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Research Article

The Optimization Model for Interregional Power System Planning considering Carbon Emissions Trading and Renewable Energy Quota Mechanism

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In China, the rapid construction of ultra-high-voltage (UHV) transmission lines promotes interregional resource optimizing configuration and interregional power system planning. This paper analyzes external environment of interregional power system planning from geographical, technical, and policy environments. Then, the paper takes the minimum system investment cost as the optimization objective and constructs the optimization model of interregional power system planning considering carbon emissions trading (CET) and renewable energy quota mechanism (REQ). Finally, this paper sets base scenario, carbon emissions trading scenario, renewable energy quota mechanism scenario, and comprehensive scenario for case simulation. The results show that interregional power system planning could connect power grids in different regions, enlarge wind power consumption space, and relieve the inconformity problem between power resource and load demand. CET and REQ can increase the installed proportion of clean energy and reduce carbon dioxide emissions, but the cost of transmission lines construction and system reserve will increase correspondingly. The optimization effect of REQ on power system planning is better than CET. When they are both introduced, the power structure will reach the best, carbon dioxide emissions will achieve the minimum, and comprehensive benefits will become more balanced.

1. Introduction

The rapid construction of ultra-high-voltage transmission line promotes interregional resource optimizing configuration, relieves contrary distribution between power resource and load demand, and offers guarantee for interregional power system joint planning in China [1]. As the direct and indirect means of influencing power source structure, the introduction of carbon emission right trading (CET) [2] and renewable energy quota mechanism (REQ) [3] can raise the proportion of clean energy grid connection, encourage power grid to interregional clean energy absorption, and offer better application prospect for interregional power system planning [4]. Therefore, implementing interregional power system planning considering CET and REQ shows prominent actual significance.

In the researches on power system planning, Buygi et al. [5] simulate different kinds of uncertainty factors and utilize probability theory to solve power grid planning model based on market environment. Ng and Sy [6] utilize set pair theory to analyze uncertainty factors of grid planning in electricity market and build flexible grid planning multiobjective model. Vallée et al. [7] describe the basic thoughts, methods, and procedures of Monte Carlo in simulating grid planning considering uncertainty factors in electricity market environment. Georgilakis and Hatziargyriou [8] considered new energy absorption problem in grid planning and establish grid planning method. Desta et al. [9] build the optimization model for multitype power units and interregional power grid under the objective of the minimum power generation costs.

Then, the quota mechanism implementation situation and the operation situation of renewable energy certificate market in the USA are introduced in the literature [10]. Berendt [11] puts forward a flowing model of renewable energy certificates (RECs) trading planning, builds a national RECs trading platform, eliminates the obstacle for REC trading, and completes an adjustment price-estimation system. Marchenko [12] puts forward a long-term and short-term mathematical market mode and analyzes the economic benefits of green certificate trading mechanism. Anger and Oberndorfer [13] point out that emission right price is influenced by permission issue; if allocation is strict, supply will decrease and demand will increase, which will lead to the rise of market emission right price. Engels [14] points out that the actual energy price and the prospective energy price both can influence emission right price. Alberola et al. [15] point out that carbon emission prices have important function as a market driving force, which cannot be ignored in carbon emission-decrease process. Zhu et al. [16] discuss the influence of carbon emission trading on interregional power system planning. Ahn et al. [17] utilize elasticity model of index generalization autoregression condition to build carbon emission price forecast model, put forward carbon emission calculation method, and build power grid planning model based on dynamic carbon emission price. Based on the previous research achievements, there is little content involving the relationship among power system planning, carbon emission trading, and renewable energy quota mechanism, especially the influence of CET and REQ on interregional power system planning. Therefore, this paper regards interregional power system planning as the research object and builds the optimization model for interregional power system planning considering CET and REQ.

The rest of the paper is organized as follows. In Section 2, this paper analyzes the important role of ultra-high-voltage grid in solving the contrary distribution between power resource and load demand. CET and REQ could promote a wider range of power resource configuration. Section 2 analyzes geographical environment, technical environment, and policy environment for interregional power system planning. Section 3 mainly considers constraint condition in several aspects, takes the minimum costs as the objective, and builds interregional power investment optimization model to achieve interregional optimization allocation of power resource. In Section 4, GAMS software is used to make mathematical simulation analysis. Classification discussion is made on the simulation result in different cases. Section 6 highlights the main conclusions of this paper.

2. Environmental Analysis of Interregional Power System Planning

2.1. Geography Environment Analysis. The wind energy resource of China concentrates in north, northwest, and northeast districts as well as eastern coastal areas [18]. The solar energy which is appropriate for large-scale centralized development mainly allocates in the remote deserts of northern and western China. However, demand energy mainly allocates in northern, central, and eastern of China. The reverse distribution of energy production and energy consumption determines that China has to construct transportation channels to make clean energy accessible in a national scale with the characteristic of huge capacity and long distance [19].

2.2. Technology Environment Analysis. The construction of ultra-high-voltage transmission lines helps address the reverse distributions of power generation and load demands. By the end of 2015, State Grid of China finished the projects of "three verticality and three horizontality" backbone networks of extra-high voltage power lines which link large energy bases with main consumption centers besides 13 direct current (DC) transmission projects (including 10 extra-high voltage DC power transmission projects) [19] (Figure 1). This will form a large-scale layout of energy allocation that consists of "west-east electricity transmission project" and "north-south electricity transmission project." Table 1 is the extra-high voltage planning projects of State Grid of China [19].

The construction of ultra-high-voltage transmission lines can promote interregional transmission of clean energy by improving the efficiency of long-distance and huge-capacity power transmission, reducing power loss in transmission, and lowering transmission cost, which can optimize resource allocation and solve the contradiction of the reverse distributions of power generation and load demands. In addition, it offers broad accessibility of interregional power system planning and creates physical conditions for implementing CET and REQ.

2.3. Policies Environment Analysis

2.3.1. Carbon Emission Trade. The basic principle of carbon emission trade indicates that purchaser may use purchased quota of greenhouse gases emission to meet the emission reduction target by paying the other party to the contract. Three main environmental exchanges of China are Beijing Environmental Exchange, Shanghai Environment, and Energy Exchange and Tianjin Climate Exchange. The details can be seen in Table 2 [20].

The implementation of CET will increase power system operation cost. If it is contained in the objective function of interregional power system planning, the whole power investment will be influenced in the following three aspects:

(1) The investment choice of fossil energy units: units with different energy efficiency level have different carbon emission rates. Since CET has less effect on emission costs of low energy-consumption units than that on high energy-consumption units, investors prefer to choose low energy-consumption units.

(2) The investment choice between fossil energy units and clean energy units: the initial investment on fossil energy units is lower than clean energy units while the operation costs of fossil energy units are higher than clean energy units. The implementation of carbon trade mechanism can balance the comprehensive costs between fossil energy units and clean energy units, which helps increase the investment income and clean energy grid-connection proportion.

(3) Power source investment choice in different regions: different regions have different bearing capacities of carbon dioxide emission prices. CET can influence economic benefits of regional power source layout

Table 1: The extra-high voltage planning projects of State Grid of China.

