The water-carbon constraints’ impact on the development of coal power industry in the Yellow River Basin

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Abstract

In order to study the influence of water and carbon constraint policies on coal power industry under different scenarios, the government can adjust policies timely according to the simulation results. In this paper, a system dynamics model of coal power industry development under water-carbon dual constraints is constructed. Eight provinces in the Yellow River Basin are selected as the research objects, and the year 2020 is taken as the base year and 2021–2030 is taken as the research time zone to carry out an empirical study. The results show that: (1) under the existing water and carbon quota allocation policy, the profit of coal and power industry in the Yellow River basin will decrease obviously, and the development pressure of coal and power enterprises in the Yellow River basin will increase. (2) Water–carbon constraint has obvious extrusion effect on coal power industry. According to the calculation in this paper, the extrusion capacity will reach 395.17 TWh. (3) The water and carbon quota policy does not constrain the coal power industry at the same time. The existing water quota allocation method matches the ‘2030’ water consumption target, but the carbon quota allocation scheme has weak constraint on the coal and power industry in the Yellow River Basin, so the carbon quota should be tightened. (4) After the tightening of carbon quota, the coal emission reduction technology should be upgraded and improved before 2025. After 2025, the coal emission reduction technology can be mainly restricted by quota. (5) New energy planning should be combined with its own development situation and quota allocation policy. When the amount of coal and electricity extruded by water–carbon constraint is not enough to meet the target of new energy installation, it should be planned according to its own development situation and extrusion amount. When the amount of coal power extruded by water–carbon constraint is enough to meet the target of new energy installation, the amount of coal extruded should be taken as the main planning basis.

1. Introduction

China is the world’s largest producer and user of coal power, with about 70% of its electricity coming from coal-fired power plants (Electricity Statistical Year book 2019). Although the proportion of new energy generation has increased in recent years, the proportion of coal power industry has decreased slightly, but it is still stable at about 62% (Electricity Statistical Year book 2019). Coal power industry is a typical industry with high water consumption and high carbon emission, second only to agriculture in terms of water consumption, accounting for more than 45% of China’s carbon emissions. The eight provinces along the Yellow River basin are rich in coal resources, accounting for more than half of China’s coal production and more than a quarter of the country’s thermal power generation. The Yellow River Basin is also a serious water shortage area in China (Zhang et al. 2014), with a population of 24.15% of the country (China Statistical Year book 2020) and only 3% of the total water resources in China (Zhang et al. 2013). To ease water pressure, the Chinese government has issued requirements on the Planning and Construction of Coal-fired Power Plants, requiring new and expanded...
coal-fired power plants in water-stressed areas, including the Yellow River Basin, to control water consumption. The consumption of water resources and carbon dioxide emissions corresponding to different power generation technologies change inversely (Byers et al 2016). This paper focused on the influence of the constraints for ‘Carbon peak 2030 target’ and water-saving target in China of the energy industry, to research the influence mechanism of water-carbon constraints of coal industry, to explore the possible development path of coal and power industry in the Yellow River Basin under the water and carbon policy, and provide reference for the high-quality development of power industry and energy strategic planning.

The coupling relationship of ‘water-energy-carbon’ is the theoretical basis for studying the influence mechanism of water-carbon double constraints on the coal power industry. Many scholars pay attention to the coupling relationship of ‘water-energy-carbon’ and the matching of resources and environment policies in the power industry (Lin and Chen 2018). By studying the relationship between water-energy-carbon emissions of power plants and found that the cost of reducing carbon emissions is to increase water consumption (Wang et al 2021), and carbon dioxide sequestration technology will increase the water resource limitation for thermal power generation in water-scarce areas (Wang et al 2019). Resulting in increased vulnerability to water resources and electricity production (Frumhoff Peter et al 2015), and the transition to a less water-dependent grid may reduce the impact of carbon dioxide emissions from power generation on water resources vulnerability (Colin et al 2014). Therefore, to ensure the positive impact of carbon reduction on water resources, climate policies should be combined with energy and/or water policies (Mouratiadou et al 2017). Northern China, where the Yellow River basin is located, is currently under the dual pressure of water shortage and national greenhouse gas emission reduction targets. Policy formulation should focus on schemes that can both save water and reduce carbon emissions (Zhang et al 2014). These policies will also influence decisions on coal and power systems (Peng and Ramana 2018). In this regard, scholars have proposed two technical approaches: increasing non-coal power generation (Li et al 2017) and changing the cooling technology mix (Qin and Kopec 2015, Zhang et al 2017). After comparing the water-saving potential of the two approaches, (Li et al 2021) believes that upgrading water-saving technology is more suitable for coal-based provinces with high water consumption, while other provinces may give priority to introducing non-coal power. Some scholars also believe that if more resources are invested in the installation of clean energy, its emission reduction effect will be difficult to achieve qualitative change in a short term, and the existing power generation mode should be reformed to make it low-carbon and environmentally friendly (Yu et al 2020).

The quantitative research on the development path of coal power industry under the water-carbon double constraint has been gradually carried out. (Dodder Rebecca et al 2016) explored the potential trade off relationship between carbon emission reduction and water demand reduction by combining the market distribution energy system model with the life cycle method, providing reference for water saving and carbon reduction in coal power industry. (Shaikh et al 2017) applied footprint analysis and scenario analysis to calculate the carbon emission and water resource consumption generated by different power production structures, and studied the adjustment path of energy structure in the power industry based on the balance of the two impacts. Some scholars studied the relationship between emission reduction (Zhang and Zhou 2020) and water consumption (Shaikh et al 2017) and the power market under different policy scenarios and intensity, set up 10 scenarios to analyze the coupling relationship of ‘material-energy-water-carbon’ in the power generation sector, and discussed the scheme of coordinated management of power market, water resources and carbon emission reduction. In addition to simply considering water and carbon policies, many scholars consider both economic and social needs and market factors. Based on the existing policies of the power sector on total water consumption and carbon emissions, and taking the economic cost minimization as the objective function, the selection path of power generation technology, cooling technology and carbon reduction technology in the coal power industry is optimized. (Li et al 2020) (Huang et al 2016) analyzed the influence of carbon constraint and water price change on path selection of coal power generation technology. Tables 1-4 provide data for the data simulation in subsequent chapters.
The above research results provide a reference for judging the development path of coal and power industry in the Yellow River Basin under the water-carbon constraint, but the modeling process lacks comprehensive and systematic consideration of water and carbon trading market, policy dynamics and other factors. At present, the research on electric power development mainly focuses on the development of structure under the single constraint of water resources or carbon emissions, and there is little research on the policy making of coal power industry under the joint constraint of water resources and carbon emissions. In fact, the development of coal power industry under water-carbon constraint is a complex system involving production technology selection, water right trading market, carbon trading market, water quota policy and carbon quota allocation policy. Based on the interaction of various factors in power demand, production and operation, this paper constructs a high-order, multi-variable and multi-feedback system dynamics model of coal power industry in the Yellow River Basin under water-carbon constraints. For water carbon quotas, technical structure, makes a comprehensive analysis and factors such as new energy power generation system, under the premise that predict the total electricity demand, according to thermal power of thermal power generating capacity, combined with the water in the process of coal consumption, CO2 emissions, water and carbon allocation proportion, thermal power unit cooling way. In addition, the influence of water rights trading market and carbon emission trading market on the scale and profit of thermal power generation enterprises is studied, and the development trend of coal power industry under different water and carbon quota constraint targets is studied, as well as what policies should be matched by the government to better constrain the water consumption and carbon emission in the process of coal-fired power generation.

