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Multi-Flexibility Resources Planning for Power System Considering Carbon Trading

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Abstract: Clean and low-carbon energy represented by wind power and photovoltaic power will develop rapidly and will form a new power system with a high proportion of renewable energy. In the context of a low-carbon economy, how to make reasonable planning for power system flexibility resources is crucial for the development of new power systems. In this paper, we establish a multi-flexibility resource planning model for a power system based on a low carbon economy by considering the planning of multi-flexibility resources of "source–load–storage". First, a ladder-type carbon trading cost accounting model is proposed, and a set of power system flexibility evaluation indexes are proposed. Then, with the objective of minimizing the sum of low carbon operation cost, investment cost, and operation cost of the system, the planning model of multi-flexibility resources is established by considering constraints such as system power balance constraint, investment constraint, and wind power consumption constraint. Finally, the model proposed in this paper is validated by the IEEE-RTS96 system; the results show that: (1) collaborative planning of source–load–storage multi-flexible resources can obtain the best overall system economics, although the investment cost increases by USD 12.6M, the total system cost is reduced by 11.22% due to the reduction in coal generation consumption cost, carbon trading cost, and wind curtailment penalty cost; (2) as the penetration of wind power grows, the demand for energy storage in the power system is gradually increasing; when the installed capacity of wind power grew from 800 MW to 1600 MW, the demand for new thermal power decreased by 53.5% and the demand for new energy storage increased by 200%; (3) the total cost of the planning model considering ladder-type carbon trading decreases by 1.35% compared to the model without carbon trading, and increases by 2.5% compared to the model considering traditional carbon trading, but its carbon emissions decrease by 5.5%.

Keywords: low-carbon economy; carbon trading; power system planning; power system flexibility

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1. Introduction

With the depletion of fossil energy and the gradual intensification of environmental problems, the development of renewable energy has become the mainstream, within which wind power is developing rapidly as one of the most important components. By the end of 2020, the total installed capacity of global wind power had reached 743 GW, with 93 GW of newly installed wind power in 2020, which was an increase of 59% compared to 2019 [1]. With the increase in the penetration of renewable energy sources such as wind and photovoltaic power in the power system, the volatility and uncertainty is also increasing, which leads to a sharply rising demand for flexibility resources. The existing literature has conducted in-depth analyses on a series of issues such as the mechanism of power system flexibility balance [2], evaluation of power system flexibility [3], and operating optimization of multiple flexibility resources [4]. However, existing studies related to flexibility resource planning of power systems have usually ignored carbon emission constraints, which are difficult to apply to the decarbonization transition of a power system.

Therefore, constructing a collaborative planning method for multiple flexibility resources considering carbon trading to promote the decarbonization of the power system is the focus of current research.

All adjustment methods that can cope with fluctuations and uncertainties can become flexibility resources, which mainly include thermal power units on the power supply side, demand response on the load side, and battery storage on the energy storage side. Some studies have been conducted on the operation optimization and planning of various types of flexible resources on the "source–load–storage" side of the power system. In [5], a flexibility resources planning model for medium-term and long-term development was proposed to cope with high uncertainty in the future. The study in [6] divided conventional units into three types of flexible units according to their regulation capability, then proposed a flexible power source expansion planning model considering the wind power consumption target. In [7], a renewable energy power planning model was constructed with the objective of minimizing the full-cycle investment cost by integrating renewable energy with flexibility resources based on a quantitative flexibility assessment method. In [8], a multi-objective transmission grid planning model based on flexibility and economy was proposed considering the economic operation strategy of the system with the objective of minimizing the investment cost and operation cost. Reference [9] presented a power system planning model that balances flexibility and reliability by using thermal power units, energy storage systems, and demand-side response as flexibility resources. Reference [10] used robust optimization to deal with peak load demand and wind capacity uncertainty, and proposes a coordinated planning model for power grid expansion and thermal power flexibility reformation. In [11], considering the real-time flexibility demand and the flexibility supply capability of energy storage, a power supply expansion planning model with the objective of minimizing the investment in renewable energy, energy storage, and thermal power units was proposed. In [12], taking the port microgrid as an example, the integrated operation planning and energy management model of smart microgrid, including energy storage and power demand management, is proposed, and the positive influence of energy storage and demand-side management on the improvement of microgrid operation economy is explored. Although scholars have conducted sufficient research on power system flexibility resource optimization and planning, there are few studies on flexibility resource planning methods considering carbon trading.

In the context of the low-carbon transition of the whole society, scholars have conducted in-depth research on carbon management from various perspectives, including industry, energy, logistics, and the built environment. Reference [13] established a Computable General Equilibrium model to analyze the impact of different carbon emission trading schemes on the electricity industry and determine the best choice of carbon quota allocation scheme for the electricity industry in China. Focusing on carbon pricing rules in Germany's road transport and housing sector, Reference [14] examines three possible options for reimbursing carbon revenues, including a per-capita reallocation to private households, the reduction of electricity prices by decreasing the electricity tax, and increasing housing benefits. Reference [15] studied the impact of carbon trading on the power industry and provided ideas for power grids to adhere to a low-carbon and environmentally friendly development route.

As one of the measures to effectively reduce carbon emissions, carbon trading is used as a mechanism to trade emission rights through carbon allowances, and the cost of carbon trading is included in the power system dispatch cost to achieve low carbon goals with the help of economic leverage [16]. The paper [17] analyzed the impact of carbon trading on the energy costs of thermal power generation units. The paper [18] introduced carbon trading cost into the objective function and applied stochastic programming theory to propose a dispatching model that considers both economy and low carbon. Reference [19] introduced a carbon trading mechanism in the model to improve the wind power acceptance capacity, and proposed an optimization model for wind power consumption based on carbon trading. Reference [20] introduced carbon trading costs in a system with large-scale PV access and established a low-carbon economic dispatch model for a system containing large-scale PV. Reference [21] conducted a systematic literature review and analyzed the operational strategies and technical means to improve the energy efficiency and carbon reduction benefits of ports and terminals, and studied the low-carbon transformation of integrated port energy systems.

While the existing literature has made some progress in flexible resource planning and low-carbon operation of power systems, there are still some shortcomings: (1) Existing studies only consider one or two flexibility resources, however, with the increasing penetration of renewable energy, a single flexibility resource is no longer sufficient to meet the flexibility needs of the power system. (2) Existing studies have failed to adequately consider the negative impact of carbon emissions from power system operation on the global environment when conducting flexibility resource planning.

To sum up, a planning model that integrates multiple flexibility resources, such as source–load–storage, is the key to solving the problem of insufficient flexibility caused by a high proportion of renewable energy in the future; meanwhile, incorporating a reasonable carbon trading mechanism into the flexibility resource planning model is an effective way to achieve a low-carbon power system.

The main contributions of this paper are summarized as follows.

(1) Based on the traditional carbon trading model, a ladder-type carbon trading model considering carbon emissions is proposed, which will make low-emission units more competitive and minimize system carbon emissions while ensuring system economics.
(2) Based on the technical mechanism of multi-flexibility resources, a comprehensive flexibility evaluation index system is proposed, which enables a comprehensive evaluation of the planning results of the power system's multiple flexibility resources.
(3) With the objective of minimizing the sum of operation cost and investment cost of the system, the multi-flexibility resource planning model of the power system under carbon trading is established considering the system power balance constraint, investment constraint, wind power consumption constraint, and other constraints.

The rest of the paper is organized as follows. Section 2 constructs the ladder-type carbon trading model. The flexibility evaluation indexes of power system operation are introduced in Section 3. Section 4 presents the carbon trading-based multi-flexibility resource planning model. Section 5 presents the case study of the IEEE-RTS96 system, in which the impact of different flexibility resources allocation schemes, wind power access capacity, and different carbon trading models on the power system planning result is analyzed. Finally, Section 6 concludes the paper.