Line	Voltage level	Length	Transmission capacity	Operation time
Hami-Zhengzhou	±800 kV	2280 km	800 MW	2014.12
Xiluodu-Zhexi	±800 kV	1688 km	800 MW	2014.9
Huaidong-Chengdu	±800 kV	2600 km	1000 MW	2015
Baoqing-Tangshan	±800 kV	1500 km	800 MW	2014
Mengxi-Jiangsu	±800 kV	1450 km	800 MW	2015
Ximeng-Taihou	±800 kV	1600 km	800 MW	2015
Longdong-Jiangxi	±800 kV	1400 km	800 MW	2015
Hami-Chongqi	±800 kV	2300 km	800 MW	2015
Ningdong-Shaoxing	±800 kV	1700 km	800 MW	2015

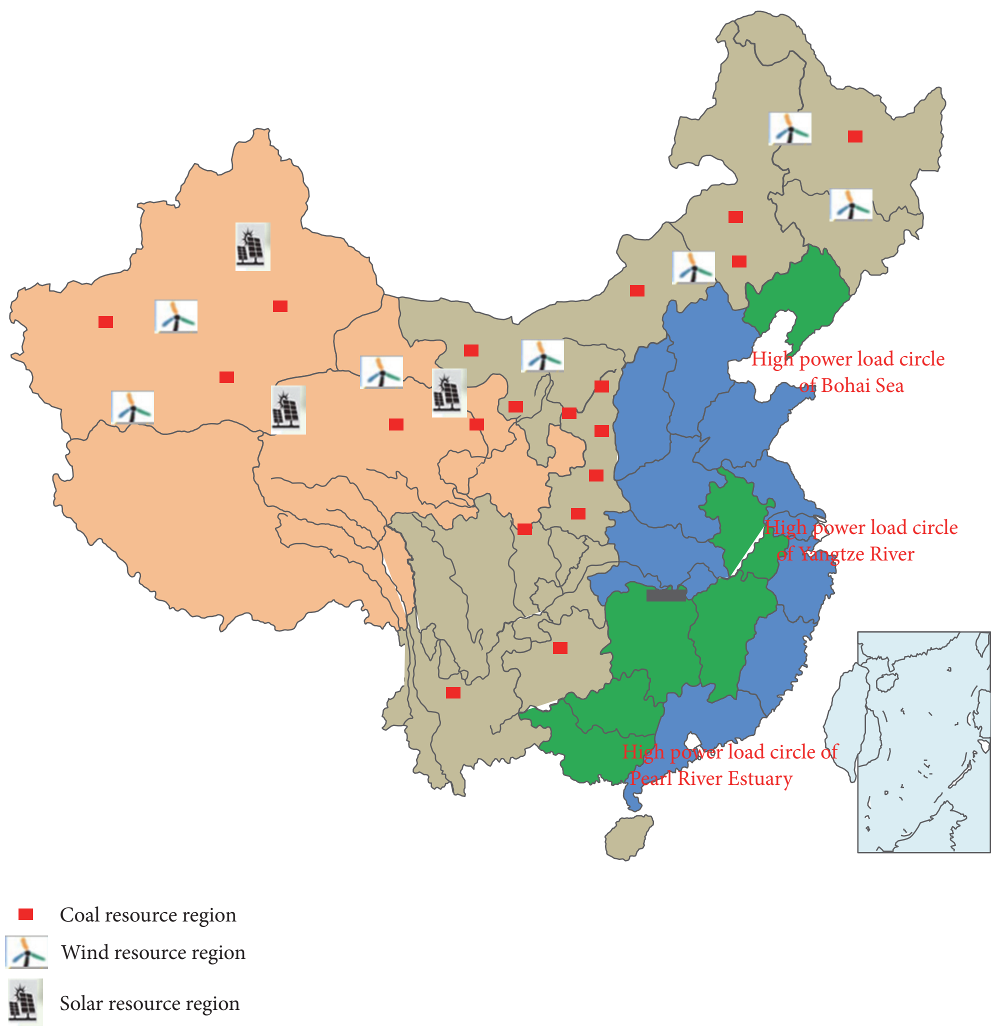

Figure 1: The distribution map of power resource and load demand in China.

and optimize allocation form of interregional power resources.

2.3.2. Renewable Energy Quota Mechanism. Renewable energy quota mechanism is a compulsive policy formulated by government to cultivate renewable energy market and guarantee renewable energy generating capacity [21]. In regional power construction, certain proportions of load demand should be met by renewable energy. Renewable energy generating capacity can also be trade among different regions (or power grids), which can solve the imbalance of interregional renewable energy.

In April, 2015, the government of the Inner Mongol Autonomous Region of China issued *Instructions on Building*

Table 2: Main carbon markets in China.

Market name	Starting time	Subjects of carbon trade	Requirements of carbon trade	Procedure of carbon trade
Beijing Environmental Exchange	2008.8.5	Individuals and enterprises	Panda standard "carbon source—carbon sink"	Certification—registration—trade
Shanghai Environment and Energy Exchange	2008.8.5	Individuals and enterprises	"Green Expo" voluntary emission reduction trading mechanism and trading platform	Paying for carbon emission through platform to achieve voluntary emission reduction
Tianjin Climate Exchange	2008.9.25	Enterprises	Voluntary participation and compulsive emission reduction	Voluntary rule design, voluntary target making, and voluntary participation

Long-Term Mechanism of Guaranteed Acquisition of Renewable Energy (hereinafter called *Instructions*) [22]. Instructions point out that the power generated by renewable energy in the Inner Mongol Autonomous Region will account for 20% of the whole social power consumption amount in 2020. Inner Mongol becomes the first province to implement REQ.

Renewable energy quota mechanism can stimulate interregional power trade. REQ promotes optimization allocation of interregional power resources and plays an important role in interregional power system planning. REQ could also encourage regions with low proportion of renewable energy power generation units to purchase power from the higher one. It is a combination of law and market mechanism to turn the environmental benefits of renewable energy into economic benefits.

3. Interregional Power System Planning Optimization Model

The essence of power planning is to optimize investment on generating units and transmission lines including type, scale, and timing. Its main purpose is to increase power supplies reliability, promote clean energy utilization, and improve power resources optimizing efficiency.

3.1. Objective Function

3.1.1. Basic Objective Function. The optimization model for interregional power system planning is built under the objective of the minimum economic investment cost during the planning period. Economic investment cost includes initial investment cost, variable cost, and operation cost of annual new generating units with construction cost of transmission lines.

$$\text{Min} \quad z = \sum_{t=1}^{T} \sum_{i=1}^{I} \gamma_t^{p/f} \left[\text{FC}_{it} + \text{VC}_{it} + \text{OM}_{it} + \text{TLC}_{it} \right] \tag{1}$$

wherein T is set of planning period. I is set of regions. $\gamma_t^{p/f}$ is discount factor at year t. FC_{it} is depreciation expense of units construction investment in region i at year t. VC_{it} is variable cost in region i at year t. OM_{it} is operation and maintenance cost of annual new generating units in region i at year t. TLC_{it} is annual allocated cost of the total investment of transmission line in region i at year t. Assume r is depreciation rate; then

$$\gamma_t^{p/f} = (1+r)^{1-t}. \tag{2}$$

The depreciation cost of investment on generating units is

$$\text{FC}_{it} = \sum_{f=1}^{F} \sum_{n=1}^{N} \left(u_{i1n}^f P_{i1n}^f \psi_{i1n}^f + u_{i2n}^f P_{i2n}^f \psi_{i2n}^f + \cdots + u_{itn}^f P_{itn}^f \psi_{itn}^f \right) \gamma_n^{f-a/p} \tag{3}$$

wherein u_{itn}^f, P_{itn}^f, and ψ_{itn}^f are newly installed number, installed capacity, and unit capacity cost of unit n in region i at year t. $\gamma_n^{f-a/p}$ is annuity coefficient of unit n. Assume T_n^f is planning operation period; then

$$\gamma_n^{f-a/p} = \frac{r(1+r)^{T_n^f - 1}}{\left[(1+r)^{T_n^f} - 1 \right]}. \tag{4}$$

Variable cost mainly refers to the fuel cost of fossil energy power units:

$$\text{VC}_{it} = \sum_{f=1}^{F} p_{it}^f q_{it}^f \tau_{it}^f \tag{5}$$

wherein p_{it}^f is the price of energy f in region i at year t. q_{it}^f is generation capacity of energy f in region i at year t. τ_{it}^f is energy-consumption rate of energy f in region i at year t. For renewable energy power units, consumption fuel cost is zero.

Operation and maintenance costs include labor cost, inspection cost, and maintenance cost:

$$\text{OM}_{it} = \sum_{f=1}^{F} \sum_{n=1}^{N} \left(u_{i1n}^f \text{OM}_{i1n}^f + u_{i2n}^f \text{OM}_{i2n}^f + \cdots + u_{itn}^f \text{OM}_{itn}^f \right) \tag{6}$$

wherein OM_{itn}^f is operation and maintenance cost of unit n of energy f in region i at year t. Interregional power planning meets regional load demand and realizes interregional energy deployment by constructing transmission lines. The total investment cost of transmission lines includes construction cost, maintenance costs, and labor and other costs.