2. Methods and models

SD solves the problem of multiple information feedback in complex systems by establishing variable relations of multiple variables, multiple feedback, high order and highly nonlinear, and analyzing the influence relations among related elements in a system qualitatively and quantitatively. In the coal power system, the generating capacity is affected by the supply and demand of the power market, and the supply and demand are affected by the policy, economy, technology and other factors, and the generating capacity in turn affects these factors and forms feedback among each other. Among them, electricity demand is influenced by population, per capita disposable income and regional GDP. The influencing factors of electricity supply are complicated and are affected by both internal and external factors of power generation enterprises. Internally affected by cost, revenue, power generation technology, etc. The revenue comes from the sale of power generation by the enterprise. The cost includes fixed cost and variable cost, etc. The power generation technology includes utilization hours, power consumption rate and cooling technology, etc. Externally, under the existing environment of water quota, water right trading market, carbon quota and carbon market, enterprises have to consider the impact of carbon emission cost and water cost on enterprise profits. Carbon emission and water

| Year | Actual value(TWh) | Simulation value(TWh) | Error |
|------|-------------------|-----------------------|-------|
| 2015 | 1570.9            | 1592.6                | 1.38% |
| 2016 | 1599              | 1622.3                | 1.46% |
| 2017 | 1681.2            | 1693.5                | 0.73% |
| 2018 | 1845.3            | 1746.4                | 5.36% |
| 2019 | 1877.5            | 1800.8                | 4.09% |
| Mean error | 2.6%          |                       |       |

| Year | Actual value(MW) | Simulation value(MW) | Error |
|------|------------------|---------------------|-------|
| 2015 | 287.7            | 287.7               |       |
| 2016 | 218.3            | 239.9               | 9.9%  |
| 2017 | 207.9            | 200.1               | 3.8%  |
| 2018 | 167              | 166.9               | ≈0%   |
| 2019 | 199.7            | 196.8               | 1.5%  |
| Mean error | 3.8%          |                       |       |
Table 4. Thermal power ratio, new energy generation capacity and new energy installed capacity under different scenarios.

| Scenario                          | Thermal power ratio | New energy generation (TWH) | Increased new installed capacity of new energy ($\times 10^4$) |
|----------------------------------|---------------------|----------------------------|---------------------------------------------------------------|
| Existing quota allocation policy | Scenario 1          | 0.66                       | 408.13                                                         | 13035                                                   |
|                                   | Scenario 2          | 0.58                       | 1080.24                                                        | 76670                                                   |
| Quota allocation policy tightened | Scenario 1          | 0.4                        | 1176.75                                                        | 37583                                                   |
|                                   | Scenario 2          | 0.35                       | 1755.46                                                        | 124593                                                  |
consumption are also affected by technical parameters and free quota. It can be seen that the power generation system is a complex system involving multiple factors and multiple feedbacks, and the system dynamics method has some advantages in studying this problem.

### 2.1. Determine system boundaries

The objective of this paper is to study the influence of water-carbon constraint on coal and power industry in the Yellow River Basin. This paper analyzes the changing trend of various elements in the coal power industry system under different quota allocation policies and development scenarios, and sets up different types of development policy optimization scenarios for simulation according to the reality, providing reference for the future development of coal power industry.

In this paper, the boundary of the constructed system model is set, and the factors within the boundary are studied as a complete system, and the changes of the factors outside the boundary will not have a great impact on the overall system. Coal power generation system involves many factors, including the demand for electricity by social and economic development, the choice of thermal power unit’s technology mode, the national requirements for energy conservation and emission reduction, and the influence of related resource prices. Based on the dual constraints of water resource consumption and carbon dioxide emission, combined with the process of coal-fired power generation, the development system of coal power industry is divided into three interrelated subsystems: demand system, production system and operation system. The three subsystems interact with each other and jointly determine the development path of coal power industry. The demand system includes per capita disposable income, gross regional product and electricity demand. The production system includes: carbon consumption per unit of power generation, carbon quota, variation ratio of carbon consumption per unit of power generation, carbon price, water consumption per unit of power generation, water quota, variation ratio of water consumption per unit of power generation, water price, proportion of cooling mode of unit and new energy generation. Operation system includes: thermal power grid price, thermal coal price, unit power generation cost, investment and construction cost of new thermal power installed capacity, etc.

1. **Demand system.** This paper chooses per capita disposable income and gross regional product as the influencing factors of electricity demand. With the increase of per capita disposable income and gross regional product, the demand for coal power gradually increases.

2. **Production system.** It is mainly reflected in the dynamic feedback system formed between technology selection (cooling technology) and development scale (electricity generation) of coal power industry and related factors under the influence of water price, carbon price, water right trading market and carbon trading market under the limit of water resource and carbon emission as undesired output. It includes two main feedback loops, water resource constraint loop and carbon emission constraint loop. The former can be described as a causal loop: water consumption per unit of power generation → water consumption per unit of power generation → water consumption per unit of power generation. The higher the water consumption per unit of power generation, the more water consumption per unit of power generation of coal power enterprises, under the premise of a certain amount of water consumption, the more water will be involved in the transaction, and the increase of water consumption will force enterprises to reduce the water consumption per unit of power generation. Under normal circumstances, in areas with water resource overload, the government will gradually reduce the allocated water quota in order to ensure that the water quota is binding. The latter can be described as a causal loop: carbon consumption per unit of power generation → carbon emission per unit of power generation → carbon volume involved in transactions → carbon consumption per unit of power generation. Coal power enterprises with higher carbon consumption per unit of power generation emit more carbon, and under the premise of a certain carbon quota, they need to purchase more additional carbon. The increase of carbon emission cost forces enterprises to reduce carbon consumption per unit of power generation. In the future, when the total amount of carbon emission control is gradually reduced, the government will gradually tighten the carbon quota. In addition, in the production system, there are also differences in water consumption and carbon emissions corresponding to different cooling modes of generator sets, which affect the allocation of water and carbon quota. Therefore, this paper considers the technical structure of coal power production as the main factor in the production system.

Operating systems. As the main market, coal power industry is a typical input-output system. Its input includes operating cost, which consists of depreciation expense, financial expense, employee salary, material expense, repair expense, environmental protection tax, entrusted operation expense, and other expenses. Fuel cost, that is, the fuel cost purchased for power generation in coal-fired power generation, is calculated by multiplying the power supply standard coal consumption by the comprehensive standard coal unit price. The
investment and construction cost generated by the new installed power generation capacity each year. Water resource transaction cost and carbon transaction cost are also important input factors. As an output factor, the electricity generation and the on-grid price of thermal power jointly determine the operating income of coal power industry.

2.2. Assumptions
In order to facilitate the research, a series of assumptions are made to make the model more reasonable. For the relationship between variables in the model and the power generation process, the following assumptions are proposed:

(1) Electricity demand determines electricity generation. The fundamental purpose of electricity generation is to meet demand. According to previous statistical data, electricity consumption and electricity generation are basically the same, so this paper assumes that electricity generation is completely determined by electricity demand.

(2) In order to simplify the model, the thermal power generation proposed in the system constructed in this paper refers to coal-fired power generation, excluding gas-fired power generation. New energy power generation only considers the installation of wind power and photovoltaic power sets, excluding hydropower, nuclear power, biomass power generation and other power generation forms.

(3) Setting range of carbon price and thermal coal price. The carbon price is influenced by both the carbon emission of thermal power generation and the carbon quota target set by the government. The thermal coal price is determined by supply and demand, regardless of the impact of sudden market fluctuations on these two prices.

(4) The floating range of electricity price. This paper is formulated according to the pricing mechanism of coal on-grid electricity price 'base price + fluctuation ratio', in which the upward fluctuation ratio does not exceed 10% and the downward fluctuation ratio does not exceed 15%. Assume that the construction cycle of thermal power units and new energy installations is one year.

2.3. Causal analysis of the system
According to system dynamics, there are usually some main loops and main variables that play a leading role in a complex system. Therefore, a higher-order system is formed by coupling of several feedback loops. Feedback refers to that system variable A influences variable B, which in turn influences variable A through a series of causal chain in the system, thus forming a feedback loop. In the positive feedback loop, the increase or decrease of the variable will be intensified due to its own feedback effect. A negative feedback loop can produce homing behavior.