2. Modeling of Carbon Trading Costs

Considering the "low carbonization" requirement of the future power system, carbon allowance and carbon trading costs need to be considered in the optimization model. During the operation of the power system, thermal power units burning coal to generate electricity are the main source of carbon emissions. Sources such as hydropower, wind power, photovoltaic power, and energy storage produce almost no carbon emissions during power system operation. Therefore, in this paper, only the carbon emissions of thermal power units are modeled. Considering that the power carbon trading market is in its initial stage, this paper adopts a carbon emission allowance allocation method based on power generation, and the main idea is that the baseline method is used to determine the carbon emission allowance of the market player based on the average emission intensity of the power industry and the actual power generation amount of the market player.

$$CE_C = \eta \sum_{t=1}^{T} \sum_{i=1}^{N_G} P_{i,t} \tag{1}$$

where CE_C is the carbon allowance allocated to the power system, N_G is the number of thermal units, $P_{i,t}$ is the output of thermal unit i at time t, T is the dispatch period, η is the carbon allowance per MW of the unit output.

The reference [22] gave a method for calculating carbon emissions from thermal power units in power systems, where the actual carbon emissions are determined by the following equation:

$$CE_A = \sum_{t=1}^{T} \sum_{i=1}^{N_G} \left(\alpha_i P_{i,t}^2 + \beta_i P_{i,t} + \lambda_i \right) \tag{2}$$

where CE_A is the actual carbon emissions of thermal units, α_i, β_i and λ_i are carbon emission factors of thermal power unit i.

The carbon trading cost of a power system is related to the carbon trading volume of the system, which is generally based on the net emissions of the system, i.e., the difference between the carbon emissions of the system and the carbon emission allowances as the carbon trading amount of the system. After calculating the net carbon emissions, the traditional carbon trading model generally takes Equation (3) to calculate the carbon trading cost. It indicates that if the system's carbon emissions are smaller than the carbon emission allowances in a certain time, the remaining credits can be sold to gain revenue; if the system carbon emissions are larger than the carbon emission allowance, it needs to pay extra to buy the allowance.

$$C_C = f^C \Delta CE = f^C (CE_A - CE_C) \tag{3}$$

where f^C is the carbon trading price per unit of carbon emissions, ΔCE indicates the net carbon emissions.

In order to further control carbon emissions and guide the power system toward low-carbon and clean development, this paper adopts a ladder-type carbon trading model [23,24] to divide the system carbon trading cost into more detailed intervals. An incentive factor is introduced to characterize the government subsidy when the system carbon emissions are lower than the carbon allowance; a penalty factor is introduced to characterize the higher carbon trading cost when the system needs to purchase carbon allowance. The ladder-type carbon trading cost model constructed in this paper takes the net carbon emissions of the power system as the interval division criterion, and the net carbon emissions are linearized in segments when solving the model. The mathematical expression of the model is shown in Equation (4).

$$C_C = \begin{cases} f^C(1+3\mu)(\Delta CE + 2d) - f^C(2+3\mu)d & \Delta CE \le -2d \\ f^C(1+2\mu)(\Delta CE + d) - f^C(1+\mu)d & -2\mathrm{d} < \Delta CE \le -d \\ f^C(1+\mu)\Delta CE & -\mathrm{d} < \Delta CE \le 0 \\ f^C \Delta CE & 0 < \Delta CE \le d \\ f^C(1+\lambda)(\Delta CE - d) + f^C d & \mathrm{d} < \Delta CE \le 2d \\ f^C(1+2\lambda)(\Delta CE - 2d) + f^C(2+\lambda)d & \Delta CE > 2d \end{cases} \tag{4}$$

where C_C is the carbon trading cost of the power system under the ladder-type carbon trading model; μ and λ are respectively the incentive and penalty factors when the net carbon emissions of the system are less than or greater than the carbon emission allowance; and d is the length of the interval of segmented carbon emissions.

The relationship between carbon trading price and net carbon emissions in the above carbon trading cost calculation model is shown in Figure 1. The solid blue line indicates the "Ladder-type carbon trading model", and the red dashed line indicates the "traditional carbon trading model". A positive net carbon emission means that the system is short of carbon allowances and needs to purchase additional allowances from the carbon trading market; a negative net carbon emission means that the system has a surplus of carbon allowances and can sell the surplus for a profit. By comparison, when the system carbon emission allowance is insufficient, the system needs to accept extra penalties by using the ladder-type carbon trading cost model rather than the traditional carbon trading cost model; when there is a surplus of the system carbon emission allowance, the system can get more benefits by using the ladder-type carbon trading cost model rather than the traditional carbon trading cost model. Thus, compared with the traditional carbon trading cost model, the ladder-type carbon trading cost model used in this paper has stronger sensitivity and identification accuracy for the carbon reduction efforts or excess carbon emissions of the power system.

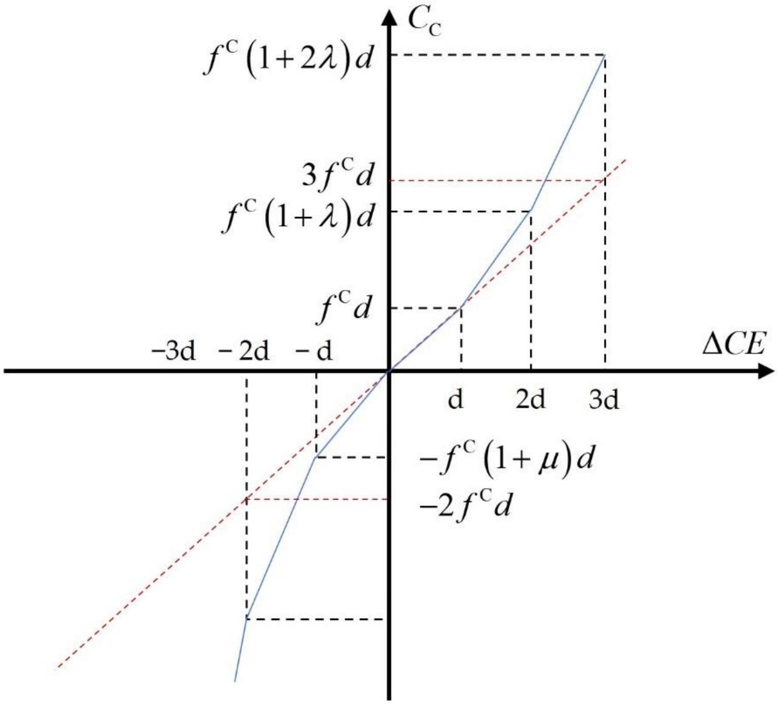

Figure 1. The relationship between carbon trading price and net carbon emissions.

3. Flexibility Evaluation Index of Power System

The power system flexibility evaluation index is mainly used to measure the operational flexibility of the power system and evaluate the effect of various types of flexibility resources in each stage of operation, so that the optimization results of the model can be evaluated and analyzed. In this paper, we propose electricity loss of upward flexibility insufficient (ELUFI), electricity loss of downward flexibility insufficient (ELDFI), power curtailment rate of upward flexibility insufficient (PCRUFI), and power curtailment rate of downward flexibility insufficient (PCRDFI).