The annual allocated cost of transmission line is

$$\mathrm{TLC}_{it} = \sum_{j,j\neq i}\left[\frac{\left(u_{ij1}^{\mathrm{TL}}p_{ij1}^{\mathrm{TL}} + u_{ij2}^{\mathrm{TL}}p_{ij2}^{\mathrm{TL}} + \cdots + u_{ijt}^{\mathrm{TL}}p_{ijt}^{\mathrm{TL}}\right)}{2}\right] \cdot \gamma^{\mathrm{TL}-a/p} \quad (7)$$

wherein u_{ijt}^{TL} is the number of transmission lines connecting region i and region j at year t. p_{ijt}^{TL} is investment cost of transmission lines connecting region i and region j at year t. $\gamma^{\mathrm{TL}-a/p}$ is annuity coefficient of transmission lines. If the average values of annual maintenance cost, labor cost, and other costs are $\mathrm{OM}_{it}^{\mathrm{TL}}$, $\mathrm{LC}_{it}^{\mathrm{TL}}$, and $\mathrm{OT}_{it}^{\mathrm{TL}}$, then, (7) could be rewritten as follows:

$$\mathrm{TLC}_{it} = \sum_{j,j\neq i}\left[\frac{\left(u_{ij1}^{\mathrm{TL}}p_{ij1}^{\mathrm{cc}} + u_{ij2}^{\mathrm{TL}}p_{ij2}^{\mathrm{cc}} + \cdots + u_{ijt}^{\mathrm{TL}}p_{ijt}^{\mathrm{cc}}\right)}{2}\right] \cdot \gamma^{\mathrm{TL}-a/p} + \mathrm{OM}_{it}^{\mathrm{TL}} + \mathrm{LC}_{it}^{\mathrm{TL}} + \mathrm{OT}_{it}^{\mathrm{TL}} \quad (8)$$

wherein p_{ijt}^{cc} is construction cost of transmission lines connecting region i and region j at year t.

3.1.2. Objective Function with CET. If CET is introduced, carbon emission cost will be incorporated into generation cost of fossil energy generating units, which is also a foremost element influencing power system planning. The objective function of power system planning with CET is as follows:

$$\mathrm{Min} \quad z = \sum_{t=1}^{T}\sum_{i=1}^{I}\gamma_t^{p/f}\left[\mathrm{FC}_{it} + \mathrm{VC}_{it} + \mathrm{OM}_{it} + \mathrm{TLC}_{it} + \mathrm{EC}_{it}\right] \quad (9)$$

wherein EC_{it} is carbon emission cost in region i at year t :

$$\mathrm{EC}_{it} = \sum_{f=1}^{F} p_{it}^{\mathrm{CO}_2}\left(q_{it}^{f}\tau_{it}^{f}\nu^{f} - E_{it}^{\mathrm{CO}_2}\right) \quad (10)$$

wherein $p_{it}^{\mathrm{CO}_2}$ is carbon emission price in region i at year t. ν^f is unit generation carbon emission conversion coefficient of energy f. $E_{it}^{\mathrm{CO}_2}$ is initial permitted cap for carbon emissions. When carbon emission exceeds the cap, power generation enterprise should purchase carbon emission permit from carbon trading market, which increases generating cost. If carbon emission is below the cap, power generation enterprise could sell carbon emission permit to carbon trading market for obtaining additional economic profits.

3.1.3. Objective Function with REQ. The implementation of REQ directly increases renewable energies power generation. If the region fails to meet the REQ requirement, it shall purchase renewable energy power generation from other regions to increase the share of renewable energy power generation.

Power system planning objective after REQ is

$$\mathrm{Min} \quad z = \sum_{t=1}^{T}\sum_{i=1}^{I}\gamma_t^{p/f}\left[\mathrm{FC}_{it} + \mathrm{VC}_{it} + \mathrm{OM}_{it} + \mathrm{TLC}_{it} + \mathrm{EQ}_{it}\right] \quad (11)$$

wherein EQ_{it} is power purchase cost in region i at year t calculated by (11).

$$\mathrm{EQ}_{it} = \begin{cases} \sum_{j=1}^{J}\sum_{k=1}^{K} p_{ij,t}^{k,\mathrm{quota}}\left(E_{it}^{k,\mathrm{quota}} - q_{it}^{k}\right), & q_{it}^{k} \le E_{it}^{k,\mathrm{quota}} \\ \sum_{m=1}^{M}\sum_{k=1}^{K} p_{im,t}^{k,\mathrm{quota}}\left(E_{it}^{k,\mathrm{quota}} - q_{it}^{k}\right), & q_{it}^{k} > E_{it}^{k,\mathrm{quota}} \end{cases} \quad (12)$$

wherein $p_{ij,t}^{k,\mathrm{quota}}$ is purchase pricing of renewable energy k by region i from region j at year t. k is index for renewable energy. K is the set of renewable energy. $p_{im,t}^{k,\mathrm{quota}}$ is selling price of renewable energy k from region i to region m at year t. q_{it}^{k} is power generation of renewable energy k in region i at year t. $E_{it}^{k,\mathrm{quota}}$ is quota requirement of renewable energy k in region i at year t.

When $q_{it}^{k} \ge E_{it}^{k,\mathrm{quota}}$, it means region i meets the quota requirement and has additional renewable energy quota for selling. Otherwise, it means region i does not meet the quota requirement and needs to purchase renewable energy for power generation from other regions.

3.2. Conventional Constraints

3.2.1. Power Generating Capacity Constraint Conditions. Power construction should meet socioeconomic development demand. To minimize the economic loss resulting from power rationing, the planning installed capacity should exceed the maximum load in corresponding year. Meanwhile, considering the reliability of power supplies and generating units' inspection, power system planning should incorporate reserve power. The constraint is as follows:

$$\begin{gathered} \sum_{i=1}^{I}\sum_{f=1}^{F} P_{it}^{f\text{-all}} \ge \frac{D_t^{\max}}{(1-\theta_t)} + \sum_{i=1}^{I} P_{it}^{b} \\ P_{it}^{f\text{-all}} = \sum_{n=1}^{N}\left(u_{i1n}^{f}P_{i1n}^{f} + u_{i2n}^{f}P_{i2n}^{f} + \cdots + u_{itn}^{f}P_{itn}^{f}\right) + \sum_{m=1}^{M}\left(u_{itm}^{of}P_{itm}^{of}\right) \end{gathered} \quad (13)$$

wherein $P_{it}^{f\text{-all}}$ is total installed capacity of energy f in region i at year t. $D_t^{\max}$ is the maximum load demand in region i at year t. θ_t is average line loss rate at year t. In general, when the transmission lines are UHV transmission lines, θ_t is less than 8%. P_{it}^{b} is standby capacity demand in region i at year t.

u_{itm}^{of} is closure variable of generating unit m from energy f in region i at year t. Assume actual operation years and designed operation years are OT_{im}^{of} and T_{im}^{of}, respectively. When $T_{im}^{of} \le \mathrm{OT}_{im}^{of}+t$, the operation time of the generator has already been bigger than the designed operation years; then, when $u_{itm}^{of}=0$, the generator will be shut down. When $T_{im}^{of} \ge \mathrm{OT}_{im}^{of}+1$, the generator does not reach the designed operation years; then, when $u_{itm}^{of}=1$, the generator will still operate. P_{itm}^{of} is installed capacity of original generating units in region i at year t.

However, power grids can be connected by transmission lines and load curves are mutually supplementary in different regions. Power loads could unlikely reach maximum at the same time in different regions. Therefore, $D_t^{\max}$ is the maximum of the sum of regions' loads rather than the sum of the maximum regions' loads. This characteristic could decrease the power capacity construction for meeting peak load in interregional power planning. The relationship between the maximum value of the total regions' load and the sum of the maximum regions' load could be described as follows (14):

$$D_t^{\max} = \operatorname*{Max}_{s}\left\{\sum_{i=1}^{I} D_{it}(s)\right\} \tag{14}$$

wherein $D_{it}(s)$ is load demand in region i at time s during year t.

