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Research Article

A Low-Carbon Planning Model for Regional Power Systems with Generation-Load-Storage Coordination considering New Energy Resources' Consumption

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With the increase in the proportion of new energy resources being generated in the power system, it is necessary to plan the capacity configuration of the power supply side through the coordination of power generation, grid, load, and energy storage, to create a relatively controllable power generation output and ensure the safe and stable operation of the power system is a key problem that needs to be solved at present. Therefore, combined with national and regional policies and resource constraints in China, this paper firstly determines the requirements and boundary conditions of various power supply planning in the regional power system and proposes a "generation-grid-load-energy storage" coordination mode. Secondly, establish a regional power system coordination planning model considering the proportion of new energy consumption and low-carbon cost. Finally, in three scenarios with a high, medium, and low proportion of new energy resources, the new installed capacity configuration of regional power supply is optimized to verify the effectiveness of the proposed model and provides reference for regional power supply planning.

1. Introduction

At present, due to the massive consumption of fossil fuel energy, resource shortages, climate change, and pollution have become major and urgent challenges [1]. Therefore, developing renewable energy (RE) is an important measure to deal with the current energy crisis. In this context, China, as the world's largest energy producer and consumer, announced in 2020 that it would increase the national contribution and adopt more effective policies and measures. China proposed carbon peaking and carbon neutrality goals, i.e., it will strive to hit peak carbon dioxide emissions before 2030 and then will aim for carbon neutrality by 2060. In 2021, China proposed building a new type of power system with new energy resources as the main source, to increase the proportion of new energy resources in energy production and consumption. Therefore, the energy sector, as one of the key areas involved in the implementation of the carbon peaking and carbon neutrality goals, will focus on the low-carbon transition of the power system and increase the generation and consumption of renewable energy sources (RES) [2].

With the increase in new energy resource (NER) generation, a large proportion of wind power, photovoltaic, and other energy sources characterized by intermittence, volatility, and randomness will be connected to the power grid, and the balance between the supply and demand side of the power system will become the main challenge. Therefore, all aspects of the power system should be integrated to form planning schemes including generation, grid, load, and storage elements to realize the overall coordination and optimization of the power system, so as to ensure the safety, stability, and economical operation of the power system [3].

Existing studies have considered the impact of energy storage and load-side demand response in generation planning models. Zhang et al. [4, 5] proposed a novel equilibrium-inspired multiagent optimizer with extreme transfer learning for decentralized optimal carbon-energy

combined-flow of large-scale power systems, and optimize the power system planning in the Southern Region. And in terms of energy storage in power generation planning, Moradi-Sepahvand and Amraee [6], in order to cope with the intermittency and uncertainty of RES, established a generation–transmission coordination planning model considering battery energy storage (BES) as a flexible resource. Mao et al. [7] proposed a generation capacity expansion model considering energy storage systems, and evaluated the role of energy storage in the decarbonization of distributed power systems. Zhou et al. [8] proposed a new capacity expansion planning method for wind power and energy storage systems, considering the actual multistage operation process of power system. Flores-Quiroz and Kai [9] proposed an integrated generation, transmission, and energy storage planning model accounting for short-term constraints and long-term uncertainty, solved based on the novel Column Generation and Sharing algorithm, which ensures the solution speed.

In terms of the demand response in power generation planning, Lu et al. [10] introduced the quantitative evaluation index system of flexibility, and put forward a power generation and load-side coordination planning model and ideas for its solution. In the study by Xu et al. [11], flexibility indicators were introduced to quantitatively evaluate the regulatory potential of various energies, and the evaluation results were considered in the generation planning model as optimization decision variables. Li et al. [12] proposed the concept of a generalized flexible power supply integrating generation, load, and storage, and established a two-layer overall planning model including investment decision and operation simulation verification. Zhang et al. [13, 14] incorporated demand-side resources into the generation–grid system planning model, and realized the overall planning of supply-side power units, grid, and demand-side resources.

To sum up, although there have been a large number of studies on power system generation planning, most of them do not take into account the coordinated planning of all aspects of the generation, grid, load, and energy storage at the same time, but only study power planning from the perspective of the economy, and rarely consider the weight of NER consumption responsibility and carbon emission factors. Therefore, we first analyze the requirements of the generation–grid–load–storage coordination planning model and all kinds of power generation planning boundary requirements, and propose a reasonable coordination mode. Secondly, considering the consumption of NERs, we establish a regional power system that incorporates a low-carbon planning model and propose a solution process. Finally, the capacity configuration of coal power, wind power, photovoltaic power, and energy storage in 2025 is planned using actual data from a certain region to verify the validity and practicability of the proposed model.

Compared with previous studies, the planning model proposed in this paper fully considers the policy requirements in China, such as "carbon peaking and carbon neutrality goals", NER consumption responsibility mechanism. Based on the requirements and boundaries, this makes an overall planning of various flexible resources of generation, load, and storage, which has strong practical guiding significance for the planning and construction of regional power system.

2. Requirements and Boundaries of the System Optimization Model

In order to determine the requirements and boundaries of the generation–grid–load–energy storage coordinated low-carbon planning model, we first clarify specific strategic requirements through the interpretation of energy policies in the region, and then technical development conditions and resource constraints through basic engineering research. Then, combined with the national strategic requirements, technological development conditions, and resource constraints, the design of a coordinated regional "generation–grid–load–energy storage" planning framework is put forward.

2.1. Coal Power Development Requirements and Boundaries. The development of NERs has become an important way to change the energy development path and optimize the energy structure of all countries in the world, and NERs will continue to develop rapidly in the future. China's "carbon peaking and carbon neutrality goals" marked the beginning of a new era of China's energy revolution. Implementing carbon reduction policies and ultimately achieving carbon neutrality will be the core of China's energy development in the future [15].

"The key to the source-side energy structure of regional power systems is to determine the proportion of carbon emissions and coal consumption while balancing the requirements of carbon reduction and economic development. Considering the average coal consumption of power generation and the reduction of coal power utilization hours under the condition of a high proportion of NERs being connected to the grid, the maximum installed capacity of coal power in the planning year can be obtained:

$$K_{\max} = \frac{R_{\text{coal}} \times \eta_{pc}}{\phi_{pc} \times \gamma_{pc}}. \tag{1}$$

In the equation above, $K_{\max}$ is the maximum installed capacity of coal power in the planning year, R_{coal} is the total coal consumption in the planning year, η_{pc} is the proportion of coal consumption in the planning year, ϕ_{pc} is the number of hours of coal power utilization in the planning year, and γ_{pc} is the average coal consumption for generation in the planning year.

2.2. NER Development Requirements and Boundaries. Under the "carbon peaking and carbon neutrality goals," the key to formulating a scientific and reasonable scale of NER development is to analyze the total scale of NER development in the region, the weight responsibility of NER consumption, and the energy consumption structure [16].

First, considering the resource endowment, development law, technological maturity, and other factors of the

wind power and photovoltaic industries in the region, we can determine the reasonable scale of wind power and photovoltaic power generation development in 2025. The total scale of new energy development is mainly related to the developable amount of wind power, photovoltaic, and other resources in the region.

Secondly, according to the weight of NER consumption responsibility assigned by the local government, we can determine the bottom-line demand for NER development in the province. The forecast of the reasonable installed capacity of NERs in this region needs to consider the responsibility weight of RES consumption. Assuming that the renewable energy in this region is mainly composed of wind power, photovoltaics, and hydropower, the calculation model of the maximum installed capacity of wind power, photovoltaics, and hydropower, considering the responsibility weight of RES consumption and of nonhydropower RES consumption, responsibility is shown in Equations (2) and (3):

$$\sum_{t=1}^{T}\left(h_t^{pu}H_{\max}+w_t^{pu}W_{\max}+p_t^{pu}W_{\max}\right)=\sum_{t=1}^{T}\left(p_{d,t}-p_{\mathrm{d},t}^{\mathrm{dr}}\right)\times LRNR-\sum_{t=1}^{T}p_{r,t}^{\mathrm{out}}. \tag{2}$$

In these equations, h_t^{pu}, w_t^{pu}, and p_t^{pu} are the per-unit values of hydropower, wind power, and photovoltaic output at time t, respectively, and $H_{\max}$, $W_{\max}$, and $W_{\max}$ are the maximum installed capacity of hydropower, wind power, and photovoltaics in the region, respectively. $p_{d,t}$ is the user load demand at time t, $p_{\mathrm{d},t}^{\mathrm{dr}}$ is the user demand response amount at time t, LRNR is the responsibility weight of RESs consumption in the region, and $p_{r,t}^{\mathrm{out}}$ is the external RESs at time t.

$$\sum_{t=1}^{T}\left(w_t^{pu}W_{\max}+p_t^{pu}W_{\max}\right)=\sum_{t=1}^{T}\left(p_{d,t}-p_{d,t}^{dr}\right)\times \mathrm{LNHRNR}-\sum_{t=1}^{T}p_{nr,t}^{\mathrm{out}}. \tag{3}$$

In the equations above, LNHRNR is the nonhydropower RES consumption responsibility weight in the region, and $p_{nr,t}^{\mathrm{out}}$ is the external nonhydropower RES at time t.