The flexibility resources studied in this paper come from the thermal power units, demand response, and energy storage, and the flexibility supply capacity is shown in Equation (5). The flexibility demand of the power system mainly considers the load fluctuation, load, and wind power forecast inaccuracy, which is calculated as shown in Equation (6).

$$\begin{cases} P_{G,t}^{up} = P_{g,t}^{up} + P_{L,t}^{up} + P_{B,t}^{up} \\ P_{G,t}^{down} = P_{g,t}^{down} + P_{L,t}^{up} + P_{B,t}^{up} \end{cases} \tag{5}$$

$$\begin{cases} P_{R,t}^{up} = (L_{t+1} - L_t) + \xi_{up} L_{t+1} + \lambda_{up} P_{W,t+1} & \text{if } L_{t+1} \geq L_t \\ P_{R,t}^{down} = (L_t - L_{t+1}) + \xi_{down} L_{t+1} + \lambda_{down} P_{W,t+1} & \text{if } L_{t+1} < L_t \end{cases} \tag{6}$$

where $P_{G,t}^{up}$ and $P_{G,t}^{down}$ are upward and downward supply capacity of the flexibility resource, $P_{R,t}^{up}$ and $P_{R,t}^{down}$ are the upward and downward flexibility requirements of the power system, L_t is the system load forecast at time t, $P_{W,t}$ is the predicted output of wind power at moment t, ξ_{up} and ξ_{down} are the upward and downward flexibility demand factors due to load forecast errors, λ_{up} and λ_{down} are the upward and downward flexibility demand factors due to wind power forecast errors.

3.1. Electricity Loss of Flexibility Insufficient

Electricity loss of flexibility insufficient is the cumulative value of load electricity loss or renewable energy curtailment due to the upward and downward flexibility demand being greater than the flexibility resource supply capacity in the statistical cycle.

$$E_L = \sum_{t=1}^{T} \Delta P_t^{up} \mathrm{sgn}\left\{ P_{R,t}^{up} - P_{G,t}^{up} \right\} \tag{7}$$

$$E_R = \sum_{n=1}^{T} \Delta P_t^{down} \mathrm{sgn}\left\{ P_{R,t}^{down} - P_{G,t}^{down} \right\} \tag{8}$$

where E_L and E_R are electricity loss of upward flexibility insufficient and electricity loss of downward flexibility insufficient, ΔP_t^{up} is the electricity loss at time t, ΔP_t^{down} is the curtailed power of renewable energy at time t.

3.2. Power Curtailment Rate of Flexibility Insufficient

Power curtailment rate of flexibility insufficient is the ratio of the accumulated value of electricity loss to the total load electricity demand or the ratio of renewable energy curtailment power to renewable electricity generation due to the upward and downward flexibility demand being greater than the flexibility resource supply capacity.

$$\eta_{up} = \frac{\sum_{t=1}^{T} \Delta P_t^{up} \mathrm{sgn}\left\{ P_{R,t}^{up} - P_{G,t}^{up} \right\}}{\sum_{t=1}^{T} L_t} \tag{9}$$

$$\eta_{down} = \frac{\sum_{t=1}^{T} \Delta P_t^{down} \mathrm{sgn}\left\{ P_{R,t}^{down} - P_{G,t}^{down} \right\}}{\sum_{t=1}^{T} P_{E,t}} \tag{10}$$

where η_{up} and η_{down} are power curtailment rate of upward flexibility insufficient and power curtailment rate of downward flexibility insufficient, $P_{E,t}$ is the power output of renewable energy generation at time t.

4. Carbon Trading Based Multi-Flexibility Resource Planning Model

4.1. Framework of the Planning Model

The main purpose of power system flexibility resource planning is to obtain the investment decision plan for new flexibility resources in the planning year, so that the system can meet the requirements of economy and flexibility at the same time. The planning target may include both thermal and hydropower sources that can meet the power demand, and there may be a variety of flexibility resources involved in the planning, such as energy storage and demand response resources used to meet the flexibility demand of the system.

The flowchart of the power system multi-flexibility resource planning model is shown in Figure 2. The model mainly considers the planning of thermal power units, energy storage and interruptible load, with the objective of minimizing the total annual cost of the whole power system; it considers constraints such as unit operation constraints, energy storage operation constraints, interruptible load constraints, wind power consumption constraints, and investment ceiling constraints. The model takes the original system parameters, load and wind power typical scenario data, and parameters of the flexibility resources to be built as inputs; optimizes the variables such as the type and number of flexibility resources to be built, all unit output, energy storage output, and interruptible load interruption. The final output is the type and number of flexibility resources to be built, the system operation economy index, and the system operation flexibility index.

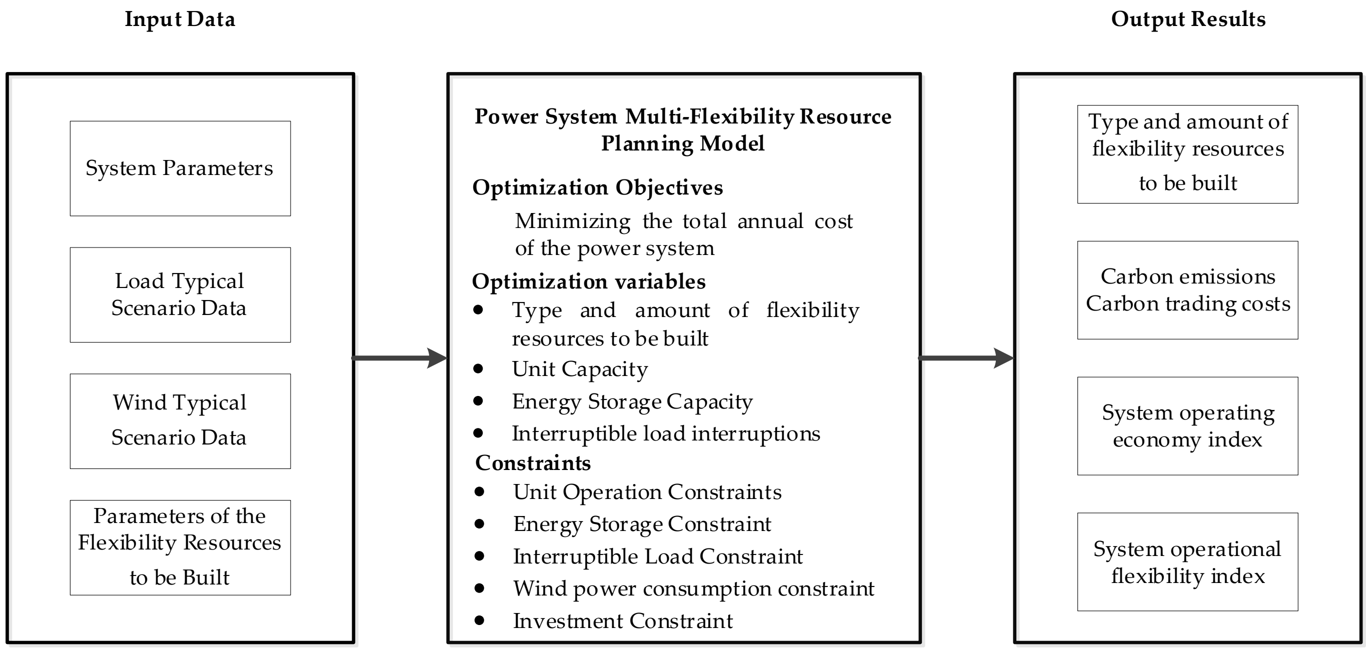

Figure 2. The flowchart of the power system multi-flexibility resource planning model.

4.2. Objective Function

The multi-flexible resource capacity planning model of the power system under the low carbon economy is aimed at minimizing the total annual cost of the power system, which includes the investment cost of thermal units, energy storage, interruptible load, and the total operating cost of the system. The specific mathematical expression of the objective function is shown in Equation (11).

$$\text{Min.}C = C_{\text{IV}} + C_{\text{OP}} \tag{11}$$

where C is the total annual cost of the power system, C_{IV} is the annual value of the total investment cost for flexibility resources, and C_{OP} is the annual operating cost of the power system.