3.2.2. Power Demand Constraint Conditions. Power generating capacity constraints only ensure that instantaneous power meets the maximum load demand. But when considering generation units maintenance and total primary energy supply, the annual utilization hours will be below 8760 hours. Therefore, power constraint should also be considered in system planning to ensure that total power supply meet the total load demand.

$$\begin{aligned}8760\sum_{i=1}^{I}\sum_{f=1}^{F}&\left[\sum_{n=1}^{N}\left(u_{i1n}^{f}P_{i1n}^{f}\chi_{i1n}^{f}+\cdots+u_{itn}^{f}P_{itn}^{f}\chi_{itn}^{f}\right)\right.\\&\left.+\sum_{m=1}^{M}\left(u_{itm}^{of}P_{itm}^{of}\chi_{itm}^{of}\right)\right]\ge\sum_{i=1}^{I}\frac{Q_{it}}{(1-\theta_{it})}\end{aligned} \tag{15}$$

wherein χ_{itn}^{f} and χ_{itm}^{of} are the availability rates of generating units. Q_{it} is load demand in region i at year t. Power consumption in planning period of different regions can be estimated based on average load rate, maximum load rate, and growth rate of load demand.

$$\sum_{i=1}^{I}\frac{Q_{it}}{(1-\theta_{it})}=\sum_{i=1}^{I}\sum_{f=1}^{F}q_{it}^{f}. \tag{16}$$

China formulated regulations on *Method of Energy-Saving Power Generation and Dispatching (Trial Implementation)* in 2007 [23] to promote clean energy development and control pollutants emission. Under this background, renewable energy power generation units will be dispatched in priority. Its power supply can be estimated based on installed capacity and unit availability rate:

$$\begin{aligned}q_{it}^{f}=8760&\left[\sum_{n=1}^{N}\left(u_{i1n}^{k}P_{i1n}^{k}\chi_{i1n}^{k}+u_{i2n}^{k}P_{i2n}^{k}\chi_{i2n}^{k}+\cdots\right.\right.\\&\left.\left.+u_{itn}^{k}P_{itn}^{k}\chi_{itn}^{k}\right)+\sum_{m=1}^{M}\left(u_{itm}^{ok}P_{itm}^{ok}\chi_{itm}^{ok}\right)\right].\end{aligned} \tag{17}$$

3.2.3. Wind Power Installed Capacity Constraints. To minimize the influence of wind power uncertainty on system operation, the proportion of wind power installed capacity in total installed capacity should be reasonably controlled. Meanwhile, since interregional transmission of wind power relies on interregional transmission lines, the transmission lines capacity should be considered.

$$\begin{aligned}&P_{it}^{w\text{-all}}\le P_{i}^{w\text{-max}}\\&P_{it}^{w\text{-all}}\le\sum_{f=1}^{F}\beta_t^{f}P_{it}^{f\text{-all}}\\&\qquad+\sum_{j,j\ne i}\left(u_{ij1}^{\mathrm{TL}}+u_{ij2}^{\mathrm{TL}}+\cdots+u_{ijt}^{\mathrm{TL}}\right)P_{ij}^{\mathrm{TL}}\\&\sum_{i=1}^{I}P_{it}^{w\text{-all}}\le\sum_{i=1}^{I}\sum_{f=1}^{F}\beta_t^{f}P_{it}^{f\text{-all}}\end{aligned} \tag{18}$$

wherein $P_{it}^{w\text{-max}}$ is the limitation of total wind power installed capacity determined by wind power resources. P_{ij}^{TL} is the limitation of transmission capacity from region j to region i. β_t^{f} is constraint factor of wind power capacity. Assume $\Delta\beta_t^{f}$ is the growth ratio of constraint factor of wind power capacity within planning period; then

$$\beta_t^{f}=\left(1+\Delta\beta_t^{f}\right)\beta_{t-1}^{f}. \tag{19}$$

In China, negative correlation exists between growth ratio of wind power installed capacity and its grid-connection rate. Therefore, the growth rate of new energy should be controlled to develop new energy in an organized manner and avoid investment waste resulting from asymmetrical development between power grids and new energy.

$$\sum_{i=1}^{I}P_{it}^{w\text{-all}}\le(1+\omega)\sum_{i=1}^{I}P_{i,t+1}^{w\text{-all}} \tag{20}$$

wherein ω is the allowable growth ratio of total installed capacity of wind power.

3.2.4. Transmission Capacity Constraint. The real-time interregional transmission capacity should be lower than the limitation of transmission capacity. Then, the total power supply from local region and other regions should meet local load and reserve load. The transmission line capacity should be satisfied:

$$\sum_{j,j\neq i}\left(u_{ij1}^{\mathrm{TL}}+u_{ij2}^{\mathrm{TL}}+\cdots+u_{ijt}^{\mathrm{TL}}\right)P_{ij}^{\mathrm{TL}}\left(1-\eta_{ij}^{\mathrm{TL}}\right) \geq \frac{D_t^{\max}}{\left(1-\theta_{it}\right)}+P_{it}^{b}-\sum_{f=1}^{F}P_{it}^{f\text{-all}} \tag{21}$$

wherein η_{ij}^{TL} is transmission line loss rate between region i and region j.

3.2.5. Fuel Consumption Constraint. The variable cost of fossil power generation units is mainly fuel consumption cost during power generation. With the increase of combustion thermal efficiency, power generation fuel consumption of thermal unit and gas power unit is on decline [24]:

$$\tau_{it}^{f}=a_i^1+b_i^1\exp\left(-c_i^1t\right) \tag{22}$$

wherein a_i^1, b_i^1, and c_i^1 are parameters of unit fuel consumption, respectively. exp() is exponential function relating to natural constant e.

3.2.6. Fuel Price Prediction. If energy supply cannot meet energy demand, the fossil fuel price would steadily increase according to the energy supply-demand relationship. Therefore, assume price equation is [10]

$$\tau_{it}^{f}=a_i^2+b_i^2\exp\left(-c_i^2t\right) \tag{23}$$

wherein a_i^2 and b_i^2 are parameters of fuel price in region i.

3.2.7. Prediction of Power Generation Units Cost. Now the installation cost of wind power units is high. However, with maturing of wind power technology, the cost will decline [25].

$$\psi_{itn}^{f}=a_{in}^3+b_{in}^3\exp\left(-c_i^3t\right) \tag{24}$$

wherein a_{in}^3, b_{in}^3, and c_i^3 are installed cost parameters of power unit n in region i at year t.

3.3. CET Constraints. Carbon emission trading constraints include price constraint and emission constraint. Since carbon emission prices are policy-based, it may be on the rise due to the tight government policy on carbon emission. The fitting equation may be [10]

$$p_{it}^{CO_2}=a_i^{CO_2}+b_i^{CO_2}t \tag{25}$$

wherein $a_i^{CO_2}$ and $b_i^{CO_2}$ are parameters of carbon emission price. With respect to carbon emission constraint, carbon emission within the region and permitted cap should be taken into account. Carbon emission constraint within planning period is as indicated in

$$\sum_{f=1}^{F}q_{it}^{f}\tau_{it}^{f}\nu^{f}+E_{it}^{S}-E_{it}^{B}\leq E_{it}^{CO_2} \tag{26}$$

wherein E_{it}^{S} and E_{it}^{B} are carbon emission right permit purchased and sold, respectively, within region i at year t. Carbon emission reduction target should be met by the end of planning period in

$$\sum_{f=1}^{F}q_{iT}^{f}\tau_{iT}^{f}\nu^{f}\leq E_{iT}^{CO_2}. \tag{27}$$

Equation (27) elaborates that carbon emission reduction target would be realized though energy structure adjustment in planning period.

3.4. REQ Constraints. The implementation of REQ promotes interregional power trading. If the region cannot meet the mandate of REQ mechanism, it has to purchase renewable energy for power generation from other regions. The constraint is as indicated in the following equations [26]:

$$\begin{gathered}q_{it}^{k}+Q_{it}^{k,S}-Q_{it}^{k,B}\geq E_{it}^{k,\text{quota}}\\ \sum_{k=1}^{K}\left(q_{it}^{k}+Q_{it}^{k,S}-Q_{it}^{k,B}\right)\geq E_{it}^{\text{quota}}\end{gathered} \tag{28}$$

wherein $Q_{it}^{k,S}$ and $Q_{it}^{k,B}$ are power generation from renewable energy purchased and sold in region i at year t, respectively. $E_{it}^{k,\text{quota}}$ is quota requirement of renewable energy k in region i at year t.

