stp,maxdown}}^{t+1} \end{cases}. \tag{17}$$

3.6.3. Capacity Constraints. Because of the influence of power sources construction cycle, construction conditions, construction sequence, and other reasons, the newly built power sources of each type shall not exceed the set threshold.

$$\sum_{i=1}^{N} C_{\mathrm{type,new}}^{i,y} = C_{\mathrm{type,plan}}^{y}, \tag{18}$$

3.6.4. Section Constraint. The power system network has a certain transmission power threshold, and the transmission power of the line cannot exceed its maximum power threshold.

$$\sum_{m=1}^{n} P_{i,m} \leq P_{i,\mathrm{section,\ max}}. \tag{19}$$

3.7. Model Solving

(1) Enter the initial data, including the initial installed capacity of each type of power supply and the annual natural resources and load values of each node.

(2) Combined with the CAS theory, the smallest construction unit of new energy power supply is selected as the agent. Initialize the object function value and feature identification sequence of the agent.

(3) Carry out stochastic production simulation calculations in consideration of wind and solar volatility and obtain the consumption value of each agent and its characteristic identification sequence. Two groups of agents are randomly selected, and if the two agents meet the aggregation conditions, they are gathered.

(4) If the new energy consumption of the system increases, the aggregation coefficient between the two agents will increase, and they continue to participate in the iterative process in the current form. Otherwise, the two groups of aggregates cancel the aggregation relationship and reduce the aggregation coefficient, and the internal agents are randomly assigned to other nodes.

(5) Judge whether the power capacity at each node in the system converges. If converged, output the planning plan. Otherwise, go to step 3 for iterative calculation.

The specific process is shown in the appendix.

4. Example Analysis

Taking China's actual provincial power system as an example (Figure 9), 7 sections are divided according to their actual operating conditions. At the same load level and the total capacity of various power sources remaining unchanged, the method proposed in this paper is used to relayout and calculate the specific distribution of various power sources. The planning scheme is shown in Table 1 and is compared with the planning scheme obtained using a multiscenario analysis method (Appendix Table. a1, a2).

Since the wind power output scenario and the photovoltaic output scenario are calculated separately, the correlation between natural resources is ignored, which does not match the actual situation. Therefore, this paper randomly selects one day every month as a typical scene and considers the correlation of scenery resources through cluster analysis, selects a typical scene every month, and uses two multiscene analysis methods for power planning. The production simulation calculation data of each method are shown in Table 2.

Different output scenarios will lead to different power planning schemes. Randomly selecting one day each month as a typical scenario (Appendix Table A3) for planning is not representative, and the obtained planning plan is not as accurate as the original plan. Considering the correlation of landscape resources, a typical scene (Appendix Table A4) is selected for planning every month through cluster analysis. The clustering method directly processes the original data to obtain the required load and wind power output scenarios, which is beneficial to maintain the relevance of the original data. However, in the typical scenario planning method, the output of wind power coupled with photovoltaic power is obtained by multiplying the output of the selected typical scenario and the power supply capacity, i.e., the output of wind and solar power is considered to be proportional to the capacity. However, the coupling relationship between wind power and photovoltaic power sources is very complicated,

Table 1: Planning scheme (MW).

	Wind power	Photovoltaic power	Hydro power	Thermal power	Solar thermal power
2	1300	6000	10 × 50	3 × 300	200
3	0	0	0	2 × 600	0
5	0	1050	2 × 50	0	0
6	0	0	4 × 320	0	0
11	0	0	0	2 × 300	0
15	750	1050	10 × 100	0	0
18	0	0	5 × 10	2 × 150	0
20	0	0	2 × 50	2 × 300	0
22	0	0	5 × 700	0	0
25	0	0	4 × 400	0	0
26	0	0	10 × 50	0	0
28	0	0	10 × 300	0	0

Table 2: Production simulation data.

Total output(GWh)	Original plan	CAS plan	Random scenario plan	Clustering scenario plan
Wind power	3814.63	3777.45	3732.34	3740.05
Photovoltaic	11694.28	11945.73	11658.81	11902.71
Hydropower	52509.69	52326.71	52618.18	52395.45
Thermal power	10758.10	10751.70	10763.30	10751.93
Solar thermal	269.64	285.07	271.76	269.72
Traditional energy consumption	63267.80	63078.41	63381.48	63147.37
New energy consumption	15778.55	16008.25	15662.92	15912.48

with typical nonlinear characteristics, and independent planning of each power source is not possible.

The multiscenario planning method essentially describes the uncertainty of renewable energy output in deterministic scenarios and fundamentally still cannot fully reflect the uncertain characteristics of wind power and photovoltaic power output. There is no unified standard for the selection of typical scenarios. The analysis method enumerating limited typical scenarios is not comprehensive enough, and the best solution is likely to be missed. Because of the large randomness and intermittence of wind power and photovoltaic power output, multienergy power planning is a multivariable and multiconstrained nonlinear optimization problem that takes into account the uncertainty.