4.2.1. Investment Cost of Flexibility Resources

Since this paper focuses on the expansion planning of thermal power, energy storage, and interruptible load, the investment cost of flexibility resources consists of the investment cost of conventional thermal power, energy storage, and interruptible load together, and the specific mathematical expressions are shown below.

$$C_{\text{IV}} = C_{\text{G,IV}} + C_{\text{T,IV}} + C_{\text{D,IV}} \tag{12}$$

where $C_{\text{G,IV}}$ is the equivalent annual value of investment cost for new thermal units, $C_{\text{T,IV}}$ is the equivalent annual value of investment cost for new energy storage devices, and $C_{\text{D,IV}}$ is the equivalent annual value of investment cost for new interruptible load.

$$C_{\text{G,IV}} = \sum_{i \in \Omega_G} x_i C_i G_i \delta_{\text{CRF}}(r, Y_G) \tag{13}$$

$$C_{\text{T,IV}} = \sum_{j \in \Omega_T} y_j (k_P P_j + k_E E_j) \delta_{\text{CRF}}(r, Y_{\text{T}}) \tag{14}$$

$$C_{\text{D,IV}} = \sum_{m \in \Omega_D} z_m Q_m P_m \delta_{\text{CRF}}(r, Y_D) \tag{15}$$

$$\delta_{\mathrm{CRF}}(r,Y)=\frac{r(1+r)^{Y}}{(1+r)^{Y}-1} \tag{16}$$

where Ω_G, Ω_T, and Ω_D denote the set of thermal units, the set of energy storage, and the set of interruptible loads to be selected, respectively; the binary variables x_i, y_j, and z_m indicate whether the thermal units, energy storage, and interruptible loads are put into construction; C_i is the construction cost per unit capacity of candidate thermal power unit i; G_i is the installed capacity of the candidate thermal power unit i; k_P and k_E are the price per unit power and per unit capacity of energy storage; Q_m is the investment cost per unit capacity of interruptible load; P_m is the power demand of the candidate interruptible load m; $\delta_{\mathrm{CRF}}(r,Y)$ is the equal annual value factor, whose value is related to the operating life of each flexible resource Y and the discount rate r.

4.2.2. Operation Costs

The total operating costs of the system include energy generation costs, start-up and shutdown costs, carbon trading costs, wind curtailment penalty costs, and load interruption compensation costs, which are calculated as shown in Equation (17).

$$C_{\mathrm{OP}}=C_G+C_{QT}+C_C+C_{QW}+C_{DR} \tag{17}$$

where, C_G is the operation cost of thermal power units, and its value includes the operation cost of original units and new units; C_{QT} is start-up and shutdown costs of thermal power units; C_C is carbon trading costs; C_{QW} is wind curtailment penalty costs; C_{DR} is load interruption compensation costs for users who participate in demand response.

$$C_{\mathrm{G}}=N_T\sum_{s=1}^{N_S}\left[\rho_s\sum_{t=1}^{T}\left(\sum_{i=1}^{N_G}\left(a_i {P_{s,i,t}^{\mathrm{G}}}^2+b_iP_{s,i,t}^{\mathrm{G}}+c_iu_{s,i,t}^{\mathrm{G}}\right)+\sum_{j\in\Omega_G}x_j\left(a_j{P_{s,j,t}^{\mathrm{G}}}^2+b_jP_{s,j,t}^{\mathrm{G}}+c_ju_{s,j,t}^{\mathrm{G}}\right)\right)\right] \tag{18}$$

$$C_{QT}=N_T\sum_{s=1}^{N_S}\left[\rho_s\left(\sum_{t=1}^{T}(\sum_{i=1}^{N_G}u_{i,s,t}^{G}(1-u_{i,s,t-1}^{G})S_{QT,i}+\sum_{j\in\Omega_G}u_{j,s,t-1}^{G}(1-u_{j,s,t-1}^{G})S_{QT,j})\right)\right] \tag{19}$$

$$C_{QW}=Q_W\times N_T\sum_{s=1}^{N_S}\sum_{t=1}^{T}\rho_sP_{W,s,t}^{LOSS} \tag{20}$$

$$C_C=N_T\sum_{s=1}^{N_S}\rho_sC_{C,s} \tag{21}$$

$$C_{DR}=N_T\sum_{s=1}^{N_S}\rho_s\sum_{t=1}^{T}\left(\sum_{n=1}^{N_{IL}}K_nP_{n,s,t}^{IL}+\sum_{j\in\Omega_D}K_nP_{j,s,t}^{IL}\right) \tag{22}$$

where, N_T is the total statistical period; ρ_s is the probability of the scenario s; N_G is the number of existing generating units; $u_{i,s,t}^{G}$ is the operating state of thermal power unit i at time t under scenario s; a_i, b_i, and c_i are the energy cost coefficients for generation of thermal power unit i; $S_{QT,i}$ is the start-up and shutdown cost of thermal power unit i; Q_W is the cost factor of wind curtailment penalty; $P_{W,s,t}^{LOSS}$ is the curtailed wind power at the time t under scenario s; $P_{n,s,t}^{NL}$ is the interrupted load power of user n at time t under scenario s; K_n is the coefficient for load interruption compensation.

4.3. The Constraints

The constraints of the multi-flexible resource capacity planning model of power system under low carbon economy include system power balance constraint, investment constraint, wind power consumption constraint, energy storage operation constraint, transferable load constraint, interruptible load constraint, etc.

(1) System power balancing constraints

$$\sum_{i\in\Omega_{GS}} P^{G}_{i,s,t} + P_{W,s,t} + \sum_{j\in\Omega_{BS}} P_{B,j,s,t} + \sum_{n\in\Omega_{IL}} \mu_{n,s,t} P^{IL}_{n,s,t} = P_{L1,t} + L_{TLin,s,t} - L_{TLout,s,t} \quad (23)$$

where $P_{W,s,t}$ is the output of wind farm at time t under scenario s; $P_{B,j,s,t}$ is the output of energy storage j at time t under scenario s; $P^{G}_{i,s,t}$ is the output of thermal power unit i at time t under scenario s; Ω_{GS} is the set of thermal power units, which includes the exciting units and candidate units; Ω_{BS} is the set of energy storage; Ω_{IL} is the set of interruptible load; $\mu_{n,s,t}$ is the load interruption state variable of user n at time t under scenario s; $L_{TLin,s,t}$ and $L_{TLout,s,t}$ are the transferred-in and transferred-out load power at time t under scenario s.

(2) Flexibility Resource Investment Constraints

$$\sum_{i\in\Omega_G} x_i C_i G_i + \sum_{j\in\Omega_T} y_j(k_P P_j + k_E E_j) + \sum_{m\in\Omega_D} z_m Q_m(q_P P_m + q_E D_m) \le I_{\max} \quad (24)$$

where $I_{\max}$ is the upper limit of total investment in flexibility resources.

(3) Wind Power Consumption Constraints

$$\sum_{s=1}^{N_S}\sum_{t=1}^{T} P^{LOSS}_{W,s,t} / \sum_{s=1}^{N_S}\sum_{t=1}^{T} P_{W,s,t} \le D_W \quad (25)$$

where, D_W is the maximum allowable wind curtailment rate of the power system.

(4) Energy Storage Operating Constraints

Equation (26) is the energy state constraint of the energy storage device; Equation (27) is the battery storage power balance constraint; Equation (28) indicates that the beginning and end residual capacities of the energy storage device need to be kept equal.

$$S_{\mathrm{BESS,min}} \le S_{\mathrm{BESS},s,t} \le S_{\mathrm{BESS,max}} \quad (26)$$

$$\max(-P_B, \frac{E_{B,s,t} - E_B}{\Delta t}\eta_d) \le P_{B,s,t} \le \min(-P_B, \frac{E_{B,s,t} - E_{B,\min}}{\Delta t \eta_c}) \quad (27)$$

$$E_{\mathrm{B},0} = E_{\mathrm{B,T}} \quad (28)$$

where, $E_{B,s,t}$ is the value of the power stored in the battery at time t under scenario s; $S_{\mathrm{BESS},s,t}$ is the state of charge of the battery energy storage at time t in scenario s.