4. Scenarios Set

To increase wind power grid connection, peak-shaving power is required to be established by gas power with great flexibility. Three-North Regions (Northeast China, North China, and Northwest China) with rich wind power have great reserve in natural gas. Therefore, wind power generation, gas power generation, and thermal power generation are mainly discussed for interregional power system planning in this paper. To analyze the impact of CET and REQ on power system planning, four scenarios are designed as follows.

Case 1 (basic scenario). Interregional power system planning without CET and RQS: this only comparatively analyzes the interregional joint planning (IRJP) and regional independent planning (RIP). Referring to the literature [18], the paper sets operation parameters of alternative power generation units in Table 3. IRJP and RIP both rely on interregional transmission lines, and cost parameters of transmission lines are shown in Table 4 [19].

Case 2 (CET scenario). Interregional power system planning with CET: this scenario mainly analyzes the influence of CET on IRJP. This paper selects region A with rich wind power resource and region B with inferior conditions for wind power development as the simulating objects. Assume region A with 6000 MW wind power development capacity; the constraint factors are 0.08 and 0.5. The growth ratio of wind power generation capacity is constrained not more than 50%.

Table 3: Coefficients of alternative units.

f	n	P_{itn}^{f}	ψ_{itn}^{f}	OM_{itn}^{f}	T_{n}^{f}	χ_{itn}^{f}
Wind	$N1$	200	860	1600	20	27%
	$N2$	100	910	900	20	27%
Coal	$N3$	600	420	15000	30	96%
	$N4$	300	450	7200	30	95%
Gas	$N5$	400	410	9800	25	70%
	$N6$	200	430	5000	25	70%

Table 4: Coefficients of transmission line.

p_{ijt}^{TL}	P_{ijt}^{TL}	T^{TL}	η_{ij}^{TL}
40000	400	20	3%

Case 3 (REQ scenario). Interregional power system planning with REQ: this scenario mainly analyzes the influence of REQ on power system planning. The parameter of renewable energy quota is reference to the literature [27]. The renewable energy quota in region A is required to exceed 15% in the middle of planning period and is required to reach 20% by the end of the planning period. Since region B is short of wind power resource, the quota is only required to reach 8% by the end of the planning period.

Case 4 (comprehensive scenario). Interregional power system planning with CET and REQ. This scenario is utilized to analyze the influence of CET and REQ on joint power system planning. Related parameters are as the same as that of Cases 2 and 3.

5. Case Simulation

In order to analyze the validity and applicability of the proposed optimization model, the section mainly takes two regions in China for case simulation. If simulation results meet the expected requirements, then the influence of CET and REQ on power system planning could be analyzed. The proposed model could be used for interregional power system planning. But if simulation results do not meet the expected requirements, the proposed model has to revise again.

5.1. Basic Data. Region A and region B both have 30 units with the unit parameters shown in Table 5. Their annual maximum load remains 7800 MW in the first year with λ being equal to 0.95. Within the planning period, the annual growth rate is 8% with average load rate of 75%, comprehensive line loss rate of 5%, power reserve ratio of 10%, and discount rate of 8%. The cost equation parameter of wind power installation unit capacity is reference to the literature [25], as shown in Table 6. The trend equation parameters of fuel consumption and fuel price for thermal power generation and gas power generation are in Table 7.

5.2. Simulation Result. The simulation has been implemented with GAMS optimization software of CPLEX 11.0 linear solver. The CPU time required for solving the problem for different case studies with an idea pad 450 series laptop computer powered by core T6500 processor and 2 GB of RAM was less than 10 s.

Table 5: Coefficients of original units.

Unit	f	P_{itm}^{of}	T_{im}^{of}	OT_{im}^{of}	χ_{itm}^{of}	Number
1#	coal	600	30	5/8/14	95%	3
2#	coal	400	30	9/12/17	95%	3
3#	coal	400	30	6/18/27	90%	3
4#	coal	300	30	3/17/21	93%	3
5#	coal	300	25	2/15/19	95%	3
6#	coal	300	20	6/16/18	96%	3
7#	coal	200	25	15/17/24	90%	3
8#	coal	200	25	7/11/16	87%	3
9#	coal	150	25	14/18/23	87%	3
10#	wind	100	20	2/5/7	27%	3

Note: operated year refers to the respective operating year of 3 relevant units.

Table 6: Coefficients of unit capacity cost of wind power.

n	a_{in}^{3}	b_{in}^{3}	c_{i}^{3}
1	460	400	0.09
2	490	420	0.09

Table 7: Correlative coefficients of power generation fuel.

f	a_{i}^{1}	b_{i}^{1}	c_{i}^{1}	a_{i}^{2}	b_{i}^{2}
Coal	0.26	0.08	0.07	1200	50
Gas	280	50	0.06	1.2	0.05

5.2.1. Planning Result in Case 1. The optimization results of both IRJP and RIP are comparatively analyzed in Case 1. The total power installed capacity is 36600 MW in RIP mode, which is higher than 34800 MW in IRJP mode. The installed capacity of wind power and gas power is 800 MW and 400 MW in IRJP mode, which are both higher than that in RIP mode. The installed capacity of thermal power is 3000 MW, which is lower than that in RIP mode. Hence, IRJP could optimize system installation structure and enhance wind power installed capacity, while the installed capacity of gas power generation unit is correspondingly increased as reserve peak-shaving power. The investment optimization results in IRJP mode and RIP mode are shown in Table 8.

In terms of installed structure, the installed capacity of wind power in two regions is 5100 MW in RIP mode, which is 800 MW lower than that in IRJP mode. The peak regulation value of gas power unit declines restricted by wind power installed capacity. The installed capacity for gas power unit is 5600 MW in RIP mode, which is 400 MW lower than that in IRJP mode. The installed capacity of thermal power unit in RIP mode is 25900 MW, which is 3000 MW higher than that in IRJP mode. The optimization results of system power planning in IRJP mode and RIP mode are shown in Table 9.

In terms of total fuel consumption, the total standard coal consumption is 391 million tce with total gas consumption 72.05 billion m^3 in IRJP mode during the planning period,

Table 8: The investment optimization results in IRJP mode and RIP mode.

Year	Region A planning units (IRJP, RIP)						Region B planning units (IRJP, RIP)				Transmission lines
	$N1$	$N2$	$N3$	$N4$	$N5$	$N6$	$N3$	$N4$	$N5$	$N6$	
1	(1, 1)	(1, 1)	(0, 0)	(0, 0)	(0, 0)	(0, 0)	(0, 1)	(1, 0)	(0, 0)	(0, 0)	1
2	(2, 1)	(0, 0)	(0, 0)	(0, 0)	(0, 2)	(0, 0)	(1, 2)	(0, 0)	(0, 0)	(0, 0)	1
3	(3, 2)	(0, 0)	(0, 0)	(0, 0)	(1, 2)	(0, 0)	(1, 2)	(0, 0)	(2, 0)	(0, 0)	0
4	(4, 2)	(0, 0)	(0, 0)	(0, 0)	(2, 2)	(0, 0)	(0, 2)	(0, 0)	(2, 0)	(0, 0)	1
5	(5, 3)	(0, 0)	(0, 0)	(0, 0)	(1, 1)	(0, 0)	(0, 2)	(0, 0)	(2, 0)	(0, 0)	1
6	(4, 2)	(0, 0)	(0, 0)	(0, 0)	(1, 1)	(0, 0)	(0, 2)	(0, 0)	(1, 0)	(0, 0)	1
7	(4, 3)	(0, 0)	(0, 0)	(0, 0)	(2, 2)	(0, 0)	(2, 2)	(0, 0)	(2, 0)	(0, 0)	1
8	(2, 3)	(0, 0)	(0, 0)	(0, 0)	(0, 2)	(0, 0)	(2, 2)	(0, 0)	(0, 0)	(0, 0)	0
9	(1, 3)	(0, 0)	(0, 1)	(0, 0)	(0, 1)	(0, 0)	(2, 2)	(0, 0)	(0, 0)	(0, 0)	0
10	(0, 2)	(0, 0)	(0, 2)	(0, 0)	(0, 0)	(0, 0)	(3, 3)	(0, 0)	(0, 0)	(0, 0)	0

Table 9: The optimization results of system power planning in IRJP mode and RIP mode.