From the data of production simulation results, two groups of different scenarios will get different planning schemes. The consumption of new energy in the randomly selected scenario planning scheme is reduced, which shows that the selection of scenario is very important, and the randomly selected scenario cannot get a good planning scheme. Through the planning scheme obtained by clustering scenes, the results of production simulation data are better than the original planning scheme, which shows that the clustering method of the selecting scenario is effective and feasible. However, compared with the planning scheme proposed in this paper, the consumption of new energy is reduced by 0.61%. It is because the scenario planning method considers that the power output is directly proportional to the installed capacity of the power supply, i.e., the linear relationship, which violates the basic point of complex nonlinearity of a multienergy power system. Secondly, the method proposed in this paper pays more attention to the complementary characteristics of different types and regions of new energy, and the mutual cooperation of different types and regions of new energy is conducive to smooth the output fluctuation of new energy and improve the consumption of new energy.

In terms of the solving algorithm, when the power planning scheme changes, the production simulation calculation must be carried out to calculate the corresponding consumption data. The genetic algorithm and other intelligent algorithms have a large number of samples, and the calculation time shows an exponential growth trend, making it difficult to solve. This paper introduces a cooperation mechanism based on the characteristics of the power supply agent, which is more in line with the idea of multienergy complementary and coordinated planning of multienergy power systems. According to the production simulation data, under the premise that the total installed capacity of various types of power sources remains unchanged, after the re-layout of power sources, the output of thermal power and hydropower has decreased, and the consumption of wind and solar energy has increased significantly. The increase in the wind power and photovoltaic power supply replaces some thermal power generation, which helps reduce fuel consumption and carbon emissions and improves economic and environmental benefits.

The output of renewable energy for five days in a year is randomly selected for comparison, as shown in Figure 10. It can be seen from the figure that after the method proposed in this paper is used for planning, the fluctuation of the sum of the system wind power and photovoltaic power output is reduced. It is because, in the optimization model, each agent uses complementary indicators to make cooperative judgments to compare with the load. The lowest volatility is the aggregation of interactive signs to ensure that the system

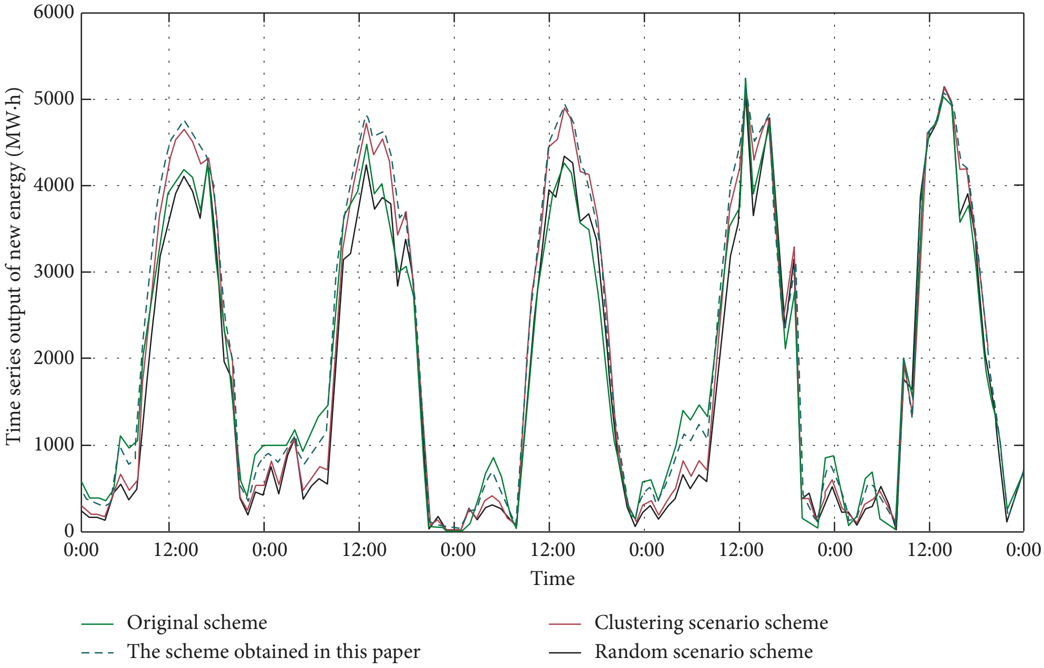


Figure 10: Sequential output of new energy.

makes full use of the complementary characteristics of wind and solar energy, making the multienergy power system more economical and reliable and better able to adapt to natural resources and the power system environment. Compared with the multiscenario analysis and planning method, it can maximize the reasonable utilization of wind and solar resources, effectively smooth the volatility of wind power and photovoltaic power output, and realize the continuity and smoothness of power generation.

5. Conclusion and Prospect

The adaptation process of a CAS is essentially a dynamic and generalized optimization evolution process that is based on the group. Because of the existence of mutual adaptation and mutual influence, the parts that make up the whole are not equal to simple linear accumulation, and attention must be paid to the emergence of structure and function from the bottom up at the system level brought about by the combination of elements. The CAS theory provides good theoretical support for the study of dynamic, nonlinear, and uncertain problems and can also be seen as a new method that replaces the traditional derivation analysis method.