In this paper, the degradation of the load storage system is not considered, thus reducing the difficulty of solving the model.

(5) Constraints of Transferable Load

When customers participate in demand response, the load demand of each time period will change with the price of electricity, but customers do not change the electricity consumption of the whole time period, and only adjust the electricity consumption of each time period. So, it is necessary to meet the electricity conservation constraint of customers.

$$\sum_{t=1}^{T} L_{TLin,s,t} = \sum_{t=1}^{T} L_{TLout,s,t} \quad (29)$$

The amount of power load transferred during each period cannot exceed the maximum load capacity that can be transferred.

$$L_{TLin,s,t} \le L_{TLin,\max} \quad (30)$$

$$L_{TLout,s,t} \le L_{TLout,\max} \quad (31)$$

where $L_{Tin,\max}$ indicates the maximum electric load capacity that can be transferred in; $L_{Tin,\max}$ indicates the maximum electric load capacity that can be transferred out.

(6) Constraints of Interruptible Load

Equation (32) is the load interruption amount constraint at time t, Equation (33) is the interruption time constraint, and Equation (34) is the interrupt count constraint.

$$P_n^{\text{IL.min}} \leq P_{n,s,t}^{\text{IL}} \leq P_n^{\text{IL.max}} \tag{32}$$

$$\begin{cases} \left(T_{n,s,t-1}^{on} - T_{n,\min}^{on}\right)(\mu_{n,s,t-1} - \mu_{n,s,t}) \geq 0 \\ T_{n,s,t}^{on} \leq T_{n,\max}^{on} \end{cases} \tag{33}$$

$$\sum_{t=2}^{T} (1 - \mu_{n,s,t-1})\mu_{n,s,t} \leq N_n^{\text{IL.max}} \tag{34}$$

where $P_n^{\text{IL.min}}$ and $P_n^{\text{IL.max}}$ denote the maximum and minimum interrupted electrical power demand of customer n at time t; $T_{n,s,t}^{on}$ denotes the duration time of the continuous interruption of the interruptible user n at time t under scenario s; $T_{n,\min}^{on}$ and $T_{n,\max}^{on}$ are the minimum and maximum interruption time for user n; $N_n^{\text{IL.max}}$ is the maximum number of interrupts for user n.

5. Case Study

In this paper, the modified IEEE-RTS96 system [25] is used to carry out a case study. The number of exciting thermal power units is 26, the total installed capacity of thermal power is 3105 MW, the maximum system load is 4800 MW, and the system load curve is shown in Figure 3. The capacity of exciting energy storage is 50 MW/150 MWh, and the charging and discharging efficiency of which is 90%; detailed data on energy storage are shown in [26]. The maximum wind curtailment rate D_W of the power system is 5%, Q_W takes the value of 40 USD/MWh [27]. The system has three exciting interruptible load users, each with an interruptible capacity of 60 MW, a maximum interruption time of 3 h, and a minimum interruption time of 1 h; the compensation cost of load interruption for the user is 40 USD/MWh [28]. The installed capacity of the existing wind farms in the system is 1200 MW, the typical scenes of wind power output are obtained by K-means clustering, and the results are shown in Figure 4. The upward and downward flexibility demand factors from load forecasting errors are $\xi_{up} = \xi_{down} = 0.05$, and the upward and downward flexibility demand factors from wind forecasting errors are $\lambda_{up} = \lambda_{down} = 0.01$. According to the carbon emission factor data of the power grid in the "Notice on the Key Work Related to the Management of Enterprise Greenhouse Gas Emissions Reporting in 2022" issued by the Ministry of Ecology and Environment of People's Republic of China [29], the carbon emission allowance per unit of power generation is set at 0.5810tCO$_2$eq/MWh, the carbon trading price of 30 USD/t, and the incentive and penalty factors of carbon trading are set at $\mu = 0.2$ and $\lambda = 0.25$, respectively. The parameters of thermal power, energy storage, and interruptible load to be built are shown in Table 1, and the social average discount rate takes the value of 0.08. The MATLAB platform is used to employ CPLEX to solve the model proposed in this paper, and the overall computation time is less than 5 min.

Since wind power output is characterized by randomness and uncertainty, it is impossible to analyze and evaluate every wind power output scenario in the analysis process, and cluster analysis, as an effective tool for cutting scenarios, can solve this problem well. In this paper, the K-means clustering algorithm is used to cluster the wind power output scenarios. Based on the one-year wind power generation data of a wind farm in western China, the number of target clusters is set to six, and the six typical clustering output curves and the corresponding scenario probabilities are shown in Figure 4.

There are three types of flexibility resources that can be selected to be built, which includes thermal power units, battery energy storage devices, and interruptible load. Thermal power units have a selectable capacity from 20 MW to 400 MW, and their annual value of per unit capacity investment is 65,000 USD/MW. Battery energy storage has a selectable capacity from 50 MW/150 MWh and 150 MW/450 MWh, and its annual value of per unit capacity investment is (16,500 USD/MW)/(22,000 USD/MWh). Interruptible load has a selectable capacity of 30 MW/90 MWh and 60 MW/180 MWh, and its annual value of per unit capacity investment is (10,000 USD/MW)/(90 USD/MWh). The detailed investment data of thermal power units and energy are shown in [27], and the detailed investment data of interruptible load are shown in [28].

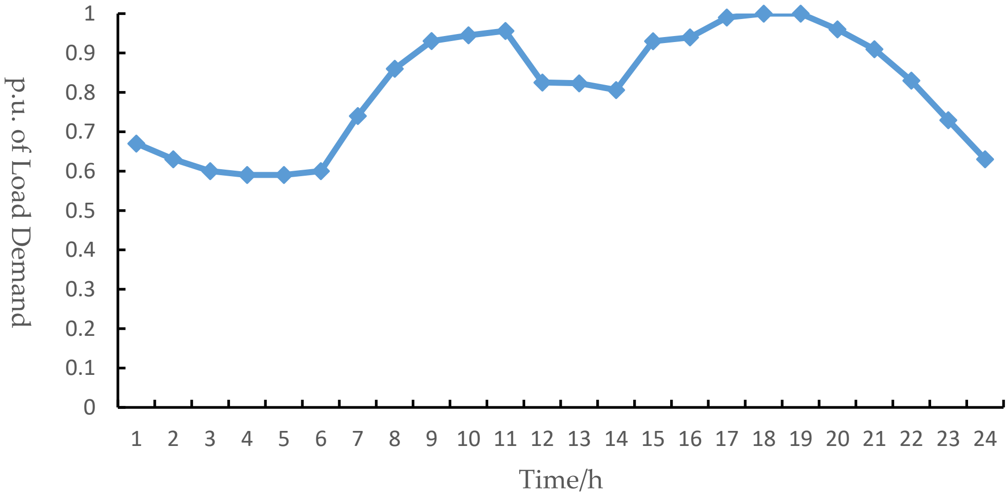

Figure 3. Load power forecast p.u. curve.