Year	Region A accumulative installed capacity (IRJP, RIP)			Region B accumulative installed capacity (IRJP, RIP)		
	Wind	Thermal	Gas	Wind	Thermal	Gas
1	(600, 600)	(8550, 8550)	(0, 0)	(300, 300)	(8850, 9150)	(0, 0)
2	(1000, 800)	(8350, 8350)	(0, 800)	(300, 300)	(8950, 10150)	(0, 0)
3	(1600, 1200)	(7900, 7900)	(400, 1600)	(300, 300)	(9100, 10900)	(800, 0)
4	(2400, 1600)	(7500, 7500)	(1200, 2400)	(300, 300)	(8700, 11700)	(1600, 0)
5	(3400, 2200)	(7200, 7200)	(2000, 3200)	(300, 300)	(8400, 12600)	(2400, 0)
6	(4200, 2600)	(7200, 7200)	(2400, 3600)	(300, 300)	(8400, 13800)	(2800, 0)
7	(5000, 3200)	(6900, 6900)	(3200, 4400)	(300, 300)	(9300, 14700)	(2800, 0)
8	(5400, 3800)	(7950, 6750)	(3200, 5200)	(300, 300)	(10350, 15750)	(2800, 0)
9	(5600, 4400)	(8950, 7150)	(3200, 5600)	(300, 300)	(11350, 16750)	(2800, 0)
10	(5600, 4800)	(10250, 7850)	(3200, 5600)	(300, 300)	(12650, 18050)	(2800, 0)

while the total standard coal consumption is 408 million tce with total gas consumption 62.12 billion m^3 in RIP model. The installed capacity of wind power and gas power is higher in IRJP mode compared with RIP model. The increased generation of wind power and gas power squeezes the market share of thermal power generation. Therefore, system standard coal consumption is less and gas consumption is more. Figure 2 is fuel consumption comparison in IRJP mode and RIP mode.

In terms of environmental perspective, IRJP is more conducive to wind energy resource development and utilization in the destination areas. The growth and scale of the installed capacity of wind power generation in IRJP mode are superior to those in RIP mode. CO_2 emission in IRJP mode is lower than that in RIP mode. CO_2 emission is about 1.27 billion t in IRJP mode during the planning period, which is 30 million t lower than that in RIP mode. The installed capacity of wind power and CO_2 emission in IRJP mode and RIP mode is shown in Figure 3.

From the perspective of accumulated installed capacity, the installed capacity of wind power in the whole interregional power system gradually increases by 5900 MW by the end of the planning period. Meanwhile, in order to provide sufficient peak-shaving reserve for wind power generation,

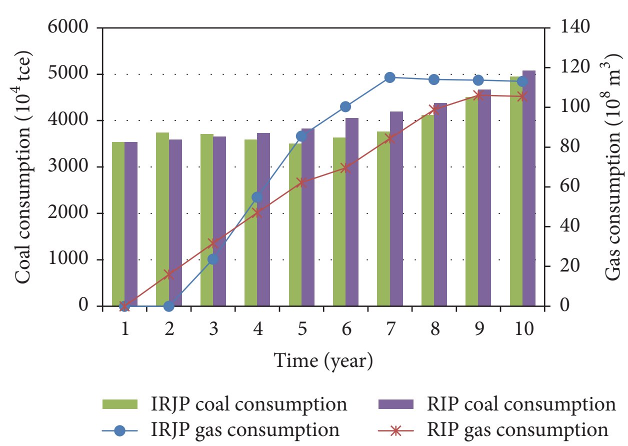

Figure 2: Fuel consumption comparison in IRJP mode and RIP mode.

the installed capacity of gas power generation also increases by 6000 MW. The installed capacity of thermal generation will shrink at the early stage and expand at the remaining period. At the middle and preliminary stages, the capacity proportion of thermal generation decreases from 95% at the early stage to the minimum 59% in the seventh year.

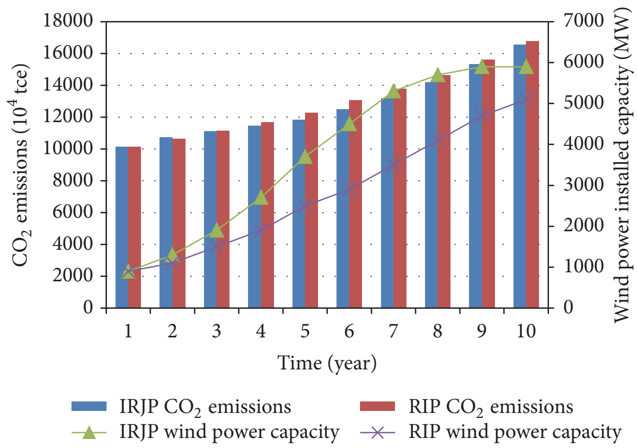

Figure 3: Wind power installed capacity and CO_2emission by joint planning and independent planning.

Table 10: Interregional power system planning results with CET.

Year	Unit of region A						Unit of region B				Transmission lines
	1	2	3	4	5	6	3	4	5	6	
1	1	1	0	0	0	0	0	0	0	0	0
2	2	0	0	0	0	0	0	0	1	2	1
3	3	0	0	0	1	0	0	0	3	0	0
4	4	0	0	0	2	0	0	0	2	0	1
5	6	0	0	0	2	0	0	0	1	0	1
6	4	1	0	0	2	0	0	0	1	0	2
7	6	0	0	0	1	0	0	0	2	0	1
8	0	0	0	0	0	0	4	0	0	0	2
9	0	0	4	0	0	0	1	0	0	0	0
10	0	0	3	0	0	0	3	0	0	0	0

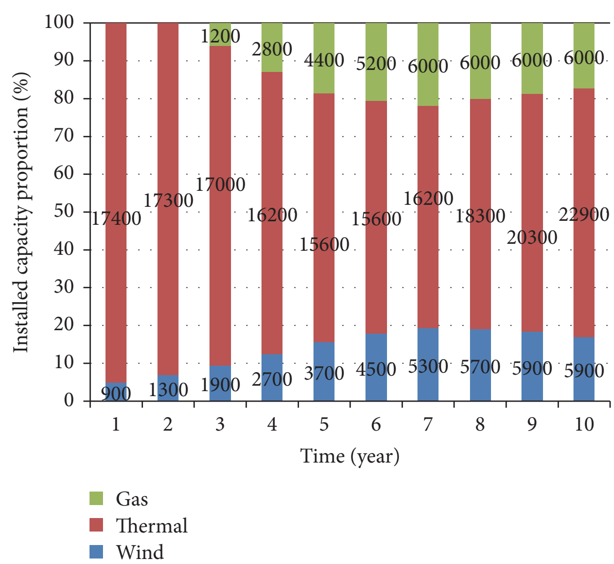

Figure 4: Structure of interregional installed capacity.

When the installed capacity of wind power reaches the regional resource cap value, the installed capacity of thermal unit reaches 10250 MW by the end of planning period. The installation capacity structure is shown as in Figure 4.

Through the above analysis, the advantage of IRJP mode mainly reflects in the two aspects. One is to establish a large-scale grid to expand wind power consumptive space by connecting each region with transmission lines, which is better to take full advantage of regional wind resource and optimize regional resource allocation. The other is to realize the peak shifting management of interregional power load by using the time lag of the maximum load combining with regional power load feature, which could reduce the power installed capacity of satisfying load peak demand and decrease power investment.

5.2.2. Planning Result in Case 2. In Case 2, carbon emission cost is brought into optimization model of power system planning. Since wind power generation needs regional transmission lines to transfer and improve wind power installed capacity and construction cost of transmission lines, within the planning period, 8 transmission lines will be constructed with 3200 MW delivered capacity, 800 MW more than Case 1, which reflects that CET could enlarge interregional power resource allocation. Interregional power system planning results with CET are shown in Table 10.