This paper studies the complex connections between the power sources of multienergy power systems and the nonlinear coupling relationships between heterogeneous energy sources and proposes a multipoint layout planning model of a multienergy power system based on the CAS theory. Taking the actual power system as an example, under the circumstance that the total capacity of various power sources remains unchanged, through the re-layout and planning of power sources, the resulting plan has increased the consumption of new energy by 1.5% compared with the original plan. Compared with the multiscenario analysis and planning optimization method, the consumption of new energy can be increased by 2.21%, and the output curve of new energy will be more stable. The recommended solution obtained by applying the proposed model has better results, which can guide planning decision-makers to determine a final planning solution and has a reference value for the current multipoint layout planning of multienergy power systems. In future research, the key issues that should be considered are as follows:

(1) In this paper, it is considered that the total capacity of the power supply remains unchanged, and only the location of the power source is planned and designed. In the future research, the planning of power source structure should be increased.

(2) In the future research, we should add consideration to the change of power grid and carry out the coordinated planning of power source and power grid

(3) A complex adaptive system is very suitable for the study of system evolution. In follow-up research, we can combine the theory of complex adaptive systems to study the evolution process of power systems.

Abbreviations:

Ψ_k:	The tag sequence of the agent k
$p_{t,n}^{k}$:	The actual output at time t of iteration$n$ of agent k
$\max(\sum_{t=1}^{8760} P_{t,n}^{k})$:	The maximum absorption value of agent k statistics in 24 hours
$\eta_n^{k,\mathrm{load}}$:	The matching degree between agent k and the load in iteration$n$
$\eta_n^{k,l,\mathrm{load}}$:	Tthe matching degree of the combined output and load of agent k and agent$l$

v:	The real-time wind speed
k, c:	The shape parameters and scale parameters
$P_{win,N}$:	The rated power of the fan
$v_{ci}, v_{\mathrm{co}}, v_N$:	The cut-in wind speed, cut-out wind speed, and rated wind speed of the turbine
$\alpha\Delta\beta$:	The shape parameters
Γ:	The gamma function
$P_{\mathrm{PV,N}}$:	γ_{N}: the rated power and rated light intensity of photovoltaic power
$P_{hyd,\min}$:	$P_{hyd,\max}$: the minimum and maximum output power of the hydropower
$P_{hyd,up}$:	$P_{hyd,down}$: the climbing and downhill power of the hydropower
$P_{hyd,up\max}$:	$P_{hyd,down\max}$: the maximum climbing and downhill power of the hydropower
$P_{the,\min}$:	$P_{the,\max}$: the minimum and maximum output power of the thermal power. $P_{the,up}$, $P_{the,down}$: the climbing and downhill power of the thermal power
$P_{the,up\max}$:	$P_{the,down\max}$: the maximum climbing and downhill power of the thermal power
$P_{stp,N}$:	γ_N: the rated power and rated light intensity of the photovoltaics
$P_{stp,sto,in}^{\max}$:	$P_{stp,sto,out}^{\max}$: the maximum charging and discharging power
$\eta_{p,h}$:	$\eta_{h,e}$, $\eta_{p,e}$: the photothermal, thermoelectric, and photoelectric conversion efficiencies
H:	The aggregate generated by the aggregation of multiple agents
m_{type}:	The power type of the agent
i:	The agent number
Q_H:	The annual consumption of new energy of aggregate H
$Q_{h_{m_{\mathrm{type}},i}}$:	The annual consumption of new energy of agent $h_{m_{\mathrm{type}},i}$ contained in aggregate H
P:	The column vector of active power injected into a node
B:	The node admittance matrix
θ:	The phase angle column vector of node voltage
$\Delta P_{i,up}^t$:	The climbing power of node i at time t
$P_{i,the,\max up}^t$:	$P_{i,hyd,\max up}^t$, $P_{i,stp,\max up}^t$: the maximum climbing power of thermal power, hydropower and solar thermal power of node i at time t
$\Delta P_{i,do\ wn}^t$:	The downhill power of node i at time t
$P_{i,the,\mathrm{maxdown}}^t$:	$P_{i,hyd,\mathrm{maxdown}}^t$ and $P_{i,stp,\mathrm{maxdown}}^t$: the maximum downhill power of thermal power, hydropower, and solar thermal power of node i at time t
$C_{type,new}^{i,y}$:	The new type power capacity of node i in year y
N:	The total number of nodes
$C_{type,plan}^{y}$:	The total capacity of the $type$ power supply planned to be added in year y
$P_{i,l}$:	The transmission power of line l in the section of node i
$P_{i,\mathrm{section},\max}$:	The maximum transmission power of node i

Data Availability

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request (including wind speed, light intensity, system node load, and power line parameters).

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Supplementary Materials

The calculation flow diagram is shown in the appendix. The planning scheme obtained using the multiscenario analysis method is shown in Tables A1 and A2 (Appendix Tables A1 and A2). One day is randomly selected every month as a typical scenario, as shown in Table A3 (Appendix Table A3). A typical scenario is selected by cluster analysis every month, as shown in Table A4 (Appendix Table A4). (*Supplementary Materials*)

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