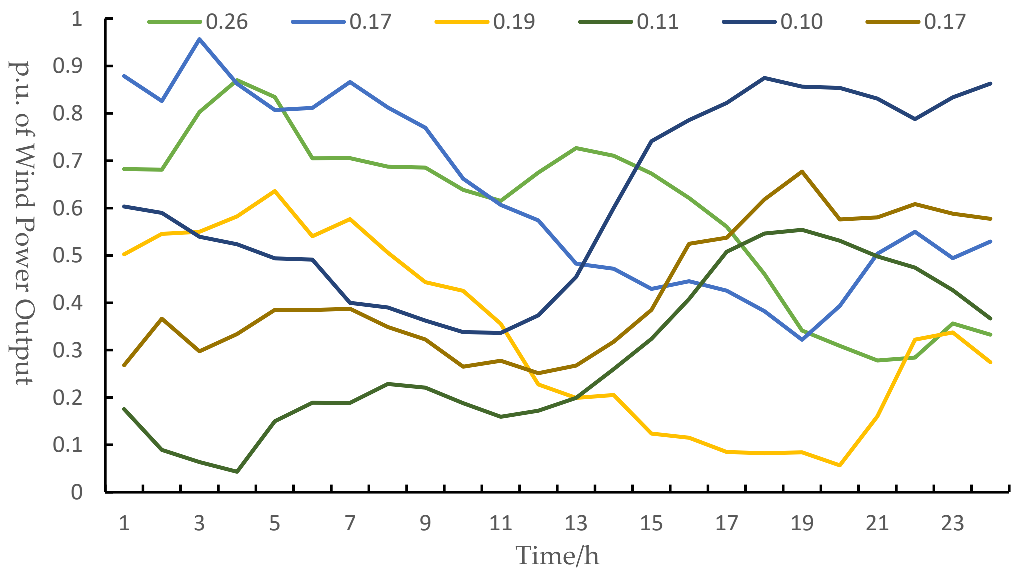

Figure 4. Typical Scenes of Wind Power Output Obtained by K-means Clustering.

Table 1. Parameters of flexibility resources to be built.

	Thermal Power	Energy Storage	Interruptible Load
Selectable Capacity (MW/MWh)	20, 50, 100, 200, 400	50/150, 150/450	30/90, 60/180
Annual Value of Per Unit Capacity Investment (USD/MW)/(USD/MWh)	65,000	16,500/22,000	10,000/90

5.1. Impact of Different Flexibility Resources on Power System Planning

In order to deeply explore the impact of different flexibility resources on power system expansion planning, this paper compares and analyzes the system planning results under the following four scenarios.

Scenario 1: Consider thermal power only as a flexibility resource for expansion planning.

Scenario 2: Consider thermal power and energy storage as flexibility resources for expansion planning.

Scenario 3: Consider thermal power and demand response as flexibility resources for expansion planning.

Scenario 4: Consider thermal power, energy storage, and demand response as flexibility resources for expansion planning.

According to the calculation results, the planned unit types and capacities under each scenario are shown in Figure 5, and the economic indicators as well as the flexibility evaluation indicators are shown in Tables 2 and 3, respectively.

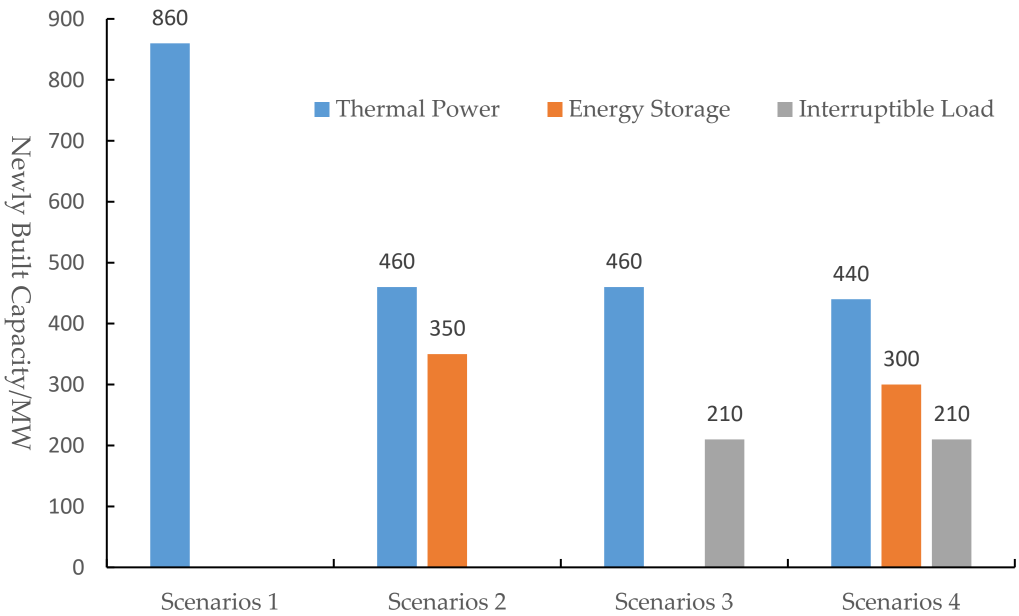

Figure 5. Unit types and capacities for flexibility resource planning in different scenarios.

Table 2. Economic indicators corresponding to each flexibility resource planning scheme.

Cost/($\$10^6$)	Scenario1	Scenario 2	Scenario 3	Scenario 4
Total cost	2160.1	1962.5	1959.5	1917.6
Investment cost	55.9	58.8	32.1	68.5
Operation cost	2104.2	1903.7	1927.4	1849.1
Coal consumption cost	1727.2	1708.2	1707.0	1673.0
Start-up and shutdown cost	54.0	51.1	46.8	34.3
Carbon trading cost	171.6	133.8	145.9	119.1
Wind curtailment penalty cost	6.9	0	5.1	0
Penalty for loss of load	133.8	0	0	0
Load interruption cost	10.6	10.6	22.7	22.7

Table 3. Flexibility evaluation metrics for each flexibility resource planning scheme.

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
ELUFI /(10^6 kW)	66	27	0	0
PCRUFI	0.23%	0.09%	0	0
ELDFI /(10^6 kW)	241	0	185	0
PCRDFI	4.1%	0	3.0%	0

Table 2 shows the economic indicators corresponding to each flexibility resource planning scheme, which shows the total annual cost of the power system and the detailed investment cost of the flexibility resource, operation cost of power system, carbon trading cost, etc.

There are 4 types of flexibility evaluation metrics in Table 3: electricity loss of upward flexibility insufficient (ELUFI), electricity loss of downward flexibility insufficient (ELDFI), power curtailment rate of upward flexibility insufficient (PCRUFI), and power curtailment rate of downward flexibility insufficient (PCRDFI).

Combining Figure 5 and Tables 2 and 3, it can be seen that under the expansion planning scenario considering only thermal power as a flexibility resource, on the one hand, without the addition of new energy storage and demand response resources, the system does not have sufficient up-regulation as well as down-regulation capacity, making the system appear to have insufficient up-regulation and down-regulation flexibility, and the up-regulation and down-regulation insufficient curtailment rates reach 0.23% and 4.1%, respectively. On the other hand, due to the large number of thermal units and lack of sufficient flexibility resources, although there is a reduction in investment costs, the system curtailment penalty costs, carbon trading costs, generation costs, and start-up and shutdown costs have increased, making the total system costs increase accordingly.

In Scenario 2, the installation of new energy storage increases the flexible regulation capacity of the system, and compared with Scenario 1, the wind curtailment phenomenon is significantly improved, and the system operation cost and carbon trading cost are also reduced, but the construction cost of energy storage is relatively high, which makes the investment cost increase.

In Scenario 3, the new interruptible load increases the up-regulation capacity, which can reduce the thermal power start-up and improve the system's load loss phenomenon, while the new demand for thermal power decreases, and the system operation cost, carbon trading cost, and start-up and shutdown cost are reduced, but the system wind curtailment phenomenon is still relatively serious, and the annual curtailment rate reaches 3.0%.

In Scenario 4, the best overall system economics are achieved by planning for the three kinds of flexibility resources. Compared with Scenario 1, although the investment cost increases by USD 12.6M, the total system cost is reduced by 11.22% due to the reduction of coal generation consumption cost, carbon trading cost, and wind curtailment penalty cost. At the same time, the system does not experience a shortage of upward and downward flexibility due to the addition of energy storage and interruptible load to meet the system flexibility needs.