2.3. Energy Storage Capacity Configuration Principles. In this study, the energy storage capacity configuration principle is set according to the two objectives of maximizing the utilization rate of energy storage and maximizing the satisfaction of the power grid.

2.3.1. Energy Storage Power Configuration Principle. Firstly, the power of each statistical period in every day (365 days a year) should be determined, and the power of each statistical period should be judged to be higher than (or lower than) the average power of the day, so as to obtain the positive or negative power difference. Secondly, combined with the duration of the power difference, the discharge (or chargeable) power of the time period is calculated, and then the total discharge (or chargeable) power of the day, referred to as the "power deviation" below, is determined.

Second, set a number of continuous power deviation intervals, and calculate the probability distribution in each interval.

Third, the average power deviation corresponding to the high probability of a power deviation interval is selected as the power configuration basis of the energy storage system.

2.3.2. Capacity Configuration Principle. Firstly, the maximum difference (Pmax–Pave, Pave–Pmin) between the daily maximum/minimum load and the daily average load on all days (365 days in a year), hereinafter referred to as the "load deviation," is calculated.

Second, a number of continuous load deviation intervals are set and the probability distribution in each interval is calculated.

Third, the average load deviation corresponding to a high probability of load deviation is selected as the capacity configuration basis of the energy storage system.

2.4. "Generation-Grid-Load-Energy Storage" Coordination Framework

2.4.1. Connotation. Zeng [17, 18] put forward a preliminary concept of coordinated optimization of "generation–grid–load–energy storage" power system, and further extended this concept in [19]. In the traditional sense, the coordinated optimization of a "generation–grid–load–energy storage" power system is mainly a method to improve the overall dynamic balance of the system and achieve multiple objectives such as safety, low carbon, and economy on the basis of maximizing the utilization efficiency of energy resources and renewable energy through a variety of optimization means, system tools, and information interaction means. This method is an overall solution for the bilateral stochastic problems of the power system. The method includes the following three aspects.

(1) "Generation–generation complementarity" emphasizes the coordination and complementation

between all available resources in the power supply side. This complementation system includes two aspects.

The first is the coordination between renewable energy and traditional power generation resources. Distributed renewable energy (such as small wind turbines and distributed photovoltaics) needs to be coordinated with other controllable distributed energy and power supply resources of the power grid. In a wide area, centralized renewable energy is coordinated with conventional generator sets. The purpose of the above coordination and optimization is to reduce the randomness and intermittence of renewable energy power generation output in a wide area, so as to form a relatively optimized and reliable power supply system.

Second, demand-side resources are regarded as having the same supply-side resources as generation sources, and demand-side management technologies such as demand-response programs are used to reduce the adverse impact of the backload characteristics of renewable energy generation on the safe and stable operation of the power system [20].

(2) "Generation–grid coordination" requires the power grid to expand the capacity and level of accepting diversified generation sources; make use of intelligent regulation technology, optimization technology, and information technology; and give play to the complementarity and coordination between different generation sources and different combination modes under the guidance of "generation–generation complementarity" thinking, so as to optimize the combination of supply-side resources at both decentralized and centralized levels. At the same time, it can fully mobilize the schedulable potential of demand-side resources, and maximize the power grid's acceptance of renewable energy power generation on the basis of ensuring the safety, reliability, and economy of the system [21].

(3) "Grid–load–energy storage interaction" regards energy storage, electric vehicles, and user-side equipment or user-side resources with integrated power supply and demand as demand-side resources in a broad sense. The orderly charging and discharging of energy storage equipment guides the demand-side electricity load to actively track the power generation output of RES, and improves the matching degree of time and space between the supply and demand sides of the system [22].

2.4.2. Guidelines. Combined with the national strategic requirements and the resource constraints of energy development in the region, the design criteria for the planning of the regional power system "generation–grid–load–energy storage" coordination are put forward: first, the guiding ideology is to build a clean, low-carbon, safe, and efficient modern energy system. The second is to promote the large-scale development and utilization of wind and photovoltaic resources to achieve a high proportion of NER access; the third is to use an ultra-high-voltage (UHV) transmission grid to increase the proportion of RES in the region as the main means to ensure the balance of power supply and demand in the region [23].

According to the above guidelines, considering the technical maturity of the power system in the region and the development potential of various resources, a "generation–grid–load–energy storage" coordination planning scheme includes the following technical types.

(1) Through the UHV transmission network, large-scale wind-photovoltaic power transmission and reception across regions can be realized.

(2) Large wind and photovoltaic (PV) power generation bases can provide abundant renewable energy power.

(3) Peak-shaving power sources such as pulverized coal (PC) and hydro (HD) can meet the peak-shaving needs of the power system.

(4) Large-scale energy storage systems, including pumped storage power stations, electrochemical energy storage, etc., can improve the power output stability of renewable energy and grid friendliness.

(5) Demand response (DR), which guides the consumption behavior of power users to respond to market price signals or incentives, so that some price-sensitive industrial and commercial electricity loads can be shifted from peak time to valley time, and "peak shaving and valley filling" can be realized from the power consumption side.

2.4.3. Planning Scheme. Combining the regional power system "generation–grid–load–energy storage" coordination planning, design criteria, and technology types, a regional power system "generation–grid–load–energy storage" coordination planning scheme is proposed, as shown in Figure 1. The power output of the wind–photovoltaic base can be adjusted through peak shaving power supplies and large-scale energy storage. The excess will be used for local consumption or for cross-regional transmission, and the insufficient part can also be input through the cross-regional power grid. Demand response for local loads can improve the power supply and demand balance and operational stability.

On the power supply side, complementary coupling between conventional power sources such as coal power, natural gas power, wind power, photovoltaic power, hydropower, and new energy resources can be realized by utilizing the flexible adjustment characteristics of conventional power sources. On the grid side, cross-regional transmission of electricity can meet the demand for electricity between regions, promote the development of new energy resources power generation, and provide flexible adjustment capabilities for the system. On the load side, giving full play to the response potential of the demand side can realize peak shaving and valley filling of the power system. As an important, flexible resource, energy storage

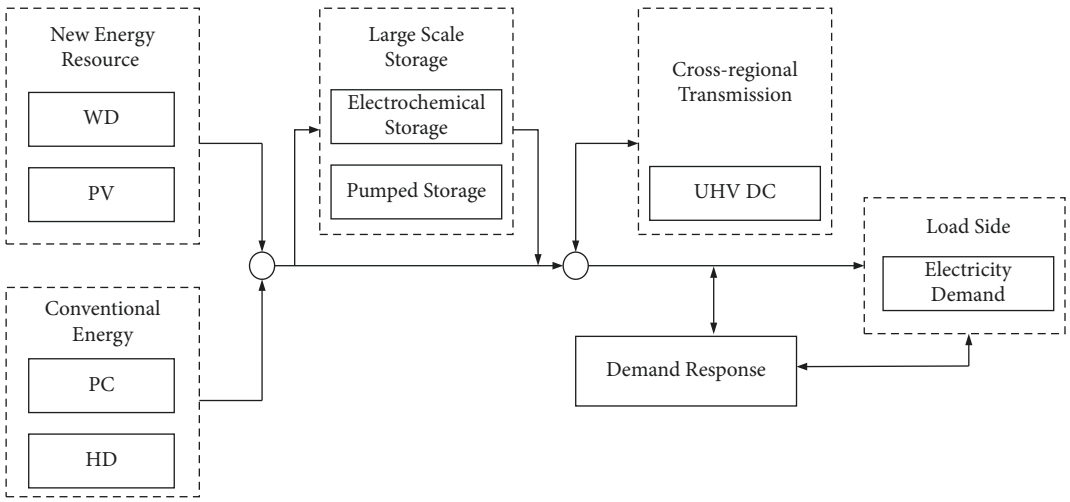

Figure 1: Planning scheme of regional power system.

has many application scenarios, and its large-scale application can become an important support for the reliable operation of a high-proportion clean power system in the future [24].