Firstly, the relationship between carbon market price, carbon quota supply and demand, water rights trading market, water quota supply and demand, and electricity generation of various energy sources in electricity market is simulated. Figure 1 shows the causal loop diagram of water and carbon trading in the power industry. It can be seen from the figure that the thermal power unit will consume water and produce carbon dioxide for power generation, and the amount of water consumption and carbon emission depends on the choice of cooling mode of the thermal power unit. Under the current policy restrictions on water use and carbon emission, the market mechanism is the main factor driving thermal power enterprises to shift to cleaner power generation, which will also drive the adjustment of the power generation structure of the entire power industry. When the water and carbon credits allocated to enterprises cannot meet their needs, the power generation enterprises will purchase them through the exchange market to meet the demand. Increased demand will lead to higher water and carbon prices. When these two prices rise, the cost of water and carbon emission of thermal power enterprises will increase. In the case that the on-grid electricity price remains unchanged, the profit of thermal power enterprises will be reduced, the thermal power generation will be reduced, the carbon emission will be reduced, the carbon quota expected to be sold by thermal power enterprises will increase, the carbon price will decrease, and finally the equilibrium state will be reached.

Based on the analysis of the system theoretical framework, the causal feedback relation of the model is established combining with the logical relation among subsystems. See figure 2.

By analyzing the above causality diagram, it can be concluded that: (1) the coal power industry can achieve the purpose of reducing water consumption and carbon consumption per unit of power generation by improving technology, and at the same time reduce the demand for water and carbon emission, and reduce the cost of water and carbon emission. Among them, the technological progress of thermal power generation is mainly reflected in changing the cooling mode of the generator set, such as the choice of circulating water cooling, dc water cooling and air cooling technologies, and improving the energy efficiency of the generator set,
so that the power generation process is more clean and efficient. (2) The increase of thermal power generation leads to the increase of water consumption, and the expected water quota of coal power industry increases. In order to force coal-fired power companies to reduce their use of water, the government will reduce quotas, which will increase the amount of water they need to buy. In the water trading market, the greater the demand, the higher the price of water, the higher the cost of water. In order to control the cost, the coal power industry will reduce the thermal power generation, thus forming a negative feedback loop. The same is true of the carbon emission process of the coal power industry alone. At the same time, the water consumption and carbon emission in thermal power generation are two processes, which depend on the choice of cooling mode of thermal power unit. Dc cooling consumes more water and emits less carbon, while air cooling consumes less water and emits more carbon. (3) When the coal industry of water and carbon credits, coal-fired power...
generation in the process of actual water usage and carbon emissions more than the initial quota allocation amount, and the market does not have enough water and carbon credits to buy, to meet the demand of the coal industry should be water and carbon credits outside of the electricity generated in the form of new energy power generation.

2.4. System flow diagram construction

The interaction and feedback relationship among the elements of the system can be visually described through the causal diagram, and the process of constructing the causal diagram is also the process of analyzing the model structure, which is the basis for the subsequent quantization of the model and simulation. Therefore, on the basis of structural analysis, we need to distinguish the types of system variables to build a system flow diagram and refine the established system model. In order to further establish the functional relationship between variables, the use of functional equations and data to enrich the logical relationship between variables. Based on the dynamic feedback relationship between variables in 2.3 structural analysis, this paper distinguishes the properties of variables within the model boundary, involving variables of different properties such as state variables, rate variables, auxiliary variables and constants, thus establishing the system flow diagram as shown in figure 3.

Nine state variables are selected in the system model, including electricity demand, carbon consumption per unit of power generation, carbon price change, water consumption per unit of power generation, coal price, electricity price change, installed capacity of new energy, installed capacity of new thermal power, installed capacity of new energy, etc. Rate variables such as growth rate of electricity demand, change rate of carbon consumption per unit of power generation, carbon price, change rate of water consumption per unit of power generation, change rate of water price, change rate of thermal coal price, and auxiliary variables such as carbon emission of thermal power, water consumption of thermal power, coal consumption of thermal power units, and unit cost of power generation.

In this paper, the development of coal power industry under water and carbon constraint is taken as the main entry point to study the changes of the scale and profit of coal power industry brought by the restriction of water and carbon emission quota in the process of coal power generation under the background of water rights trading market and carbon trading market. Selection of electricity demand, the unit power generation carbon consumption, water consumption unit power generation, thermal power unit cooling way as input variables, such as selection of extrusion of new energy power generation, thermal power ratio, thermal power unit profit, such as the carbon price as output variables, to look at different water carbon constraints the development of the coal industry under the different emphases development trend.

2.5. Relationship between parameter settings and functions

According to the causal relationship between water consumption and carbon emission in the process of power generation, the statistical data of coal power industry in the Yellow River Basin are collected comprehensively, the relationship between the main variables is analyzed in detail, and the system dynamics model of the system is established by calculating the parameters.
Parameters in the system are mainly determined by the following methods:

(1) Based on published statistical data, such as China Electric Power Statistical Yearbook, China Energy Statistical Yearbook, Statistical Yearbook, China Electric Power Industry Annual Development Report 2021, national standards, etc.

According to China Electric Power Statistical Yearbook 2021, the line loss rate is set at the national average of 5.6%, and the power consumption rate is set at the average of 5.67% in the eight provinces. Thermal power generation in the eight provinces of the Yellow River Basin accounts for 80% of the annual power generation in this region, and the standard coal consumption for power generation is set at the average of 312.9 g K^{-1}W^{-1}H^{-1} in the eight provinces. According to the Annual Development Report of China’s Electric Power Industry 2021, carbon dioxide emission per unit of power generation in China is about 832 g K^{-1}W^{-1}H^{-1}, and water consumption per unit of power generation in China is 1.21 kg/KWH. According to China coastal thermal coal purchase Price Index (CECI Coastal index) shows that the annual average thermal coal price of 576 yuan/ton in 2020; According to the transaction price of the national carbon trading market, the initial carbon price is set at 50 yuan/ton. According to the Notice of the National Development and Reform Commission on Adjusting the Price of Water Supply for The Lower Yellow River Headwork and Yuecheng Reservoir issued by the National Development and Reform Commission in 2013 (NO. 540 [2013]), the price of non-agricultural water is adjusted to 0.14 yuan/m³ from April to June. In other months, the value is adjusted to 0.12 yuan/m³, and the average value is 0.13 yuan/m³ in this paper. The base price of thermal power on-grid electricity price is 0.3247 yuan/KWH average of the eight provinces in the Yellow River Basin.

The carbon quota of thermal power units in the eight provinces of the Yellow River Basin is calculated according to the quota allocation method stipulated in The ‘2019–2020 National Total Carbon Emission Trading Quota Setting and Implementation Plan (Power Generation Industry)’, and the proportion of coal-fired units with different specifications is calculated according to the ‘China Electric Power Statistical Yearbook 2021’. The results show that the proportion of conventional coal-fired units of 300MW grade or above and 300MW grade or below in eight provinces of the Yellow River Basin is 80% and 20% respectively.

According to the characteristics of water use in different industries, the government defines the scope of water withdrawal, the scope of water supply and the measurement of water withdrawal, prescribes the calculation method of water withdrawal quota and classifies quota index grades. The water intake quota standard is an important basis for verifying the amount of water withdrawn, and is one of the main indexes for assessing the utilization efficiency of water resources and water saving of enterprises. The water consumption quota shall be calculated based on the water consumption quota stipulated in the National standard of the People’s Republic of China ‘Water Intake Quota Part I: Thermal Power Generation’ (GB/T 18916.1–2021).