It can be seen that integrated planning for multiple types of flexibility resources is more competitive in terms of system economics and operational flexibility than planning for a single resource or two resources.

5.2. Analysis of Optimization Results for Different Access Wind Power Capacity

In order to study the impact of installed wind power capacity on the optimization results, we set the wind power installation in the 800–1600 MW variation to get the system in different wind power capacities access to the operational economic indicators shown in Table 4. Figure 6 shows the planning type and capacity of flexibility resources under different wind power access capacities.

Table 4. System economic indicators for different access wind power capacity.

Wind Capacity/MW	800	1000	1200	1400	1600
Total cost/(USD 10^6)	2193.3	2061.1	1917.6	1802.3	1742.2
Investment cost/(USD 10^6)	70.4	61.6	68.5	59.6	65.3
Operation cost/(USD 10^6)	2122.9	1999.6	1849.1	1742.6	1676.9
Coal consumption cost/(USD 10^6)	1884.7	1785.9	1673.0	1566.5	1494.1
Start-up and shutdown cost/(USD 10^6)	36.5	35.3	34.3	33.2	32.2
Carbon trading cost/(USD 10^6)	179.0	155.7	119.1	117.8	115.2
Wind curtailment penalty cost/(USD 10^6)	0	0	0	2.5	12.8
Penalty for loss of load	0	0	0	0	0
Load interruption cost/(USD 10^6)	22.7	22.7	22.7	22.7	22.7

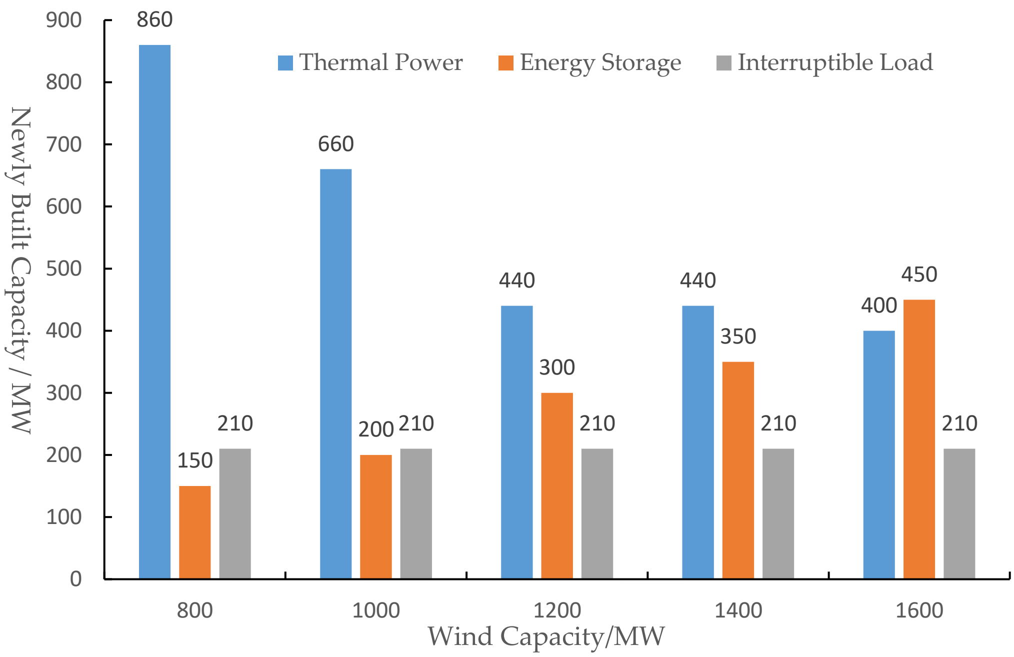

Figure 6. Impact of different wind capacities on flexibility resource planning results.

Combined with Table 4 and Figure 6, the total system cost shows a gradual decrease with the increase in wind power capacity. When the system accesses wind power capacity from 800 MW to 1400 MW, on the one hand, wind power, as a clean energy source, gradually increases with its access capacity, and the new demand for thermal power units gradually decreases, which makes the system power generation cost and carbon trading cost also gradually decrease due to the substitution effect of clean energy on fossil energy. On the other hand, wind power has certain anti-peaking characteristics, and the new wind power installation increases the flexibility demand of the system, so the energy storage planning capacity increases. When the wind power capacity increases to 1600 MW and the wind power penetration rate reaches 40%, the energy storage required to match the system also increases significantly, and the newly built energy storage capacity reaches 450 MW, so the investment cost of the system also increases significantly, and a small amount of wind curtailment phenomenon occurs in the system.

The more the wind power penetration rate increases, the more flexibility resources the system needs to match due to the increase in flexibility demand brought by it. In the future scenario of a high percentage of renewable energy, when the penetration rate of wind and other resources is getting higher, it is more necessary to have sufficient flexibility resources to ensure the stable operation of the system and the consumption of renewable energy.

5.3. Analysis of Optimization Results for Different Carbon Trading Models

In order to illustrate the rationality of the established ladder-type carbon trading model in this paper, the following three kinds of power system planning models are compared: (1) traditional power system planning model, where carbon trading cost is not considered in the objective function, and the carbon trading cost is calculated after the results are obtained; (2) power system planning model based on carbon trading, where the carbon trading cost is calculated by $C_{\mathrm{C}} = f^{\mathrm{C}}(CE_{\mathrm{A}} - CE_{\mathrm{C}})$ in the objective function; (3) power system planning model based on carbon trading, where the carbon trading cost is calculated by the ladder-type carbon trading model established in this paper.

The planning results for the different power system planning models considering different carbon trading models are shown in Table 5.

Table 5. Planning results under different carbon trading models.

	Planning Results/MW			Total Cost/ (10^6)	Investment Cost/(10^6)	Carbon Trading Cost/(10^6)	Carbon Emissions/t
	Thermal Power	Energy Storage	Interruptible Load				
(1)	560	150	210	1943.9	50.9	132.8	49,168.3
(2)	460	250	210	1870.7	52.7	102.3	48,632.5
(3)	440	300	210	1917.6	68.5	119.1	45,941.5

As can be seen from Table 5, when the objective function of the optimization model does not consider the carbon trading cost, the total cost and investment cost of scheme (1) are the smallest. When the carbon trading cost is considered in the optimization model, the total cost and carbon trading cost of scheme (2) with the traditional carbon trading model are reduced by 3.7% and 22.9%, respectively, compared with scheme (1); the new thermal power is reduced by 100 MW and the new energy storage is increased by 100 MW in the planning result. Meanwhile, the total cost and carbon trading cost of scheme (3) with the ladder carbon trading model are respectively reduced by 1.4% and 10.31%, compared with scheme (1); the new thermal power is reduced by 120 MW and the new energy storage is increased by 150 MW. When carbon trading costs are considered, the overall carbon emissions of schemes (2) and (3) are lower than that of scheme (1). Considering carbon trading costs in the power system multi-flexibility resource planning model can increase the competitiveness of low-carbon units such as energy storage and demand response on the basis of ensuring system economics, promoting system priority in using clean power, and reducing system carbon emissions.

Scheme (3) introduces the incentive and penalty mechanism of carbon emission based on scheme (2), which imposes penalties on power generation entities with high carbon emissions and gives additional incentives to clean and low-carbon power generation entities, further promoting the low carbon development of the power system. Compared with scheme (2), the total cost of scheme (3) increases by 2.5%, and the investment cost increases by 29.98%, but both carbon emissions and carbon trading costs decrease. Therefore, considering the ladder-type carbon trading model in the planning model will make the low-emission units more competitive and thus reduce the system carbon emissions, which has a stricter constraint on carbon emissions than the planning scheme considering the traditional carbon trading model, and still ensures the economics of the planning scheme.