3. Generation-Grid-Load-Energy Storage Coordination Planning Model

3.1. Model Framework. Based on a consideration of the system's carbon emissions cost, this paper takes the lowest total system cost as the optimization goal, considering the power capacity, power grid transmission channel capacity, storage capacity, and related investment decisions such as budget constraints, demand response, conventional thermal power grade and start–stop, line transmission power, energy storage charge and discharge power, supply and demand balance, and operational constraints, to optimize the new capacity of coal power, wind power, photovoltaic power, and energy storage in the target year of the system. The model framework diagram is shown in Figure 2.

3.2. Model Construction

3.2.1. Objective Function. In this model, the total system cost includes the investment cost, operation and maintenance cost, fuel cost, purchase cost of external electricity, carbon transaction cost of various power sources, and energy storage. The expression is as follows:

$$\min C_{\text{total}} = C_{\text{inv}} + C_{\text{om}} + C_{\text{f}} + C_{\text{out}} + C_{\text{emission}} + C_{\text{pen}}. \quad (4)$$

In this equation, C_{total}, C_{inv}, C_{om}, C_f, C_{out}, C_{emission}, and C_{pen} are the total planning cost, investment cost, operation and maintenance cost, fuel cost, external power purchase cost, carbon emission cost, and wind and light abandonment punishment cost of the regional power system, respectively.

(1) Investment Cost. Total system investment cost refers to the cost of investment into new capacity for various generation sources and electrochemical energy storage. The specific expression is as follows:

$$C_{\text{inv}} = C_{\text{gen}}^{\text{inv}} + C_{\text{sto}}^{\text{inv}}. \quad (5)$$

In this equation, $C_{\text{gen}}^{\text{inv}}$ and $C_{\text{sto}}^{\text{inv}}$ are the investment costs of various power sources and energy storage, respectively.

$$\begin{aligned} C_{\text{gen}}^{\text{inv}} &= \sum_{i=1}^{N_{\text{pc}}} C_{\text{pc},i}^{\text{inv}} K_i + \sum_{k=1}^{N_{\text{hy}}} C_{\text{hy},k}^{\text{inv}} H_k + \sum_{m=1}^{N_{wt}} C_{\text{wt},m}^{\text{inv}} W_m + \sum_{n=1}^{N_{\text{pv}}} C_{\text{pv},n}^{\text{inv}} P_n, \\ C_{\text{sto}}^{\text{inv}} &= \sum_{j=1}^{N_s} C_{s,j}^{\text{inv}} S_j. \end{aligned} \quad (6)$$

where N_{pc}, N_{hy}, N_{wt}, N_{pv}, and N_s are the quantities of coal power, hydropower, wind power, photovoltaic, and energy storage, respectively; $C_{\text{pc},i}^{\text{inv}}$, $C_{\text{hy},k}^{\text{inv}}$, $C_{\text{wt},m}^{\text{inv}}$, $C_{\text{pv},n}^{\text{inv}}$, and $C_{s,j}^{\text{inv}}$ are the unit investment costs of coal power i, hydropower k, wind power m, photovoltaic n, and energy storage j, respectively; K_i, H_k, W_m, P_n, and S_j are the capacity of coal power i, hydropower k, wind power m, photovoltaic n, and energy storage j, respectively.

(2) Operation and Maintenance Cost. System operation and maintenance costs mainly refer to the operation and maintenance costs of various generation sources and energy

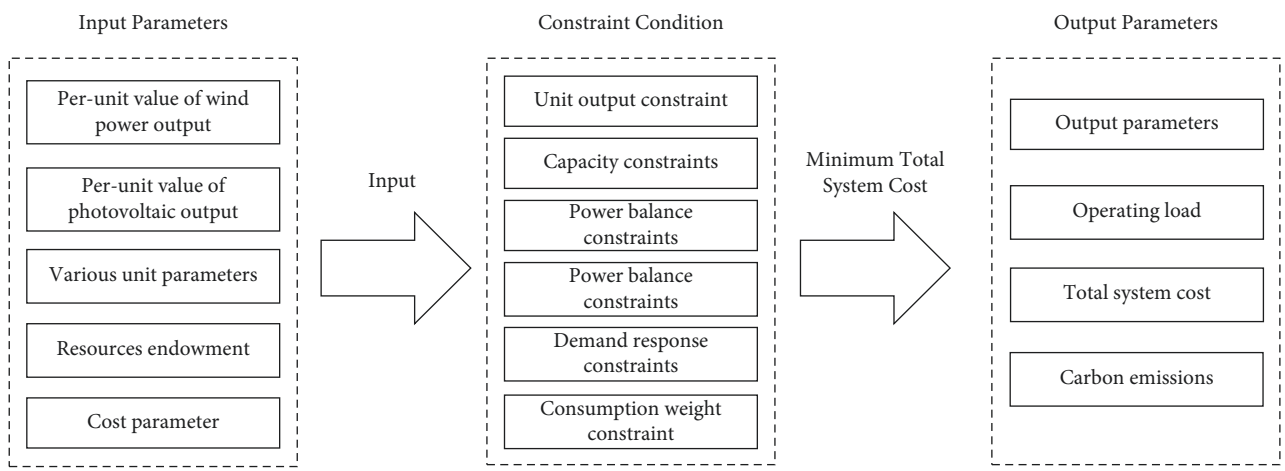

Figure 2: Model framework diagram.

storage power stations when they output. The specific expression is as follows:

$$C_{\text{om}} = \sum_{i=1}^{N_{\text{pc}}} c_{\text{pc}} K_i + \sum_{k=1}^{N_{\text{hy}}} c_{\text{hy}} H_k + \sum_{m=1}^{N_{\text{wt}}} c_{\text{wt}} W_m + \sum_{n=1}^{N_{\text{pv}}} c_{\text{pv}} P_n + \sum_{j=1}^{N_s} c_{\text{sto}} S_j. \tag{7}$$

In this equation, c_{pc}, c_{hy}, c_{wt}, c_{pv}, and c_{sto} are the unit capacity operation and maintenance costs of coal-fired power units, hydropower units, wind power units, photovoltaic units, and energy storage systems, respectively.

(3) Fuel Cost. Fuel cost mainly refers to the cost of the fuel consumed by coal-fired power generation units. The specific expression is as follows:

$$C_f = p_{\text{coal}} \cdot \sum_{t=1}^{T} \left(\xi_{\text{coal}} \cdot p_{i,t}^{\text{pc}} \right). \tag{8}$$

In this equation, p_{coal} is the coal market price in the region, ξ_{coal} is the fuel consumption per unit output of the coal-fired power unit, and $p_{i,t}^{\text{pc}}$ is the output power of the coal-fired unit at time t.

(4) External Power Purchase Cost. The cost of purchasing electricity mainly refers to the cost of purchasing electricity from outside the region through UHV when the electricity in the region cannot achieve a balance between supply and demand. The specific expression is as follows:

$$C_{\text{out}} = p_{\text{out}} \cdot \sum_{t=1}^{T} p_{e,t}^{\text{out}}. \tag{9}$$

In this equation, p_{out} and $p_{e,t}^{\text{out}}$ are the electricity price and power of the external electricity in the UHV DC transmission project in this region, respectively.