(2) With the help of system dynamics delay function, conditional function, etc, establish function expressions between variables to determine parameters. For example, the delay function is established to determine the influence of new installed thermal power capacity on generation cost. According to the latest standard, the on-grid price of thermal power is based on the base price, the upward float is not more than 10%, the downward float is not more than 15%. Based on this, the conditional function is established to express the fluctuation of the on-grid price of thermal power within the research period.

(3) For variables that have not been defined, find out the mechanism of interaction between variables according to relevant literature, and make reasonable and well-grounded estimation and judgment.

The specific relationship between variables is as follows:

(1)  
State variables: 
Electricity demand = Integ(Initial value, Incremental demand for electricity)  
Change of carbon price = Integ(Initial carbon price, Carbon quota requirement)  
Change of feed-in price = Integ(Initial feed-in tariff, Net demand for electricity)  
Coal price = Integ(Initial coal price, Coal price growth rate)  
New installed capacity of new energy = Integ(0, Construction of new energy installations started-New energy installations completed)  
Installed capacity of new energy = Integ(Initial value, New energy installations completed)  
Water consumption per unit power generation = Integ(Initial value, Incremental water consumption per unit of power generation)  
Carbon consumption per unit of power generation = Integ(Initial value, Incremental carbon consumption per unit of power generation)
(2) Rate variable
Incremental demand for electricity = Electricity demand × Demand growth
Coal price growth rate = (1-Coal supply/Coal demand) × Coal supply elasticity coefficient
Net demand for electricity = Feed-in tariff × (Electricity demand × Thermal power generation)/Electricity demand
Carbon quota requirement = Carbon emission from thermal power
Increment of newly installed capacity = Newly installed capacity × Growth rate of new installed capacity
New energy installations completed = DELAY FIXED(Construction of new energy installations started, cycle, Initial value)
Construction of new energy installations started = Installed capacity of new energy increased × Installed capacity of new energy

(3) Instrumental variables
Carbon emission from thermal power = Carbon consumption per unit of power generation × Thermal power generation
Extrusion generation under water constraint = (Water consumption × Water quota)/Water consumption per unit power generation
Extrusion generation under carbon constraint = Amount of carbon by participating in carbon trading × 10⁻³/Carbon consumption per unit of power generation
Extruded new energy generation = Extrusion generation under water constraint + Extrusion generation under carbon constraint
Carbon price = IF THEN ELSE(SMOTHI(Change of carbon price, Carbon quota, Initial carbon price) > Carbon price maximum, Carbon price maximum, IF THEN ELSE(SMOTHI(Change of carbon price, Carbon quota, Initial carbon price) < Carbon price minimum, Carbon price minimum, SMOTHI(Change of carbon price, Carbon quota, Initial carbon price)))
Coal demand = Coal consumption of thermal power unit × Thermal power generation
Coal price growth rate = (1-Coal supply/Coal demand) × Coal supply elasticity coefficient
Thermal power unit cost increment = Coal consumption of thermal power unit × Coal price
Thermal power unit cost = Fixed cost + Thermal power unit cost increment + (Coal cost + Water cost)/Thermal power generation
Feed-in tariff = IF THEN ELSE(SMOTHI(Change of feed-in tariff, 10, 0.3247) > 0.36, 0.36, IF THEN ELSE(SMOTHI(Change of feed-in tariff, 10, 0.3247) < 0.28, 0.28, SMOTHI(Change of feed-in tariff, 10, 0.3247)))
Investment cost = DELAY1(Investment and construction cost of thermal power installation unit × Newly installed capacity, Delay time)
Unit cost = Thermal power unit cost increment × Thermal power generation + Water cost + Carbon cost + Investment cost
New energy generation = ((Installed capacity of new energy × Average utilization hours of new energy) × 10⁻³) (8)

(4) Constant
Electricity demand growth = 3.12%
Auxiliary power rate = 5.67%
Line loss = 5.6%
Thermal power ratio = 80%
Water price = 0.13 ¥/m³
Growth in newly installed capacity = 4.2%
Air cooling ratio: Circulating water cooling ratio: Dc water cooling ratio = 2:1:1
Initial feed-in tariff = 0.3247
Average utilization hours of new energy = 3131 h
Note: IF THEN ELSE is a conditional function in Vensim software. It is often used for policy switching or variable selection in simulation; DELAY1 is the delay function in the software, and I is the first-order delay; SMOTHI is an infinitely differentiable function. I is the first derivative, 2I is the second derivative, and so on. 0.36 is the price when the initial price rises by 10%, and 0.28 is the price when the on-grid price falls by 15%.

2.6. Model test
Like other models, system dynamics model abstracts and simplifies complex problems in the real world. Through the ideal hypothesis in the process of modeling, the model parameters are quantified and the functional relationship between variables is constructed to simulate the system structure. Since the constructed model is a relative result that meets certain conditions and cannot fully reflect the reality, it is necessary to verify the validity
of the model to verify the degree of reflection of the model to the reality system. Only the model that passes the inspection has the ability to reflect the operation law of the actual system to achieve the reliability and accuracy of the research purpose. In the process of model testing, if the model fails to pass the test, it is necessary to adjust the structure of the model, the selection of variables, the logical relationship between variables and the functional relationship between variables until it passes the set model testing method. At the same time, the model verification is dynamic and continuous, which runs through the whole modeling process. There are many methods to test the system dynamics model. This paper mainly selects the historical value test method to test the consistency between the constructed model and the real situation.

Historical value checking refers to comparing the simulated value of the model with the historical data and calculating the relative error between the two. If the relative error is small, it proves that the constructed model can reflect the structural characteristics and operation rules of the real system. It is generally believed that the relative error between the two is within \( \pm 20\% \), indicating that the fitted model can roughly reflect the reality. The relative error between them is within \( \pm 10\% \), which indicates that the fitted model can reflect the reality of the problem well. The relative error between the two is within \( \pm 5\% \), indicating that the model fits very well.

The historical data from 2015 to 2019 in the constructed simulation model were verified by Vensim software. The results show that the average relative error of thermal power generation is 2.6\%, and the average relative error of newly installed thermal power capacity is 3.8\%. The relative error rates are kept within 5\%, indicating that the simulation model established in this paper fits the real system very well and can reflect the real situation. The specific test results are shown in the table below.

### 3. Analysis of simulation results

Scenario analysis means for the construction of the quantitative changes of related parameters in the model, analysis and forecast the feedback path of different contexts, its principle is mainly on the social, economic, technical parameters such as the evolution of the key factors of critical assumptions, on the basis of the research object in the future possible circumstances and consequences for comprehensive prediction. This chapter first analyzes the variation trend of key factors in the model under the initial value assignment scenario, and comprehensively considers the influence of each key factor on the future development of coal power industry. It plans to set two policy backgrounds of existing water and carbon quota allocation policy and tightening of water and carbon quota allocation policy. In the context of these two policies, the proportion of thermal power will remain unchanged at 80\% in the next ten years, and the proportion of thermal power will continue to decline with the increase of installed new energy capacity. For the convenience of the following description, the former situation will be recorded as scenario 1, and the latter as scenario 2. In this chapter, the production system and operation system of coal power industry under two policy backgrounds and two circumstances are simulated and analyzed. Meanwhile, the situation of water and carbon quota policy tightening is proposed, and the gap between existing quota allocation policy and quota allocation policy tightening is compared to provide reference for policy optimization analysis in the following chapters. See figure 4 for specific scenario Settings.

#### 3.1. Simulation of coal power industry development under existing water and carbon quota policy

*3.1.1. Development trend status of coal power production system*

This part considers the simulation under the existing water carbon quota allocation policy. According to the system simulation model and assumptions constructed in the previous chapter, thermal power generation is determined by electricity demand. By substituting the growth rate data of electricity demand into the system dynamics model, it can be seen that the electricity demand of the eight provinces in the Yellow River Basin will increase from 2,147.1 TWH in 2020 to 2,919.32 TWH in 2030.