In view of power investment structure, since carbon emission trade is introduced in these regions, power structure tends to be low-carbon with total installed capacity of wind power and gas power 6100 MW and 7600 MW, respectively, 200 MW and 1600 MW higher than Case 1. The wind energy resource of region A develops in a larger degree by the end of the planning year and the development rate is more than Case 1.

In medium term of the project, the total wind power installed capacity has arrived at 3900 MW with only 3700 MW in Case 1. Since CO_2 emission by thermal power generation remains higher, the total installed capacity of thermal units is only 21100 MW, 1800 MW less than Case 1. Interregional power system planning results in Case 2 are shown as in Table 11.

As for carbon emission status in Case 2, CO_2 emission fails to be controlled completely within the initial allowable range, but it is lower than Case 1, with the total emission amount decreased by 20.45 million t. CO_2 emission amount and cost in Case 2 are shown as in Figure 5.

5.2.3. Planning Result in Case 3. In Case 3, the influence of REQ on IRJP is considered. After implementing REQ, wind power installation ratio will be restricted directly. Without enough conditions to develop wind power, region B would purchase wind power from A to meet the quota requirement, which increases wind power installed capacity in region A and enlarge the demand on transmission line capacity. In Case 3, 9 lines will be constructed within the planning period with the total capacity arriving at 3600 MW. The power system planning result in Case 3 is shown in Table 12.

Table 11: Interregional power system planning capacity and structure in Case 2.

Year	Installed capacity				Installed structure		
	Wind	Thermal	Gas	Wind	Thermal	Thermal	Wind
1	900	17100	0	18000	5%	95%	0%
2	1300	16400	0	17700	7%	93%	0%
3	1900	15500	800	18200	10%	85%	4%
4	2700	14700	2400	19800	14%	74%	12%
5	3900	14100	4000	22000	18%	64%	18%
6	4800	14100	5200	24100	20%	59%	22%
7	6000	14500	6400	26900	22%	54%	24%
8	6000	16800	7600	30400	20%	55%	25%
9	6100	18500	7600	32200	19%	57%	24%
10	6100	21100	7600	34800	18%	61%	22%

Table 12: Interregional power planning optimization results with REQ.

Year	Unit of region A						Unit of region B				Transmission lines
	1	2	3	4	5	6	3	4	5	6	
1	1	1	0	0	0	0	0	1	0	0	1
2	2	0	0	0	0	0	1	0	0	0	1
3	3	0	0	0	1	0	1	0	2	0	0
4	4	0	0	0	2	0	0	0	2	0	1
5	5	0	0	0	2	0	0	0	2	0	1
6	6	0	0	0	1	0	0	0	1	0	2
7	6	1	0	0	2	0	2	0	2	0	1
8	3	0	0	0	2	0	1	2	1	0	2
9	1	0	0	0	0	0	0	1	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0

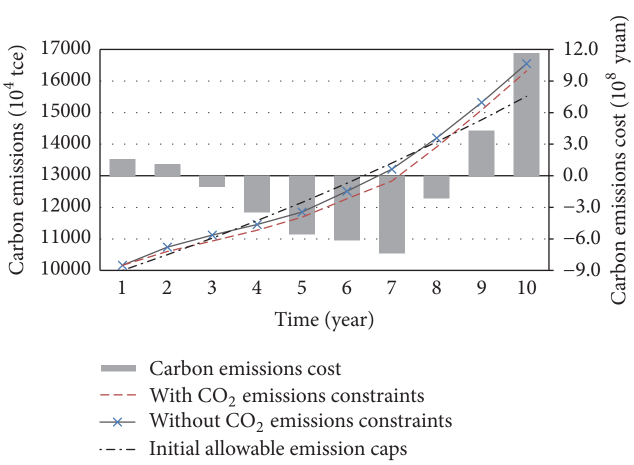

Figure 5: CO_2 emission amount and carbon emission cost.

As for power investment structure, total system installed capacity is 35300 MW, 500 MW more than Case 2. Wind power development scale in region A is higher than Cases 1 and 2, accumulated installed capacity increases by 4% in Case 3, and the installed capacity of gas generating units increases by 6%. That is to say, REQ contributes to the increase of wind power installation scale and the restraint on system load reserve.

Specifically, since the installed proportion of wind power in Case 1 in the medium term is 16%, which meets the requirement of renewable energy quota, installation distribution of system planning in the previous five years remains the same with Case 1 in order to minimize investment cost. In the latter five years, to meet the requirement of the quota, wind power installation speed is upgrading year by year till 21% in the seventh year. To control the overall power investment cost, wind power installation slows down to 20%. The system installation capacity and structure in Case 3 are shown in Table 13.

5.2.4. Planning Result in Case 4. In Case 4, in order to reduce carbon emission cost and meet REQ restraint, the installed capacity of system renewable energy arrives at a maximum status with more new transmission lines. 11 transmission lines will be constructed with 4400 MW delivered capacity during the planning period. The power system planning optimization result in Case 4 is shown in Table 14.

In this case, the overall system installed capacity is 35400 MW, higher than Case 3. The installed capacity of wind power and gas power unit reaches 7300 MW and 8000 MW. Installation proportion of wind power and gas power unit arrives at 21% and 23%, respectively, which remain higher than other cases. To minimize power investment cost, thermal power installed space is reduced to 20100 MW, 10% lower than Case 1. The system installed capacity and structure distribution in Case 4 is shown in Table 15.

In Case 4, CO_2 emission is entirely controlled within the initial allowable range with yearly emission less than Case 2. Total emission is lowered by 16.44 million t than Case 2 with a decrease degree by 1.3%. CO_2 emission amount and cost in Case 4 are shown in Figure 6.

5.3. Comparative Analysis. In order to comparatively analyze the impact of CET and REQ on IRJP, the terminal installed capacity, transmission lines construction, installation distribution of wind power, gas consumption, and coal consumption of 4 cases are sorted out. Power system planning in 4 cases is shown in Table 16.

Table 13: System installation capacity and structure in Case 3.

Year	Installed capacity				Installed structure		
	Wind	Thermal	Gas	Wind	Thermal	Coal	Wind
1	900	17400	0	18300	5%	95%	0%
2	1300	17300	0	18600	7%	93%	0%
3	1900	17000	1200	20100	9%	85%	6%
4	2700	16200	2800	21700	12%	75%	13%
5	3700	15600	4400	23700	16%	66%	19%
6	4900	15600	5200	25700	19%	61%	20%
7	6200	16200	6800	29200	21%	55%	23%
8	6800	18300	8000	33100	21%	55%	24%
9	7000	20300	8000	35300	20%	58%	23%
10	7000	20300	8000	35300	20%	58%	23%

Table 14: Power system planning optimized result in Case 4.

Year	Unit of region A						Unit of region B				Transmission lines
	1	2	3	4	5	6	3	4	5	6	
1	1	1	0	0	0	0	0	1	0	0	1
2	2	0	0	0	0	0	1	0	0	0	1
3	3	0	0	0	1	0	1	0	2	0	0
4	4	0	0	0	2	0	0	0	2	0	2
5	6	0	0	0	2	0	0	0	2	0	2
6	5	1	0	0	1	0	0	0	1	0	1
7	6	2	0	0	1	1	2	0	2	0	2
8	3	0	0	0	2	0	1	2	1	0	0
9	1	0	1	1	0	0	0	1	0	0	2
10	0	1	0	0	0	0	0	0	0	1	0

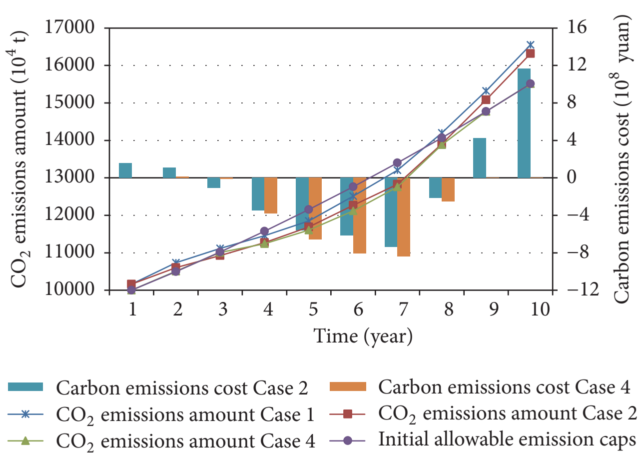

Figure 6: CO_2 emission amount and cost in Case 4.