(5) Carbon Emission Cost. The carbon emission cost mainly refers to the environmental pollution cost when the coal power unit emits carbon dioxide when generating electricity. The specific expression is as follows:

$$C_{\text{emission}} = p_{\text{car}} \sum_{t=1}^{T} \sum_{i \in \Omega_c} \text{emi}_{c,i} p_{i,t}^{\text{pc}}. \tag{10}$$

In this equation, p_{car} is the carbon emission cost coefficient, $\text{emi}_{c,i}$ is the unit carbon emission of coal power, and $p_{i,t}^{\text{pc}}$ is the output of coal power at time t.

(6) The Penalty Cost Of Abandoning Wind And Photovoltaic Power. The penalty cost of abandoning wind and photovoltaic power mainly refers to the penalty fee paid when NERs cannot be consumed. The specific expression is as follows:

$$C_{\text{pen}} = p_{\text{pen}} \sum_{t=1}^{T} \left(\left(\sum_{m=1}^{N_{\text{wt}}} w_t^{\text{pu}} W_m - p_t^{\text{wt}} \right) + \left(\sum_{n=1}^{N_{\text{pv}}} p_t^{\text{pu}} P_n - p_t^{\text{pv}} \right) \right). \tag{11}$$

3.2.2. Constraints

(1) Investment Decision Constraint. The investment decision constraints mainly include conventional coal power and hydropower units; wind power, photovoltaic, and other NER units; and the installable capacity of energy storage and power supply sufficiency of the system.

(1) System power supply sufficiency constraint

The system tries to ensure that the load shedding amount does not exceed 1/10,000 of the total load demand. The specific expression is as follows:

$$\sum_{t=1}^{T} p_{d,t}^{\text{cut}} \leq \beta \sum_{t=1}^{T} p_{d,t}. \tag{12}$$

In this equation, $p_{d,t}^{\text{cut}}$ is the load shedding amount of the load at time t, $p_{d,t}$ is the load at time t, β is the power supply sufficiency, and the cutting load is generally required to be less than 1/10,000 of the total load.

(2) Newly installed capacity constraints

Assuming that other conventional generation sources and grid capacities other than coal power have been determined, only coal power, NERs, and energy storage capacity constraints are considered:

$$\begin{aligned} &\sum_{i=1}^{N_{\text{pc}}} K_i \leq Q_{\max}, \\ &\sum_{k=1}^{N_{\text{hy}}} H_k \leq H_{\max}, \\ &\sum_{m=1}^{N_{\text{wt}}} W_m \leq W_{\max}, \\ &\sum_{n=1}^{N_{\text{pv}}} P_n \leq P_{\max}, \\ &\sum_{j=1}^{N_s} S_j \leq S_{\max}. \end{aligned} \tag{13}$$

In these equations, $Q_{\max}$, $H_{\max}$, $W_{\max}$, $P_{\max}$, and $S_{\max}$ are the upper limit of the installed capacity of coal power, hydropower, wind power, photovoltaic, and energy storage in the region, respectively.

(2) Operational Simulation Constraint. Operational simulation constraints mainly include constraints such as power balance, line transmission power, energy storage charging and discharging, conventional units, NER output, and demand response.

(1) Power Balance Constraint

After considering a certain scale of demand response, the system must ensure the balance of power supply and demand; the specific expression is as follows:

$$\begin{aligned} &\sum_{i\in\Omega_c} p_{i,t}^{\text{pc}} + \sum_{k\in\Omega_h} p_{k,t}^{\text{hy}} + \sum_{m\in\Omega_w} p_{m,t}^{\text{wt}} + \sum_{n\in\Omega_p} p_{n,t}^{\text{pv}} \\ &+ \sum_{j\in\Omega_s} \left(p_{j,t}^{\text{st},d} - p_{j,t}^{\text{st},c}\right) + p_{e,t}^{\text{out}} = p_{d,t} - p_{\text{d},t}^{\text{dr}}. \end{aligned} \tag{14}$$

In this equation, Ω_g, Ω_h, Ω_w, Ω_p, and Ω_s are the coal power, hydropower, wind power, photovoltaic, and energy storage, respectively; $p_{d,t}$ is the load at time t; and $p_{\text{d},t}^{dr}$ is the demand response amount at time t.

(2) Unit Output Constraint

(i) Coal Power Unit Climbing and Start–Stop Constraint

The coal power output should not exceed the installed capacity, and to meet the ramp rate limit, the coal power output should not exceed the online start-up capacity. The output should not be lower than the minimum output determined by the online coal power capacity. We must also determine the online installed capacity of coal power, the relationship between the start-up capacity and the shutdown capacity, the minimum start-up time, and the minimum downtime limit of coal power.

$$\begin{cases} 0 \leq p_{i,t}^{\text{pc}} \leq K_i \\ -\alpha_{g,i}^{\text{down}} K_i \leq p_{i,t}^{\text{pc}} - p_{i,t-1}^{\text{pc}} \leq -\alpha_{g,i}^{\text{up}} K_i \\ \lambda_{g,i} O_{g,i,t} \leq p_{i,t}^{\text{pc}} \leq O_{g,i,t} \\ O_{g,i,t} = O_{g,i,t-1} + g_{i,t}^{\text{on}} - g_{i,t}^{\text{off}} \\ O_{g,i,t} \geq \sum_{\tau=1}^{T_{\text{on}}} g_{i,t-\tau}^{\text{on}} \\ O_{g,i,t} \leq K_i - \sum_{\tau=1}^{T_{\text{off}}} g_{i,t-\tau}^{\text{off}}. \end{cases} \tag{15}$$

In this equation, $\alpha_{g,i}^{\text{down}}$ and $\alpha_{g,i}^{\text{up}}$ are the downward and upward ramp rates of coal power i, respectively; $O_{g,i,t}$ is the online startup capacity of coal power i at time t; $\lambda_{g,i}$ is the minimum output ratio of coal power i; $g_{i,t}^{\text{on}}$ and $g_{i,t}^{\text{off}}$ are the startup capacity and shutdown capacity of coal power i at time t, respectively; and T_{on}, T_{off} are the shortest startup time and shutdown time of coal power, respectively.

(ii) Hydroelectric Unit Constraint

In addition to meeting the ramp rate requirements of coal power, hydropower also needs to meet the constraints of hydropower:

$$\begin{cases} 0 \leq p_{i,t}^{\text{hy}} \leq H_i, \\ -\alpha_{h,i}^{\text{down}} H_i \leq p_{i,t}^{\text{hy}} - p_{i,t-1}^{\text{hy}} \leq -\alpha_{h,i}^{\text{up}} H_i, \\ 0 \leq \sum_{t=1}^{N_m} p_{i,t}^{\text{hy}} \leq E_{h,i}^{m}. \end{cases} \tag{16}$$

In this equation, $\alpha_{h,i}^{\text{down}}$ and $\alpha_{h,i}^{\text{up}}$ are the downward and upward ramp rates of hydropower i, respectively; N_m is the number of monthly periods; and $E_{h,i}^{m}$ is the monthly maximum power generation.

(iii) NERs Output Constraint

The actual output value of NERs generally does not exceed the predicted maximum output value; the specific expression is as follows:

$$\begin{cases} 0 \le p_{m,t}^{\text{wt}} \le w_t^{\text{pu}} W_m, \\ 0 \le p_{n,t}^{\text{pv}} \le p_t^{\text{pu}} P_n. \end{cases} \tag{17}$$

In this equation, w_t^{pu}, p_t^{pu} are the unit values of the predicted output of wind power and photovoltaic at time t, respectively.