In the thermal power generation is divided into two cases of simulation analysis. On the one hand, consider that the proportion of thermal power in the Yellow River Basin will remain 80\% in the next ten years, that is, the thermal power generation in the next ten years under this circumstance. On the other hand, the influence of the gradual increase of new energy generation on the proportion of thermal power is considered as case two. In the simulation of new energy generation, according to the new energy installed capacity of the country by 2030 to reach the goal of 1.2 TKW. According to the current proportion of the installed capacity of new energy in the Yellow River basin to the national installed capacity, it can be calculated that the installed capacity of new energy in the Yellow River Basin will be 0.54 TWH by 2030. Combined with the model established in this paper, the annual growth rate of new energy installed capacity in the Yellow River basin should be at least 7.2\% in the next 10 years in order to meet the national new energy installed capacity target.

The variation trend of thermal power generation and thermal power proportion under the two conditions is shown in figure 5. Under the scenario, thermal power generation will be 2,598.66 TWH by 2030. In the second case, the thermal power generation is 2,281.57 TWH. At this time, the proportion of new energy generation will
reach 24%, and the new energy generation will reach 721.717 TWH. The share of coal-fired power will fall from 80% in 2020 to 70% in 2030. Thermal power generation in both scenarios fell by 317.09 TWH.

Figure 6 shows the amount of water and carbon involved in water right trading under the two conditions. As can be seen from the figure, when new energy power generation is taken into account, the decrease in the proportion of thermal power leads to a decrease in thermal power generation, as well as a decrease in water consumption and carbon emission in the process of coal-fired power generation. Therefore, the amount of water involved in water rights trading and carbon emission involved in carbon trading decrease. And as time goes on, it decreases more. By 2030, compared with scenario 1, scenario 2, the amount of water involved in water
trading will decrease by 58.108 million m³, and the amount of carbon involved in carbon trading will decrease by 1.31 million tons.

3.1.2. Development trend of operation system
In the operation system, four variables including carbon price, feed-in tariff, unit power generation cost and profit of thermal power unit are selected to compare the two conditions. Based on the general equilibrium theory in economics, the carbon price, thermal power grid price and thermal coal price are determined. In the carbon market, the carbon price is determined by the carbon emission and carbon quota of thermal power enterprises. In the power market, the relationship between supply and demand of thermal power affects the feed-in price of thermal power, which in turn affects the net demand of electricity. The price of thermal coal is mainly affected by the supply and demand of thermal coal. The generating capacity of thermal power units affects the demand for thermal coal, which in turn affects the price of thermal coal, which in turn affects the cost of thermal power units, and ultimately affects the profit of thermal power units. When the profit of thermal power unit decreases, the enterprise will reduce the thermal power generation. The variation trends of carbon price, thermal power on-grid price, unit power generation cost and profit of thermal power unit are shown in figures 7 and 8.

The following is an analysis of the change trend, change range and change causes of the four variables under two conditions.

Firstly, the carbon price is analyzed. First, the change trend of carbon price in the two cases is roughly the same, showing a continuous upward trend. This is because the carbon emission volume of China’s power generation industry is large, and the next decade will be a stage for China to strictly control carbon emissions. The gradual rise of carbon price also indicates that carbon quota allocation policy and carbon market will play a more effective role in restraining carbon emissions. The increase of carbon price will cause additional carbon emission cost for thermal power enterprises, which will bring negative impact on their profits. When the profit loss exceeds the marginal profit of coal-fired power generation production and operation, the enterprise will restrict the operation of thermal power units. But at the same time, the social demand for electricity is increasing year by year. In order to meet the demand for electricity, coal power enterprises will choose cleaner new energy
generation forms or carry out technical improvements on thermal power units. When thermal power generation, new energy power generation and electricity demand reach a balance, the carbon price will tend to be stable. Second, the magnitude of change in both cases is small. In the scenario, the carbon price rises to 90.5 yuan/ton by 2030. In scenario two, the carbon price rises to 92 yuan per tonne by 2030. In contrast, considering the influence of new energy generation on the proportion of thermal power, the carbon price will rise, with a difference of 1.5 yuan/ton. This is because when the carbon quota remains unchanged, the decrease in the proportion of thermal power leads to a decline in the amount of carbon emitted by participating in carbon trading, and the carbon quota is not enough to constrain the coal power enterprises. The enterprise’s consciousness of emission reduction decreases, and there is no surplus carbon quota to sell in the market. The demand is greater than the supply, leading to the rise of carbon price.

Secondly, the thermal power grid price is analyzed. First, the change trend of the feed-in price in the two cases is roughly the same, showing a trend of rising first and then stable. This is because, according to the current benchmark feed-in tariff mechanism for coal-fired power generation, the feed-in price of thermal power generation is determined by the price mechanism of ‘base price + fluctuation’. Among them, the benchmark price is determined based on the current local benchmark on-grid price of coal-fired power generation, and the floating range is no more than 10% up and no more than 15% down. This system sets limits on the increase or decrease of the on-grid price. When the change of supply and demand of coal power makes the increase of the on-grid price greater than the specified value, the on-grid price of thermal power is implemented according to the highest value. Second, the fluctuation range of feed-in price is not large in the two cases. Among them, the price of case ONE will remain 0.36 yuan/KWH from 2026, and case two will remain 0.36 yuan/KWH from 2025. And before the feed-in price remains stable, the feed-in price of case 2 is higher than case 1. This is because, when the proportion of new energy gradually increases, the supply of thermal power generation is less than the demand, resulting in the rise of thermal power grid price.

Thirdly, the unit cost of thermal power generation is analyzed. First, the variation trend of unit cost of thermal power generation is the same in both cases, showing a gradually rising trend. This is because the cost of water and carbon emission, which affect the unit cost of thermal power generation, increases with the increase of carbon price and power generation, while the price of thermal coal increases continuously under the influence of the demand and supply of electricity. Three factors work together to increase the cost per unit of electricity generated. Second, the cost per unit of thermal power generation varies greatly under the two conditions. By 2030, the unit cost of thermal power generation in the case of 0.3 yuan/KWH, and the unit cost of thermal power generation in the case of 0.25 yuan/KWH, indicating that reducing thermal power generation can reduce the unit cost of thermal power generation. This is because when the amount of thermal power is reduced, the amount of water and carbon used in coal-fired power generation is correspondingly reduced, resulting in lower costs. At the same time, the ratio between thermal power generation and power demand in case 2 is smaller than that in case 1, demand is greater than supply, and thermal coal price decreases. A variety of factors ultimately show that the unit cost of power generation in case 2 is less than case 1.

Finally, the profit of thermal power unit is analyzed. First, the profit trend of thermal power units varies greatly under the two conditions. In the first case, the fluctuation rose and then fell; in the second case, the fluctuation rose and then remained stable. As for the first case, the change trend of carbon price is observed. It is found that the rise trend of carbon price in 2020–2026 is relatively gentle, and the rise trend in 2026–2030 is relatively steep, indicating that the rise rate of carbon emission cost is faster after 2026. Carbon emission cost is an important part of the cost of thermal power generation, so the total cost of thermal power generation unit will rise rapidly after 2026. When the rate of cost increase is greater than the profit of thermal power unit, the profit of thermal power unit will decline. In case two, due to the reduction of water consumption and carbon emission, and the increase of thermal power grid price, profits will steadily increase from 2026. Second, the profit of thermal power units varies greatly under the two conditions. The margin of profit change before 2026 is small, and the difference between the two cases is as high as 8.478 billion yuan. After 2026, the lowest profit difference between the two scenarios is 15.135 billion yuan.