Seen from the investment result of power system planning, CET can upgrade the installed capacity of wind power while the increasing degree is not obvious than REQ. REQ could improve the restraints on system transmission capacity. Transmission lines construction distribution is shown in Table 17.

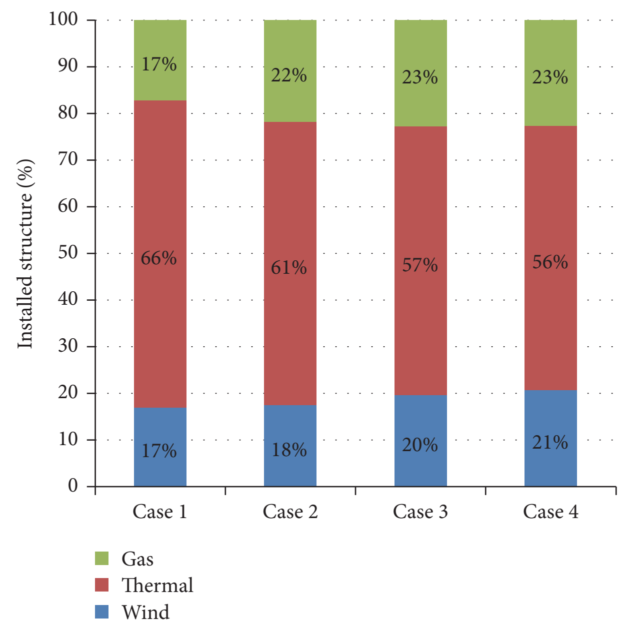

Figure 7: System installed structure at the end of period in 4 cases.

The terminal wind power installed capacity in Case 4 arrives at a maximum amount with the most transmission lines and investment cost. From a short-term perspective, CET and REQ can increase the system operation cost. In the long run, with the environment becoming worse, CET and REQ can help promote clean energy development, reduce CO_2 emission, and push forward society sustainable development. System terminal installed structure in the four cases is shown in Figure 7.

In view of the terminal system installed structure, the system installed structure is best optimization since CET and REQ are introduced compared with Cases 2 and 3. In Case 4, wind power installation proportion reaches 21%. Gas power generation installation proportion reaches 23%, higher than other three cases, which reflects that CET and REQ can optimize power system planning and realize resource optimization allocation. Wind power installation distribution in 4 cases is shown in Figure 8.

Table 15: System installed capacity and structure distribution in Case 4.

	Installed capacity				Installed structure		
	Wind	Coal	Gas		Wind	Coal	Gas
1	900	17400	0	18300	5%	95%	0%
2	1300	17300	0	18600	7%	93%	0%
3	1900	17000	1200	20100	9%	85%	6%
4	2700	16200	2800	21700	12%	75%	13%
5	3900	15600	4400	23900	16%	65%	18%
6	5000	15600	5200	25800	19%	60%	20%
7	6400	16200	6600	29200	22%	55%	23%
8	7000	18300	7800	33100	21%	55%	24%
9	7200	20100	7800	35100	21%	57%	22%
10	7300	20100	8000	35400	21%	57%	23%

Table 16: Power system planning results in 4 cases.

	Installed capacity at the end of period/MW				Transmission lines	Total investment/10^8 yuan
	Wind	Thermal	Gas	Total		
Case 1	5900	22900	6000	34800	6	4889
Case 2	6000	21100	7600	34700	8	4891
Case 3	7000	20300	8000	35300	9	4915
Case 4	7300	20100	8000	35400	11	4920

Table 17: Transmission lines construction distribution in the four cases.

Year	1	2	3	4	5	6	7	8	9	10
Case 1	1	1	0	1	1	1	1	0	0	0
Case 2	1	0	1	1	2	1	2	0	0	0
Case 3	1	1	0	1	1	2	1	2	0	0
Case 4	1	1	0	2	2	1	2	0	2	0

Wind power installation in the four cases remains similar in distribution regulation. Installation at the early stage basically keeps the same pace while it keeps growing year by year since CET and REQ are introduced at the middle of planning period. The optimization effects of system planning reaches best if both CET and REQ are introduced.

From the perspective of total fuel consumption, CET and REQ are conducive to develop and utilize wind energy resource of destination regions. Wind power resource replaces the coal resource consumption of thermal power units, reducing system coal consumption. Wind power grid connection needs gas power units to provide load reserve, which increases gas consumption. Since the energy efficiency of gas remains higher than coal, clean energy development and application are also improved in this case. Fuel consumption comparison in four cases is shown as in Table 18.

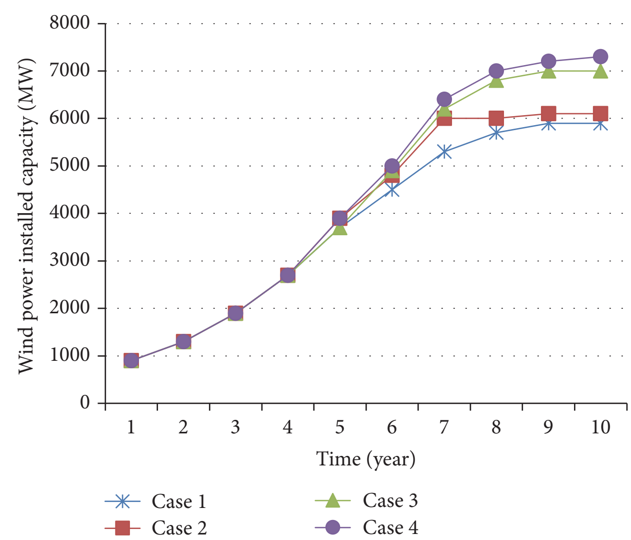

Figure 8: Wind power installation distribution within the planning period in 4 cases.

6. Conclusions

The construction of UHV transmission line promotes the construction of interregional power system, which is conducive to realizing the optimization configuration of power resource. As the direct and indirect means to improve the clean energy grid, CET and REQ can improve clean energy grid connection and influence the optimization program of power system planning. Therefore, the optimization model for interregional power system planning with CET and REQ is constructed and the result shows the following:

(1) Compared with RIP, IRJP can connect region power grid, expand wind power consumptive space, promote the utilization of wind power resource, and

Table 18: Fuel consumption in 4 cases.

Year	Gas consumption/10^4 tce				Goal consumption/10^4 tce			
	Case 1	Case 2	Case 3	Case 4	Case 1	Case 2	Case 3	Case 4
1	0	0	0	0	3543	3482	3543	3543
2	0	0	0	0	3744	3549	3744	3744
3	23.68	15.79	23.68	23.68	3705	3378	3705	3705
4	54.82	46.99	54.82	54.82	3595	3262	3595	3595
5	85.53	77.75	85.53	89.42	3509	3172	3509	3509
6	100.41	100.41	100.41	108.13	3631	3282	3631	3631
7	115.12	122.79	126.632	141.98	3766	3371	3766	3766
8	114.09	144.51	148.317	155.92	4120	3782	4120	4120
9	113.72	144.05	147.836	159.21	4513	4113	4513	4469
10	113.1	143.26	154.57	158.34	4948	4559	4386	4343

overcome the reserve distribution between power resource and load demand.

(2) CET can improve the clean energy installation proportion, optimize the power structure, and reduce the system CO_2 emission. After introducing CET, regional power structure becomes more low-carbon, and installed capacity of wind power and gas power unit increase, which decrease system overall CO_2 emission. The emission reduces by 20.45 million t compared to the case without CET.

(3) Compared with CET, REQ can improve wind power installed capacity in a large degree and enhance the utilization efficiency of wind resource. However, large-scale delivery of wind power relies on more transmission capacity, which leads the investment cost of transmission line construction to become higher.

(4) Since the introduction of CET and REQ leads to operational cost for power system increase, relevant subsidy policies are expected to be issued by government to give full incentive to the two measures, which will stimulate power grid of each region to participate in IRJP and respond to the requirement of CET and REQ.

Competing Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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