(3) Line Transmission Power Constraint

The transmission power of a line should not exceed the transmission capacity. The multiregional power grid interconnection generally adopts the transmission mode of line protocol—that is, the transmission power L of a specified line. The line transmission power constraint is

$$-L \le p_{e,t}^{\text{out}} \le L. \tag{18}$$

(4) Energy Storage Equipment Constraint

The charging and discharging constraints of energy storage equipment require that the charging and discharging power of energy storage not exceed the installed capacity, the charging and discharging process of energy storage meet the energy balance of energy storage equipment, and the charging and discharging amount of energy storage not exceed its energy capacity.

$$\begin{cases} 0 \le p_{j,t}^{st,d}, p_{j,t}^{st,c} \le S_j, \\ E_{s,j,t} - E_{s,j,t-1} \le \eta_{s,j}^{c} p_{j,t}^{\text{st,c}} \varepsilon_{j,t}^{\text{st,c}} - \dfrac{p_{j,t}^{\text{st,d}}}{\eta_{s,j}^{d}} \varepsilon_{j,t}^{\text{st,d}}, \\ 0 \le E_{s,j,t} \le T_{s,j} S_j, \\ 0 \le \varepsilon_{j,t}^{st,c} + \varepsilon_{j,t}^{st,d} \le 1. \end{cases} \tag{19}$$

In this equation, $E_{s,j,t}$ and $E_{s,j,t-1}$ are the charged state of energy storage j at time t and $t-1$, respectively; $\eta_{s,j}^{c}$ and $\eta_{s,j}^{d}$ are the charge and discharge efficiency of energy storage j, respectively: and $T_{s,j}$ is the continuous charge and discharge time of energy storage j. $\varepsilon_{j,t}^{\text{st,c}}$ and $\varepsilon_{j,t}^{\text{st,d}}$ are the charge and discharge states of the energy storage at time t, respectively, and are 0–1 variables, requiring that the energy storage j not be charged and discharged at the same time.

(5) Demand Response Constraint

Demand response constraint requires that the schedulable demand-side resources at time t not exceed the maximum user response.

$$0 \le p_{\text{d},t}^{\text{dr}} \le p_{\text{d},t}^{\text{dr,max}}. \tag{20}$$

In this equation, $p_{\text{d},t}^{\text{dr,max}}$ is the constraint of maximum demand response at time t.

(6) Renewable Energy Consumption Constraint

The consumption constraint of RESs requires that the proportion of regional consumption of RESs and nonhydro RESs not be lower than a certain value, and the specific expression is as follows.

(i) RESs Consumption Responsibility Weight Constraint

$rnr \ge LRNR$,

$$rnr = \frac{\sum_t \left(\sum_{k \in \Omega_h} p_{k,t}^{\text{hy}} + \sum_{m \in \Omega_w} p_{m,t}^{\text{wt}} + \sum_{n \in \Omega_p} p_{n,t}^{\text{pv}} + p_{r,t}^{\text{out}} \right)}{\sum_t \left(p_{d,t} - p_{\text{d},t}^{\text{dr}} \right)}. \tag{21}$$

In this equation, rnr is the consumption proportion of renewable energy power (hydropower, wind power, and photovoltaic power); $LRNR$ is the minimum consumption responsibility weight of RESs in the region.

(ii) Nonhydro RESs Consumption Responsibility Weight Constraint

$nrnr \ge \text{LNHRNR}$

$$nrnr = \frac{\sum_t \sum_{m \in \Omega_w} p_{m,t}^{\text{wt}} + \sum_{n \in \Omega_p} p_{n,t}^{\text{pv}} + p_{nr,t}^{\text{out}}}{\sum_t \left(p_{d,t} - p_{\text{d},t}^{\text{dr}} \right)}. \tag{22}$$

In this equation, rnr is the consumption proportion of nonhydropower RESs (including wind power and photovoltaic power); LNHRNR is the minimum consumption responsibility weight of nonhydroelectric RESs in the region.

3.3. Model Solving Method and Process. The programming model established in this paper belongs to the mixed integer linear programming model, which is optimized using CPLEX commercial software in MATLAB. The steps are as follows.

(1) Determine the boundary condition. According to the planning scheme, determine the target year load scale and characteristics, NERs output characteristics, power grid structure, transmission channel capacity, power supply structure, investment and operation cost at different stages, energy storage technical characteristics and cost at different stages, scale of demand response, RES consumption

responsibility weight versus nonhydropower consumption responsibility weight in the area, etc. Give the initial value of installed capacity of coal power, wind power, photovoltaic, etc., and set it as the lower limit of installed capacity.

(2) Carry out an optimization analysis. Input the typical daily scenario load forecast value and NERs output forecast value of the planning target year, take the minimum total system cost as the optimization objective, consider the constraints of power supply reliability and power balance, and take coal power, wind power, photovoltaic, and energy storage capacity configuration as the optimization variables. Optimize and solve the future development needs of coal power, NERs, and energy storage in this region under the constraints of the weight of RESs consumption responsibility and the weight of nonhydropower RESs consumption responsibility.

(3) Draw a conclusion. Based on the optimization calculation results of Step (2), the planned capacities of various power sources and energy storage in different scenarios are analyzed, and suggestions are put forward for the development of coal power, NERs, and energy storage in this region.

4. Results and Discussion

Based on the power supply and power grid planning of a certain regional power grid in 2025, the coal power, NERs, and energy storage capacity of the regional power grid in the scenario of a high, medium, and low proportion of NERs access are optimized and calculated.

4.1. Simulation Conditions. Based on the historical load characteristics of the region and the prediction of the maximum load in 2025, the 8760 h load curve of the region in 2025 is obtained, and the typical daily load curve after considering the demand response potential is shown in Figure 3. The cutting load of the system in calculation is less than 1/10,000 of the annual load, and the maximum demand response should not exceed 5% of the maximum load.

Based on the research in Section 2, considering the research related to the "14th Five-Year Plan" power planning in this region and the constraints on the maximum exploitable resources, the installed capacity of hydropower and pumped storage is no longer added, and the maximum installed capacity of coal power cannot exceed 800 MW. The newly installed capacity of wind power cannot exceed 500 MW, the newly installed capacity of photovoltaic cannot exceed 1500 MW, and the upper limit of the capacity of cross-regional transmission channels is 200 MW. The per-unit value of wind power and photovoltaic power generation output on a typical day is shown in Figure 4, the initial capacity of various units is shown in Table 1, and the unit investment cost and unit operating cost of various generation units are shown in Table 2 [25].

The per-unit value of the adjustment capacity of various power sources such as coal, gas, hydro, and biomass in this region is shown in Table 3.

4.2. Scenario Setting. Based on the NER consumption ratio requirements in Section 2.2 and the constraints of wind and photovoltaic resources in the region, this paper sets three scenarios of a high, medium, and low proportion of NERs access system to study the capacity configuration of power structure in this region.

Scenario 1: in this scenario, it is assumed that the proportion of NERs is not higher than 3050 MW;

Scenario 2: in this scenario, it is assumed that the proportion of NERs is not higher than 3100 MW;

Scenario 3: in this scenario, it is assumed that the proportion of NERs is not higher than 3150 MW.

Based on the power supply scale, load scale, transmission channel capacity, and the scale of pumped storage power stations in the region in 2020, we calculate the newly installed capacity of coal power, wind power, photovoltaic power generation, and electrochemical energy storage power station in 2025 considering "generation–grid–load–energy storage" coordination under different scenarios, in which the charging and discharging time of electrochemical energy storage power station is set to 2 h.

4.3. Simulation Results

4.3.1. Optimization Results of Each Scenario. The optimized newly installed capacity of coal power, wind power, photovoltaic power generation, and electrochemical energy storage power station under scenario 1 is 560 MW, 750 MW, 2300 MW, and 270 MW, respectively. The output of different generation units in this scenario is shown in Figure 5. Since the scale of newly installed coal power capacity in scenario 1 is significantly smaller than that in the other scenarios, the installed capacity of electrochemical energy storage power plants is the highest at this time. As can be seen from Figure 5, the electricity load demand is met by various types of power units, including coal power, wind power, photovoltaic power generation, hydropower, and electric energy transmitted across regions by UHV. Compared to other scenarios, the output of hydropower and electric energy transmitted across regions are larger in scale.

The optimized newly installed capacity of coal power, wind power, photovoltaic power generation, and electrochemical energy storage power station in scenario 2 is 600 MW, 700 MW, 2400 MW, and 225 MW, respectively. The output of different generation units in this scenario is shown in Figure 6. In this scenario, the installed capacity of coal power, wind power, photovoltaic, and energy storage are at a medium level. As can be seen from Figure 6, the output power of coal power unit and the electrochemical energy storage follows the fluctuation of load and new energy output, which promotes the consumption of NERs.