3.2. Simulation of coal and power industry development under tightening of water and carbon quota policy
3.2.1. Assumptions of tightening of water and carbon allocation policies
From 2011 to 2013, the Chinese government issued a number of policies to strictly manage and restrict water resources, and defined the ‘three red lines’ of total water consumption, water use efficiency and water function zones to limit pollution intake. Issued by The General Office of the State Council in 2013 ‘the strictest water resources management system evaluation method’ in the 2030 national and provincial regions within the scope of the water amount, water use efficiency and water environmental quality index made specific provision, including in 2030 China’s total of eight provinces in the Yellow River water control target is 132.648 billion cubic meters. According to the simulation data, the total amount of coal power and water consumption in the eight
The provinces of the Yellow River Basin in China in 2020 will be 2.313 billion cubic meters, accounting for about 2% of the total water consumption target of 120.106 billion cubic meters in the eight provinces of the Yellow River Basin in 2020. Assuming that the proportion of coal and power consumption in the total water consumption of the eight provinces under the power grid in the Yellow River basin remains unchanged in 2030, it can be calculated that the control target of coal and power consumption in the Yellow River Basin in 2030 should be 2.653 billion m³.

Since there is no specific value of carbon dioxide emission for each industry at 2030 carbon peak, this paper proposes the carbon peak theory curve of coal and power industry in the Yellow River Basin, and converts it into the adjustment coefficient of carbon quota, so as to achieve the purpose of tightening the constraint of carbon dioxide emission. By applying the dynamic carbon quota allocation scheme with adjustment coefficient to the system dynamics model of coal power industry development in the Yellow River Basin, the influence of carbon peak total target constraint on coal power industry can be simulated.

(1) The theoretical curve of coal electricity carbon peak in the Yellow River Basin
The carbon consumption per unit of power generation in the base period \( I \) (2020) is \( e^I \), the generating capacity is \( EP^I \), the average annual reduction rate of carbon reduction per unit of power generation is \( \alpha \), the average annual growth rate of generating capacity is \( \beta \), and the estimated carbon consumption in the calculation period is:

\[
E^{t}_{\text{co}_2} = e^{I}_{\text{co}_2} \times EP^{t} = e^{I}_{\text{co}_2} EP^{I} \left[ 1 - \left( \frac{t}{I} \right) \alpha \right] \times \left( 1 + \beta \right)^{t-I}
\]

The necessary and sufficient conditions for carbon peak in the first phase are:

\[
\alpha = \frac{\ln(1 + \beta)}{(t_0 - I) \ln(1 + \beta) + 1}
\]

Therefore \( t_0 = 2030 \), when the annual growth rate of coal power generation in the Yellow River Basin is \( \beta \), the carbon consumption per unit power generation needs to be reduced \( \alpha = \frac{\ln(1 + \beta)}{(t_0 - I) \ln(1 + \beta) + 1} \) year by year to achieve carbon peak.

(2) Dynamic adjustment formula of carbon quota allocation scheme for power industry under carbon peak target

The carbon peak target can only be ‘implemented’ when it is reflected in the carbon quota allocation process. Therefore, the adjustment coefficient is: \( \theta = 1 - \alpha \times \Delta t \) (\( \Delta t = t_i - 2020 \)) added into the current carbon quota allocation formula (2020). The dynamic adjustment formula of carbon quota allocation scheme in the power industry is as follows:

\[
A_e = Q_e \times B_e \times F_t \times F_T \times F_f \times \theta
\]

\( Q_e \)—Power supply of unit, unit: \( \text{MWh} \)
\( B_e \)—Power supply reference value of unit category, unit: \( \text{tCO}_2/\text{MWh} \)
\( F_t \)—Unit cooling mode correction coefficient, if the condenser cooling mode is water cooling, unit cooling mode correction coefficient is 1; if the condenser cooling mode is air cooling, the unit cooling mode correction coefficient is 1.05
\( F_T \)—Unit heating capacity correction coefficient: coal-fired unit heating capacity correction coefficient is 1–0.22 \( \times \) heating ratio
\( F_f \)—Unit load (output) coefficient correction coefficient

3.2.2. Simulation and analysis of coal power industry development
Analyze the difference between the adjustment of water carbon quota and the existing quota and the impact on the water resources and carbon dioxide involved in the trade. In this case, the pre-2030 water quota is 2.666 billion cubic meters and the carbon quota is 2.151 billion tons. The adjusted 2030 water quota is 2.652 billion cubic meters and carbon quota is 1.521 billion tons. When the water consumption per unit power generation and carbon consumption per unit power generation remain unchanged, the water consumption involved in water trading is between 352 million and 478 million cubic meters, and the additional carbon purchase is between 7.929 million and 640 million tons. Under the second scenario, the pre-2030 water quota is 2.342 billion cubic meters and the carbon quota is 1.89 billion tons. The adjusted 2030 water quota is 2.331 billion cubic meters and the carbon quota is 1.336 billion tons. When the water consumption per unit power generation and carbon consumption per unit power generation remain unchanged, the amount of additional water
resources to be purchased is between 350–420 million cubic meters, and the amount of additional carbon to be purchased is between 7.916 million tons and 563 million tons.

According to the above simulation results, under the condition that the proportion of thermal power remains unchanged, the tightening of quota allocation policy will reduce the available water of coal power industry by 800 million m$^3$ and the carbon emission by 630 million tons. Taking into account the impact of new energy generation on the share of thermal power, the tightening of the quota allocation policy will reduce the coal power industry’s water availability by 11 million cubic meters and carbon emission by 654 million tons. The water allowance calculated under the current quota allocation policy is basically in line with the 2030 water consumption target, while the gap between the carbon quota and the theoretical peak carbon quota is larger. This shows that the current carbon quota on the coal power industry is not strong binding. At the same time, compared with case 1, the intensity of water-carbon constraint is enhanced in case 2.

### 3.3. Policy simulation analysis

In order to help achieve the carbon reduction target, China has adopted three main development paths: first, promote the development of carbon reduction technologies such as carbon sequestration; second, release the energy planning targets at the stage to gradually replace traditional energy sources with new energy sources; third, establish a carbon trading market. According to the basic elements of system dynamics model of coal industry, representatives of the three selected related parameters to control the way of low carbon development, respectively is: the unit power generation water consumption, electricity carbon consumption, improve the new energy power generation, raise prices, eventually forming technology upgrade development, alternative development of new energy and price regulated development three different focus of development policy. It should be noted that when one of the parameters is adjusted, the other parameters remain unchanged, so as to compare the gap with the initial value as the baseline development policy.

#### 3.3.1. Technology upgrade development

According to the causal circuit diagram of the system, in the case of a given power generation scale, the water resources trading scale of coal power industry is jointly determined by water consumption per unit of power generation and water quota. Under China’s current water allocation scheme, the amount of water allocated is determined jointly by the cooling method of power generation and unit capacity. The carbon trading scale of coal power industry is determined by carbon consumption per unit of power generation and carbon quota. According to China’s current carbon quota allocation scheme, the carbon quota of thermal power enterprises is determined by the cooling mode of the generator set. It can be seen that the proportion of cooling methods is an important factor affecting the allocation of water allowance and carbon quota. Since the current carbon quota is calculated according to different cooling methods, while water resource consumption and carbon dioxide emissions in the process of coal-fired power generation are calculated according to the average value, regardless of cooling methods, changing the proportion of cooling methods cannot accurately reflect the carbon constraint of effluent water. Under the existing quota calculation method, the proportion of cooling method is only used to calculate the water quota and carbon quota, and other parameters are changed to meet the existing quota allocation policy. This part simulates the water and carbon trading scale under the scenario of changing carbon consumption per unit of power generation and water consumption per unit of power generation under the existing water and carbon quota allocation policy and tightening of water and carbon quota allocation policy.