6. Conclusions

As energy supply shortage, environmental pollution, global warming, and other issues become more and more significant, the development of low pollution and low emissions for the characteristics of the low-carbon power system has become the trend. However, due to the large volatility and uncertainty of wind power, photovoltaic power, and other clean energy output systems, its large-scale access will bring the severe challenge of the operational flexibility of the system, resulting in a sharp increase in the demand for power system flexibility resources. Therefore, this paper establishes a multi-flexibility resource planning model for power systems considering ladder-type carbon trading, and optimizes the newly installed capacity of various flexibility resources. The conclusions are as follows.

(1) By analyzing the results of the participation of different flexibility resources in the planning, the integrated planning of multiple flexibility resources is more competitive in terms of system economy and operational flexibility than the planning of one or two resources; although the investment cost increases by USD 12.6M, the total system cost is reduced by 11.22% due to the reduction in coal generation consumption cost, carbon trading cost, and wind curtailment penalty cost.

(2) The model proposed in this paper can effectively improve the utilization rate of the connected wind power and help the system to consume more wind power. When only thermal power is considered as the flexibility resource, the wind curtailment penalty

cost is USD 6.9 $\times$ 10^6; when considering "source–load–storage" multiple flexibility resources, the wind curtailment penalty cost is 0, which means that the wind power output is fully consumed.

(3) By comparing the results of different wind power access capacities, the rise in wind power capacity will increase the capacity demand of new energy storage and reduce the capacity of new thermal power; when the wind power penetration rate increases, there is a need for more adequate flexibility resources to ensure the stable operation of the system and the consumption of renewable energy. When the installed capacity of wind power grew from 800 MW to 1600 MW, the demand for new thermal power decreased by 53.5% and the demand for new energy storage increased by 200%.

(4) By comparing the results of different planning schemes considering different carbon trading models, the ladder-type carbon trading model established in this paper can constrain system carbon emissions more strictly when conducting flexibility resource planning, promoting low-carbon development of the power system, and still ensure the economics of the planning scheme. The total cost of the planning model considering ladder-type carbon trading decreases by 1.35% compared to the model without carbon trading, and increases by 2.5% compared to the model considering traditional carbon trading, but its carbon emissions decrease by 5.5%.

In this paper, we have studied the problem of multi-flexible resource planning for power systems considering carbon trading, and have achieved some theoretical results, but there is still some work that deserves to be continued. The model proposed in this paper only considers wind power, and the adaptability of the model can be improved by considering both PV and wind power in the flexibility resource planning model in the future. At the same time, this paper does not consider the influence of the electricity market on the system flexibility supply and demand, and the influence of market instruments on the flexibility resource planning scheme can be studied in the future.

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Abbreviations

ELUFI	Electricity Loss of Upward Flexibility Insufficient
ELDFI	Electricity Loss of Downward Flexibility Insufficient
PCRUFI	Power Curtailment Rate of Upward Flexibility Insufficient
PCRDFI	Power Curtailment Rate of Downward Flexibility Insufficient
Nomenclature	
Sets and Indices	
i	Index of units
T	Total dispatch period
t	Index of time periods
η	Carbon allowance per MW of the unit output
N_G	The number of thermal units
N_T	The total statistical period
N_G	The number of existing generating thermal power units
$\Omega_G/\Omega_T/\Omega_D$	The set of thermal units/energy storage/interruptible load to be selected
$\Omega_{GS}/\Omega_{BS}/\Omega_{IL}$	The set of all thermal power units/energy storage/interruptible load
Parameters	
α_i,β_i,λ_i	Carbon emission factors of thermal power unit i
f^C	Carbon trading price per unit of carbon emissions

μ/λ	Incentive/Penalty factors when the net carbon emissions of the system are less than or greater than the carbon emission allowance
d	The length of the interval of segmented carbon emissions
ξ_{up}/ξ_{down}	Upward/Downward flexibility demand factors due to load forecast errors
$\lambda_{up}/\lambda_{down}$	Upward/Downward flexibility demand factors due to wind forecast errors
$\delta_{\mathrm{CRF}}(r, Y)$	The equal annual value factor
r	The discount rate
ρ_s	The probability of the scenario s
a_i, b_i, c_i	The energy cost coefficients for generation of thermal power unit i
Q_W	The cost factor of wind curtailment penalty
K_n	The coefficients for load interruption compensation
$I_{\max}$	The upper limit of total investment in flexibility resources
D_W	The maximum allowable wind curtailment rate of the power system
$L_{Tin,\max}/L_{Tin,\max}$	The maximum electric load capacity can be transferred in/transferred out
$P_n^{\mathrm{IL.min}}/P_n^{\mathrm{IL.max}}$	The maximum/minimum interrupted electrical power demand of customer n at time t
$T_{n,\min}^{on}/T_{n,\max}^{on}$	The minimum and maximum interruption time for user n
$N_n^{\mathrm{IL.max}}$	The maximum number of interrupts for user n
G_i	The installed capacity of the candidate thermal power unit i
P_j/E_j	The installed capacity/storage capacity of the candidate energy storage device j
P_m	The power demand of the candidate interruptible load m
C_i	Construction cost per unit capacity of candidate thermal power unit i
k_P/k_E	The price per unit power and per unit capacity of energy storage
Q_m	The investment cost per unit capacity of interruptible load
Variables	
CE_{C}	Carbon allowance allocated to the power system
CE_{A}	Actual carbon emissions of thermal units
ΔCE	Net carbon emissions
C_{C}	Carbon trading cost of the power system
C	Total annual cost of the power system
C_{IV}	The annual value of the total investment cost for flexibility resources
C_{OP}	The annual operating cost of the power system
$C_{\mathrm{G,IV}}/C_{\mathrm{T,IV}}/C_{\mathrm{D,IV}}$	Equivalent annual value of investment cost for new thermal units/energy storage devices/ interruptible load
C_G/C_{QT}	Operation cost/start-up and shutdown cost of thermal power units
C_{QW}	Wind curtailment penalty costs
C_{DR}	Load interruption costs for users who participate in demand respond
$P_{G,t}^{up}/P_{G,t}^{down}$	Upward/Downward supply capacity of the flexibility resource
$P_{R,t}^{up}/P_{R,t}^{down}$	Upward/Downward flexibility requirements of the power system
E_L/E_R	Electricity loss of upward/downward flexibility insufficient
$\Delta P_t^{up}/\Delta P_t^{down}$	Electricity loss or curtailed power of renewable energy at time t
η_{up}/η_{down}	Power curtailment rate of upward/ downward flexibility insufficient
$x_i/y_j/z_m$	Binary variables of whether thermal power, energy storage, interruptible load is invested or not
$u_{i,s,t}^G$	The operating state of thermal power unit i at time t in scenario s
$P_{W,s,t}^{LOSS}$	The curtailed wind power at the time t under scenario s
$P_{n,s,t}^{NL}$	The interrupted load power of user n at time t under scenario s
$P_{W,s,t}/P_{B,j,s,t}$	Output of wind farm/energy storage at time t under scenario s
$P_{i,s,t}^G$	Output of thermal power unit i at time t under scenario s
$\mu_{n,s,t}$	The load interruption state variable of user n at time t in scenario s
$L_{TLin,s,t}/L_{TLout,s,t}$	The transferred-in/transferred-out load power at time t in scenario s
$E_{B,s,t}$	The value of the power stored in the battery at time t in scenario s
$S_{\mathrm{BESS},s,t}$	The state of charge of the battery energy storage at time t in scenario s
$T_{n,s,t}^{on}$	The duration time of the continuous interruption of the interruptible user n at time t under scenario s

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