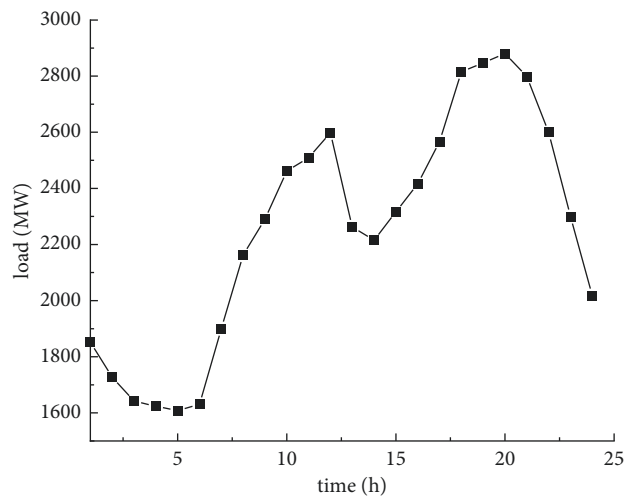

Figure 3: Typical daily load curve with DR taken into account.

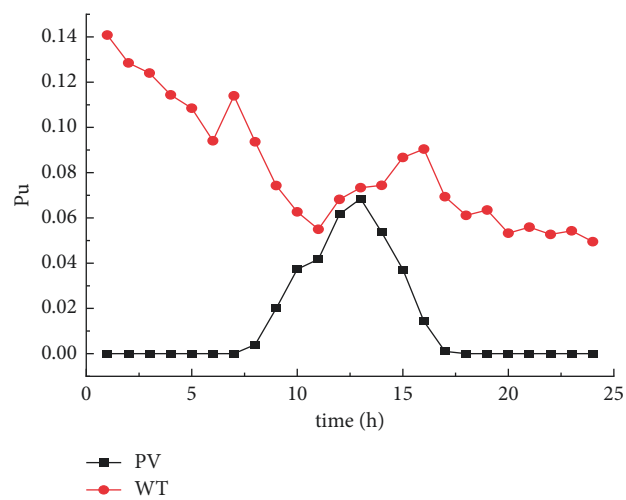

Figure 4: Wind power and photovoltaic power output per unit value on a typical day.

Table 1: Initial installed capacity of various types of units (MW).

Type of power	The cumulative installed capacity in 2020
Coal	2788
Gas	13.7
Hydro	544.7
Wind	510.3
Photovoltaic	755.9
Biomass	100.0
Other	260.23

The optimized newly installed capacity of coal power, wind power, photovoltaic power generation, and electrochemical energy storage power station under scenario 3 is 700 MW, 650 MW, 2500 MW, and 200 MW, respectively. In this scenario, the output of different generation units is shown in Figure 7. The installed capacity of coal power units in this scenario is the largest, while the installed capacity of energy storage equipment is smaller than others. As can be seen from Figure 7, the load demand of the system is mainly met by coal power units, while the output of power units such as wind power and biomass energy are small in scale.

It can be seen from Figures 5–7 that the electricity load demand in this region is mainly met by coal power. Despite the large installed capacity of new energy resources, due to the influence of environmental factors, the output of new energy units is intermittent and the output power is relatively small, which needs to be adjusted by other regulatory power supplies and energy storage equipment. In addition, the growth trend of the NER power generation capacity is consistent with the growth trend of coal power output and external power output. It can be seen from this that, in order to ensure the full consumption of NERs, the region should mainly conduct peak regulation through coal power and energy storage power stations.

4.3.2. Comparative Analysis. Figure 8 shows the "generation–grid–load–energy storage" coordination planning cost, abandoned electricity of NERs, and carbon emissions of the system under three scenarios.

Table 2: Unit investment cost and unit operating cost of various generation units.

Type of generation units	Investment cost (yuan/kW)	Operating cost (yuan/kWh)	Carbon emission index (kg/kWh)
Coal	3300	0.2	0.728
Gas	—	0.18	0.433
Wind	5500	0.15	0
Photovoltaic	3000	0.15	0
Electrochemical energy storage	6000	0.25	—

Table 3: Per-unit value of various power regulation capabilities.

Power type	Per-unit value of adjustment capacity
Coal	0.40–0.95
Gas	0.10–0.95
Hydro	0.3–1.0
Biomass	0.9–1.0

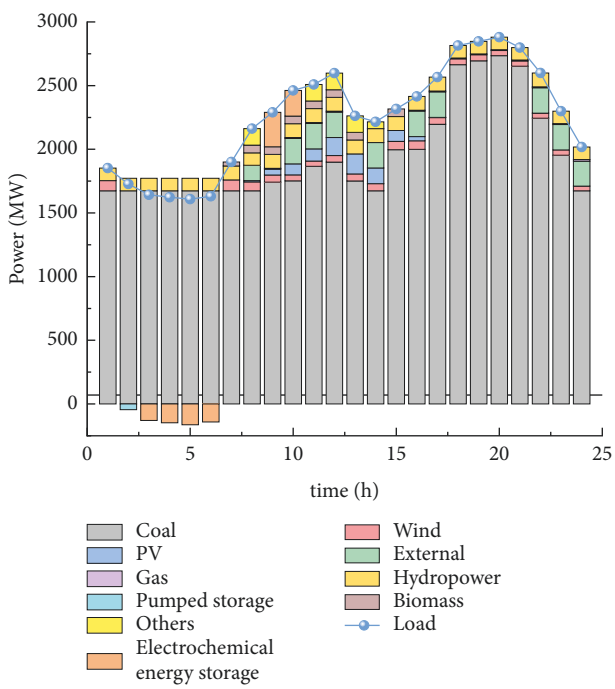

Figure 5: Power balance diagram of scenario 1.

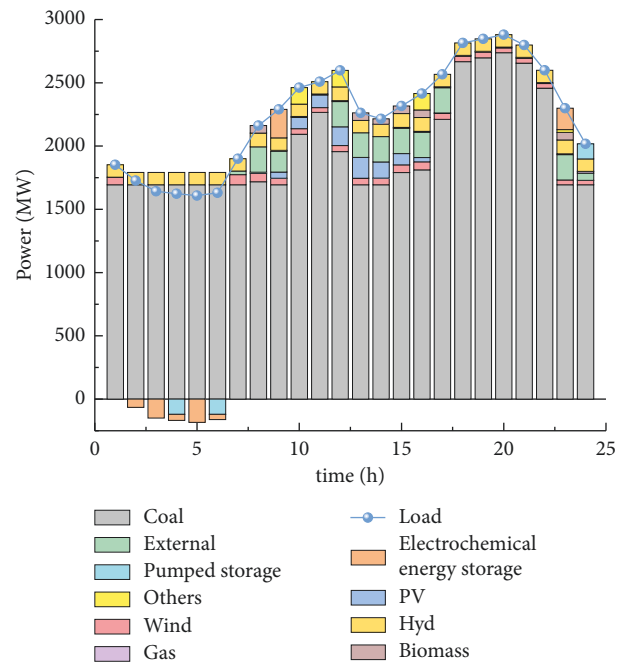

Figure 6: Scenario 2 power balance diagram.

As can be seen from Figure 8, when the proportion of NERs access is at a medium level, the total planning cost, and abandoned power of the system are the lowest, but the carbon emission is at a medium level. The main reason is that, in order to ensure the full consumption of NERs, the scale of newly installed coal power plants with high carbon emissions in this scenario is larger than in scenario 1. Therefore, on the one hand, the reduction of abandoned power is guaranteed; on the other hand, the lowest planning cost is guaranteed, and the carbon emission is at a moderate level.

Overall, scenario 2 is the best scheme. Both the economy and environmental protection are considered in this scenario. Compared with scenario 1, the planning cost of scenario 2 is reduced by 88 million yuan, the abandoned power is reduced by 15.51 MW, and the carbon emission is reduced by 369 billion tons. Compared with scenario 3, the planning cost of scenario 2 is reduced by 22 million yuan, the abandoned power is reduced by 30.2 MW, and the carbon emission is reduced by 858 billion tons.

4.4. Energy Storage Planning Effect Analysis. Assuming that no electrochemical energy storage is installed, the amount of NERs abandoned in this region in 2025 can be calculated according to the planning results. The time period when the amount of NERs abandoned is 100% is shown in Figure 9, and the amount of NERs abandoned each month is shown in Figure 10.