Under the existing water and carbon quota allocation policy, the influence of the variation range of water and carbon consumption per unit of power generation on the scale and cost of water and carbon trading under the two conditions is simulated, and the variation trend of relevant variables is observed. In this case, when the water consumption per unit of power generation is reduced by 0.4%, the water volume involved in the transaction fluctuates between 350 million cubic meters, keeping a relatively stable state, and the water cost of thermal power enterprises in the Yellow River Basin will also remain at about 46 million yuan. When water consumption per unit of electricity generation is reduced by 1.64%, the amount of water involved in transactions will be negative in 2030. The cost of water has also dropped to negative from 45.64 million yuan in 2020, meaning companies will no longer have to pay for water. Similarly, in scenario 2, when water consumption per unit of electricity generation is reduced by 1.64%, the amount of water involved in transactions will be negative in 2030. The specific change trend is shown in figure 9. It can be found that in both cases, the water consumption per unit power generation decreases in the same proportion when water constraint is satisfied. When carbon consumption per unit of electricity generation falls at a rate of 0.7% per year, the amount of carbon traded will be negative in 2021 in both scenarios. The trend is the same in both cases, but over time, the difference between the two is getting bigger and bigger. The reason for this phenomenon is that the carbon emission in the process of coal-fired power generation changes with the thermal power generation, and its change trend is roughly the same as that of thermal power generation.
When the water and carbon quota allocation policy is tightened, a 1.7% reduction in water consumption per unit of power generation can achieve zero water consumption in 2030, indicating that the water consumption quota calculated according to the existing water quota allocation policy is basically consistent with the water consumption target in 2030. When the carbon consumption per unit of power generation decreases by 3.2%, the carbon emission involved in carbon trading shows a changing trend of first decreasing and then increasing, which indicates that the carbon quota adjusted according to the theoretical carbon peak curve will have stronger binding force on the carbon emission in the process of coal-fired power generation from 2025.

According to the current allocation policy of water carbon quota for thermal power enterprises, in order to meet the quota limit, the reduction of carbon consumption per unit of power generation is less than that of water consumption per unit of power generation, and the carbon quota can meet the demand in a short time. This indicates that the current carbon quota allocation policy is facing greater pressure from the improvement of water-saving technology than the improvement of carbon reduction technology. At the same time, according to the simulation curve, reducing thermal power generation only reduces the amount of water and carbon emission in the process of coal-fired power generation, but does not change their changing trend.

3.3.2. Alternative development of new energy
This part simulates the crowding out effect of total water and carbon constraint on coal power industry under the existing water and carbon quota allocation policy and the tightening of water and carbon quota allocation policy, forcing coal power industry to transform and develop. It should be noted that the extrusion effect in this paper is different from the extrusion effect in economics. It only means that on the basis of electricity demand, in order to meet the water-carbon constraint, water consumption and carbon emission beyond the initial water-carbon quota will not be obtained through market transactions, but replaced by new energy generation. Under the existing water and carbon allocation policy, the crowding effect of water and carbon constraint on thermal power generation is simulated to observe the changing trend of thermal power proportion and new energy generation to meet the water and carbon constraint in the next decade.

In this case, the water–carbon constraint will reduce the proportion of thermal power from 80% to 66% in the next ten years, and the new energy generation will need to increase by 408.126 TWH. According to the current new energy generation utilization hours, by 2030, the newly installed energy of new energy will need to increase by at least 0.13 TKW on the existing basis. According to the requirements of the country’s 2030 new energy installed capacity target, it is not difficult to achieve this standard. In case two, considering that the proportion of new energy increases, the proportion of thermal power decreases year by year, and the new energy generation capacity extruded by water and carbon constraint. By 2030, the proportion of thermal power is 58%, and the new energy generation generated by water and carbon constraint and the original new energy generation will reach 0.11 TWH, accounting for 37% of the electricity generation in 2030. Based on the current number of renewable energy hours, the new installed capacity will reach 0.77 TKW, exceeding the national target of 0.23 TKW.

If the water and carbon quota allocation policy is tightened, the proportion of thermal power will be 40% by 2030 due to the water and carbon constraint, and the new energy generation will need to increase by an additional 1,176.75 TWH, and the newly installed energy of new energy will need to increase by at least 0.38TKW on the existing basis. According to this growth rate, by 2030 just reach the country’s new energy installed target. In case two, the increase of the proportion of new energy is considered, so that the proportion of thermal power decreases year by year, coupled with the new energy generation capacity squeezed out by water and carbon
constraints. By 2030, the proportion of thermal power will be 35%, and the new energy generation generated by water and carbon constraint and the original new energy generation will add up to 0.18 TWH, accounting for 60% of the electricity generation in 2030. The newly installed capacity of new energy will reach 1.25TGW, exceeding the national target of 0.71TGW.

The simulation results show that in the alternative development of new energy, the most appropriate development mode is to develop new energy according to the crowding effect of water and carbon constraint on thermal power generation after the policy of water and carbon constraint is tightened.

3.3.3. Price regulated development

In the model setting of this paper, the carbon price is jointly determined by the carbon quota and the carbon emission in the process of coal-fired power generation, while the water price is a fixed price. Therefore, this part simulates the impact of water price on cost and profit under different changing proportions.

When the water price is 2 times of the current water price, the cost of water is 93,826,200 ~ 112 million yuan, only equivalent to the profit of the thermal power unit 0.1%. At the same time, water cost is one of the factors affecting the cost per unit of power generation, resulting in a profit decline of 0.11%–0.23%. When the water price is 10 times of the current water price, the water cost is between 469 million yuan and 561 million yuan, which is equivalent to 0.28% to 0.6% of the profit of thermal power units, resulting in a profit decline of 0.6% to 1.1%. According to the simulation results, even a tenfold increase in water prices is affordable for coal and power companies. The low cost and high return of water make coal power industry the second largest water industry after agriculture. The current water trading market cannot restrain coal power industry, and only relying on water right trading market cannot promote coal power industry to upgrade water-saving technology and improve water efficiency.

4. Conclusions and suggestions

4.1. The conclusion

In the context of China’s 2030 carbon peak target and water saving target, based on the simulation results and policy simulation results in chapter 3, this paper puts forward the following policy suggestions for the future low-carbon water-saving development of coal power industry in the Yellow River Basin:

(1) In the next ten years, the market demand for coal power in the Yellow River Basin is still relatively strong. By 2030, the demand for electricity in the eight provinces of the Yellow River Basin will increase from 2,147.1 billion KWH in 2020 to 2,919.32 billion KWH. Under the condition of keeping the proportion of thermal power unchanged, the thermal power generation capacity of the eight provinces in the Yellow River Basin will reach 2,598.66 billion KWH by 2030. When considering the influence of new energy generation on the proportion of thermal power, thermal power generation will reach 2.28157 billion KWH and new energy generation 721.717 billion KWH by 2030.

(2) The on-grid price of thermal power shows a rising trend in the fluctuation, and reaches the upper limit of the regulated on-grid price at a certain time. The carbon price will continue to rise in the next decade, and will rise to 90.5 yuan/ton in 2030 if the proportion of thermal power remains unchanged, and to 92 yuan/ton in 2030 if the impact of new energy generation on the proportion of thermal power is taken into account. According to the current price trend, water carbon constraint will make the profit of coal and power industry in the Yellow River Basin decline in 2026. Water prices are so low that even a tenfold increase would have little impact on the profits of the coal power industry.

(3) Under the existing quota allocation policy, considering the impact of new energy generation on the proportion of thermal power, the water consumption involved in trading will be reduced by 58.108 million m³, and the carbon emission involved in carbon trading will be reduced by 1.31 million tons. The tightening of the quota will reduce the amount of water available in the coal power industry by 0.08 million cubic meters and 630 million tons of carbon emissions, assuming the share of thermal power remains unchanged. Taking into account the impact of new energy generation on the share of thermal power, the tightening of the quota allocation policy will reduce the coal power industry’s water availability by 11 million cubic meters and carbon emission by 654 million tons.