It can be seen from Figures 9 and 10 that, in 2025, the abandoned electricity of the region in May is the highest, reaching 900 million kwh, followed by 780 million kwh in April. The period with high abandoned electricity rate in 2025 is concentrated in February to June, 0–6 h/day. The annual electricity waste is about 4.4 billion kwh, the electricity r waste rate is 11.61%, and the consumption rate is 88.39%.

According to the development status of large-scale energy storage technology, it is appropriate for the electrochemical energy storage in this region to be configured for

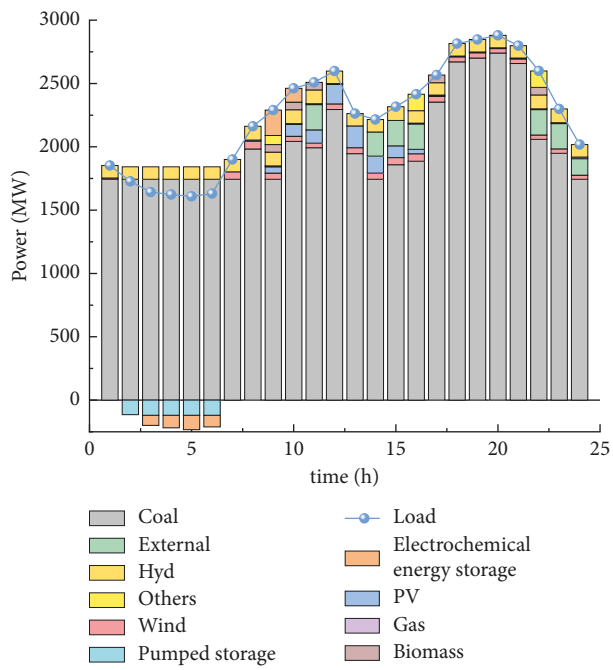

Figure 7: Scenario 3 power balance diagram.

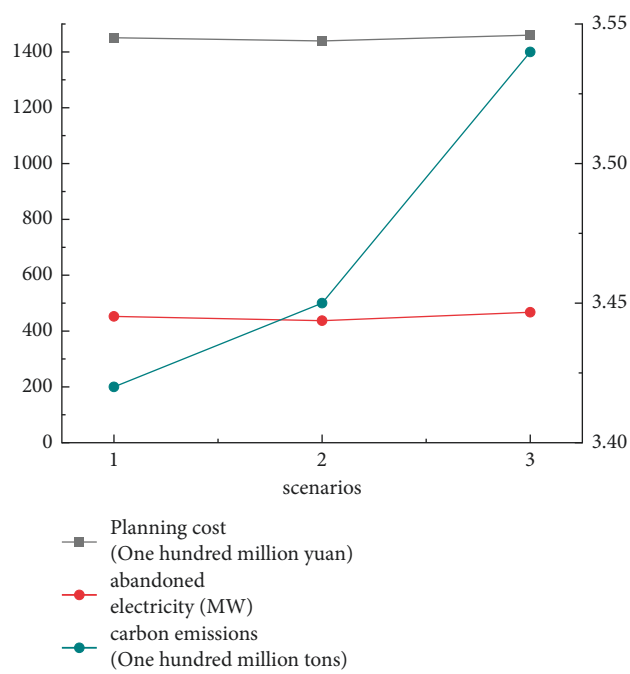

Figure 8: Comparison results in different scenarios.

2 h at present. In order to improve the NER consumption rate, we should analyze the improvement in NER consumption rates under installed electrochemical energy storage versus the planned electrochemical energy storage, the specific results are shown in Figure 11.

When 2.25 million kW of electrochemical energy storage is configured, the NER consumption rate increases to 95.01%, which is 6.62% higher than without energy storage. Therefore, it is recommended to install electrochemical energy storage in this region to increase the proportion of NER consumption.

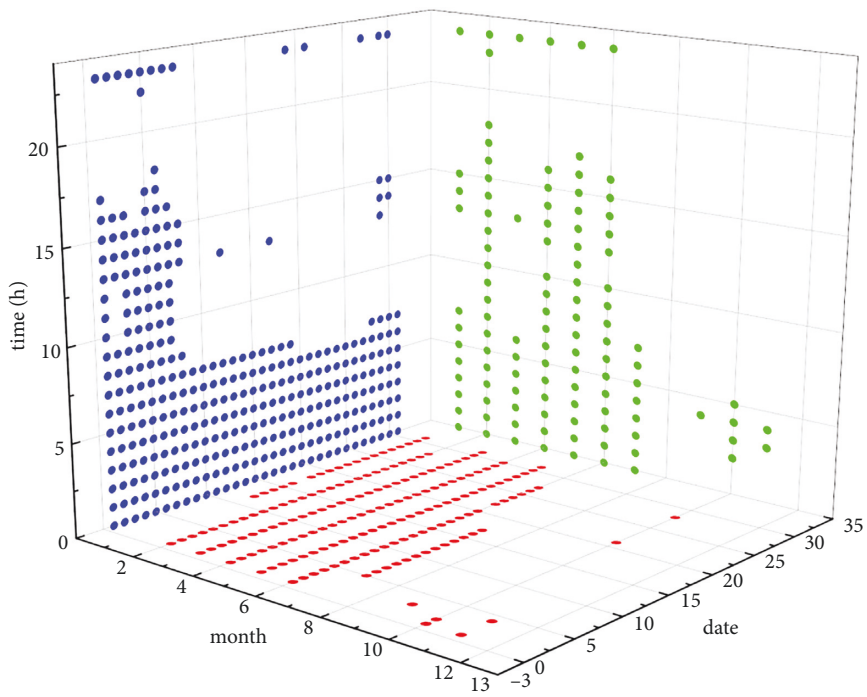

Figure 9: Time period with high proportion of power abandonment when no electrochemical energy storage is installed.

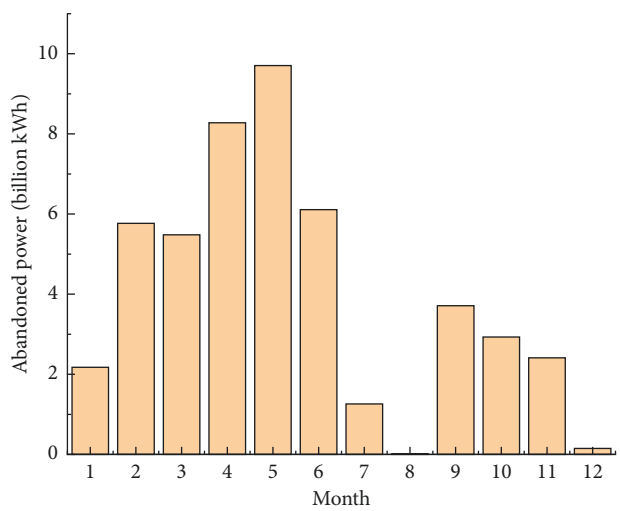

Figure 10: The amount of electricity abandoned in each month.

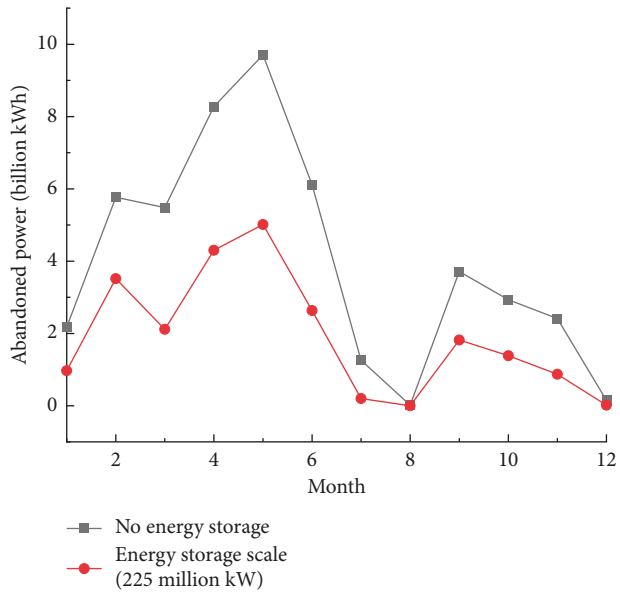

Figure 11: Abandoned electricity in each month of 2025 at different energy storage scales.

5. Conclusion

This paper establishes a regional power system "generation–grid–load–energy storage" coordination low-carbon planning model considering NER consumption. Based on the development boundary of coal power and NER under the requirements of national policy, the optimization goal is to minimize the total planning cost of the system, and investment decision constraints and operation constraints are considered. After overall optimization, the capacity configuration results of the newly installed coal power, wind power, photovoltaic power generation, and electrochemical energy storage power stations in the region in 2025 are 600 MW, 700 MW, 2400 MW, and 225 MW. Suggestions for follow-up planning are as follows.

With the proposal of "carbon peaking and carbon neutrality goals," the cost of carbon emission was added into the traditional system planning cost, which limited the development of coal and electricity in this region. In addition, with the increase in NERs in the power system, the assessment of NERs abandoned electricity is also becoming more and more important. This paper proves that "generation–grid–load–energy storage" coordination planning can achieve economic optimization on the basis of ensuring that the proportion of NER access meets the requirements of regional NER consumption. Therefore, in order to reduce carbon emissions, ensure an increase in the proportion of NERs, and ensure the balance of power supply and demand, more attention should be paid to the coordinated construction of generation–grid–load–energy storage links.

With the increase in proportion of NERs, in order to solve the problem of insufficient power supply or NER consumption problems caused by the volatility and intermittence, after considering the scale of demand response in this region, it is still necessary to deploy large-scale coal power and electrochemical energy storage power stations for peak shaving and valley filling. Therefore, we suggest that more attention should be paid to the flexible transformation of coal power and the supporting construction of electrochemical energy storage power stations to improve the flexible adjustment ability of the system.

Due to the limited consideration of the technical types of source-side generation units and the response potential of demand-side various types of units in this paper, the next step will be to strengthen the coordination between various types of units on the source side, and consider how to introduce a power market mechanism to achieve better generation-load coordination so that the resources on the load side can become stable. In addition, although the carbon emission cost/environmental protection goal is added to the planning goal, the final planning result is still dominated by a single economic goal. In the future, environmental protection objectives, and economic objectives will be considered together, so as to establish a multi-objective "generation-grid-load-energy storage" coordinated planning model.

Data Availability

The authors confirm that the data supporting the findings of this study are available within the article.

Conflicts of Interest

The authors declare no conflicts of interest.

Acknowledgments

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References

[1] S. a. Zheng and G. Qian, "Overview of hydro-wind-solar power complementation development in China," *Global Energy Interconnection*, vol. 2, no. 4, pp. 285–289, 2019.

[2] J. Li, F. Liu, Z. Li, and C. X. Shao, "Grid-side flexibility of power systems in integrating large-scale renewable generations: a critical review on concepts, formulations and solution approaches," *Renewable and Sustainable Energy Reviews*, vol. 93, pp. 272–284, 2018.

[3] B. A. Frew, S. Becker, M. J. Dvorak, and G. B. M. Z. Andresen, "Flexibility mechanisms and pathways to a highly renewable US electricity future," *Energy*, vol. 101, pp. 65–78, 2016.

[4] X. Zhang, Y. Chen, T. Yu, B. Yang, K. Qu, and S. Mao, "Equilibrium-inspired multiagent optimizer with extreme transfer learning for decentralized optimal carbon-energy combined-flow of large-scale power systems," *Applied Energy*, vol. 189, pp. 157–176, 2017.

[5] X. Zhang, T. Yu, B. Yang, L. Zheng, and L. Huang, "Approximate ideal multi-objective solution Q(λ) learning for optimal carbon-energy combined-flow in multi-energy power systems," *Energy Conversion and Management*, vol. 106, pp. 543–556, 2015.

[6] M. Moradi-Sepahvand and T. Amraee, "Integrated expansion planning of electric energy generation, transmission, and storage for handling high shares of wind and solar power generation," *Applied Energy*, vol. 298, no. 15, Article ID 117137, 2021.

[7] J. Mao, M. Jafari, and A. Botterud, "Planning low-carbon distributed power systems: evaluating the role of energy storage," *Energy*, vol. 238, Article ID 121668, 2022.

[8] Y. Zhou, Q. Zhai, W. Yuan, and J. Wu, "Capacity expansion planning for wind power and energy storage considering hourly robust transmission constrained unit commitment," *Applied Energy*, vol. 302, no. 6, Article ID 117570, 2021.

[9] A. Flores-Quiroz and S. Kai, "A distributed computing framework for multi-stage stochastic planning of renewable power systems with energy storage as flexibility option," *Applied Energy*, vol. 291, Article ID 116736, 2021.

[10] Z. X. Lu, H. B. Li, and Y. Qiao, "Power system flexibility planning and challenges considering high proportion of renewable energy," *Automation of Electric Power Systems*, vol. 40, no. 13, pp. 147–158, 2016.

[11] T. H. Xu, Z. X. Lu, Y. Qiao, and J. An, "High penetration of renewable energy power planning considering coordination of source-load-storage multi-type flexible resources," *Journal of Global Energy Interconnection*, vol. 2, no. 1, pp. 27–34, 2019.

[12] H. B. Li, Z. X. Lu, and Y. Qiao, "Bi-level optimal planning of generation-load-storage integrated generalized flexibility resource," *Automation of Electric Power Systems*, vol. 41, no. 21, pp. 46–54, 2017.

[13] N. Zhang, H. Zhaoguang, S. Cecilia et al., "Source-grid-load coordinated planning model considering randomness and fuzziness," *Automation of Electric Power Systems*, vol. 40, no. 1, pp. 39–44, 2016.

[14] N. Zhang, H. C. Dai, Z. G. Hu et al., "A source-grid-load coordinated planning model considering system flexibility constraints and demand response," *Electric power*, vol. 52, no. 2, pp. 61–69, 2019.

[15] C. Jin, D. W. Ren, J. Y. Xiao et al., "Power system source-grid-storage flexibility resource optimization planning to support carbon neutrality goals," *Electric power*, vol. 54, no. 08, pp. 164–174, 2021.

[16] H. Niu, F. Yu, B. Li, and J. Chen, "Research on operation optimization of integrated energy system," *IOP Conference Series: Earth and Environmental Science*, vol. 267, no. 3, Article ID 032094, 2019.

[17] M. Zeng, "To the clean energy transformation in our country and the two key problems in the process of implementation," *State Grid News*, vol. 1, no. A1, pp. 09–26, 2014.

[18] M. Zeng, "Power planning in a mixed energy context," *Shanghai Securities News*, vol. 1, no. A1, pp. 10–16, 2014.

[19] M. Zeng, Y. Q. Yang, D. N. Liu et al., "Energy Internet 'source - gird - load – storage' coordination optimization operation mode and key technologies," *Power System Technology*, vol. 40, no. 1, pp. 114–124, 2016.

[20] T. J. Pu, K. W. Liu, N. Z. Chen et al., "Design of ADN based urban energy internet architecture and its technological issues," *Proceedings of the CSEE*, vol. 35, no. 14, pp. 3511–3521, 2015.

[21] W. Cai, H. Zhao, J. F. Wang, and L. Chuan, "A unifying network topological model of the energy internet macroscope structure," *Proceedings of the CSEE*, vol. 35, no. 14, pp. 3503–3510, 2015.

[22] S. M Tian, W. P. Luan, D. X. Zhang, and Y Sun, "Energy internet technology forms and key technologies," *Proceedings of the CSEE*, vol. 35, no. 14, pp. 3482–3494, 2015.

[23] B. Liu, Y. Q. Zhang, L. W. Ma et al., "Research on technical scheme design and optimization of integrated energy system of source bases in northwest China," *Proceedings of the CSEE*, vol. 41, no. 02, pp. 568–581, 2021.

[24] M. X. Zhang, T. Yan, X. K. Lai, J. Z Chen, M. Niu, and S. Xu, "Technology vision and route of energy storage under new power grid function configuration," *Power System Technology*, vol. 42, no. 5, pp. 1370–1377, 2018.

[25] D. W. Ren, C. Jin, J. M. Hou et al., "New energy with energy storage replace thermal power planning model based on sequential operation," *Electric power*, vol. 54, no. 07, pp. 18–26, 2021.