(4) Under the existing carbon quota allocation policy, 1.64% reduction of water consumption per unit of power generation can meet the water quota, and 0.7% reduction of carbon consumption per unit of power generation can meet the carbon quota. When the quota allocation policy is tightened, the water consumption per unit of power generation is reduced by 1.7% to meet the water quota, and the carbon
consumption per unit of power generation is reduced by 3.2%, the amount of carbon involved in the transaction will decrease before 2025, and then increase after 2025.

(5) The installed capacity of new energy squeezed out of coal power industry by water and carbon constraint is affected by water and carbon quota allocation policy and coal power development. Under the existing water and carbon quota allocation policy, when the proportion of thermal power generation remains unchanged, the installed capacity of new energy extruded by coal power will be 130.35 million kW by 2030. When considering the influence of the gradual increase of new energy generation on the proportion of thermal power, the installed capacity of new energy extruded by coal power will be 766.7 million kW by 2030. Under the scenario of tightening water and carbon quota policy, the installed capacity of new energy extruded from coal power will be 375.83 million kW by 2030 when the proportion of thermal power remains unchanged. When considering the influence of the gradual increase of new energy generation on the proportion of thermal power, the installed capacity of new energy extruded by coal power will be 1,245.93 million kW by 2030.

4.2. Suggest
According to the simulation results and policy simulation results from chapter 3, the following policy suggestions are made:

First, under the existing water and carbon quota allocation policy, the profit of the coal and power industry in the Yellow River Basin will decline due to the joint constraint of water and carbon. Some coal and power enterprises will automatically choose to shut down their units, so it is necessary to pay attention to the security of energy supply. When water consumption and carbon dioxide emissions in the process of coal-fired power generation exceed the quota allocated by the state, the cost incurred by the coal power industry choosing to purchase all the shortfall water and carbon from the market will cause a decline in profits. If the continuous decline of profits is not enough to support the continued operation, the Yellow River Basin, as the heart of the country’s primary energy, will also cause a crisis to the country’s energy and power supply when it faces a shortage.

Second, the water carbon quota allocation policy cannot form a two-wheel drive, and the carbon quota constraint is insufficient, so the existing carbon quota policy needs to be tightened. Compared with the existing water quota allocation policy, the carbon quota allocation policy has a weak constraint on the coal and power industry in the Yellow River Basin. Under the two rigid constraints of water and carbon, if the carbon quota cannot form a good constraint on the coal and power industry in the Yellow River Basin, it may lead to a strict water resource constraint, and the technology choice is more inclined to the direction of low water consumption and high carbon consumption.

Thirdly, the formulation of water and carbon quota allocation policy should be combined with the degree of technological improvement in coal power industry. Under the existing quota allocation policy, the pressure of water saving technology improvement in the Yellow River Basin is greater than the pressure of carbon emission reduction technology improvement, so the coal and power industry should be more stringent carbon constraints. In the case of tightening quota allocation policy, the Yellow River Basin faces more pressure from carbon emission reduction technology improvement than from water saving technology improvement, so it is necessary to implement more stringent water constraints on coal and power industry. At the same time, when the existing carbon quota is tightened according to the theoretical carbon peak curve constructed in this paper, the tightened carbon quota will not exert strong restraint on the coal and power industry in the Yellow River Basin before 2025. Therefore, after the tightening of carbon quota, the coal emission reduction technology should be upgraded and improved before 2025, and the quota constraint can be the main constraint after 2025.

Fourthly, the government’s planning of new energy construction should combine the formulation of water and carbon quota allocation policy with its own development situation. Under the existing water and carbon quota allocation policy, the amount of coal and electricity extrusion under the water and carbon constraint is not enough to meet the installed target of new energy, so the installed capacity of new energy should be planned according to the development situation of new energy and the amount of new energy extrusion. When the water and carbon quota allocation policy is tightened, the amount of coal power extruded by water and carbon constraint is enough to meet the installed target of new energy, so the amount of coal extruded should be the main planning basis. If the installed capacity of new energy is only based on the amount of water and carbon extruding coal and electricity, there will be insufficient power supply, or there will be too much installed capacity of new energy, resulting in insufficient consumption of new energy and idle resources.

Fifth, a unilateral increase in water prices will not affect the profits of the coal industry in the Yellow River basin so much that it will not consider adopting more water-saving measures. Therefore, policy making should be more oriented towards total water use control. If the water consumption in the process of coal-fired power
generation exceeds the total water consumption control target, the water consumption limit for the next year will be reduced by a certain proportion, forcing the coal power enterprises to improve water-saving technology.

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**Data availability statement**

The data that support the findings of this study are available upon reasonable request from the authors.

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**References**

Byers E A, Hall J W, Amezaga J M et al 2016 Water and climate risks to power generation with carbon capture and storage Environ. Res. Lett. 11 024011

Colin C, William Y, Rebecca D et al 2014 Strategic responses to CO2 emission reduction targets drive shift in U.S. electric sector water use Energy Strategy Reviews 4 16–27

Department of Energy Statistics 2019 National Bureau of Statistics (Beijing, China: China Energy Statistical Year book)

Dodder Rebecca S, Barrwell Jessica T and Yelverton William H 2016 Scenarios for low carbon and low water electric power plant operations: implications for upstream water use Environmental Science & Technology 50 1146–70

Frumhoff Peter C, Virginia B, Jackson Robert B et al 2014 Spatio-temporal variations of precipitation in arid and semiarid regions of China: The Yellow River basin as a case study Global Planet. Change 114 38–49

Huang W, Ding M and Wenying C 2016 Connecting water and energy: assessing the impacts of carbon and water constraints on China’s power sector Appl. Energy 185 1497–505

Li J, Zhang Y and Deng Y 2021 Water consumption and conservation assessment of the coal power industry in China Sustainable Energy Technologies and Assessments 47 101464

Li M Q, Dai H C and Xie Y 2017 Water conservation from power generation in China: a provincial level scenario towards 2030 Appl. Energy 208 580–91

Lin L and Chen Y D 2017 Evaluation of future water use for electricity generation under different energy development scenarios in China Sustainability 10 30

Mourratiadou I, Bevione M, Bijl D L et al 2017 Water demand for electricity in deep decarbonisation scenarios: a multi-model assessment Clim. Change 147 91–106

National Bureau of Statistics 2020 (Beijing, China: China Statistical Yearbook)

Peng Wei W F and Ramana M V 2018 Managing china’s coal power plants to address multiple environmental objectives Nature Sustainability 1 693–701

Qin E C and Kopec G M 2015 China’s energy-water nexus - assessment of the energy sector’s compliance with the ‘3 Red Lines’ industrial water policy Energy Policy 82 131–43

Shaikh M A, Kucukvar M and Onat N C 2017 A framework for water and carbon footprint analysis of national electricity production scenarios Energy 139 406–21

Wang J, Yu Z and Zeng X 2021 Water-energy-carbon nexus: a life cycle assessment of post-combustion carbon capture technology from power plant level J. Clean. Prod. 312 127772

Wang, Byers E and Parkinson S 2019 Vulnerability of existing and planned coal-fired power plants in developing asia to changes in climate and water resources Energy Environ. Science 12 3164–3181

Yu X, Wu Z and Wang Q 2020 Exploring the investment strategy of power enterprises under the nationwide carbon emissions trading mechanism: A scenario-based system dynamics approach Energy Policy 140 1111409

Zhang C, Anadon and Laura D 2013 Life cycle water use of energy production and its environmental impacts in china Environmental Science & Technology 47 14459–67

Zhang J L and Zhou X X 2020 Impact analysis of market-oriented carbon emission reduction policies in power generation industry based on system dynamics Electric Power 53 114–23

Zhang Qiang, Peng J and Singh Vijay P 2014 Spatio-temporal variations of precipitation in arid and semiarid regions of China: The Yellow River basin as a case study Global Planet. Change 114 38–49

Zhang C, Anadon L D, Mo Hongnin, Zhao Z and Liu Z 2014 Water – Carbon Trade-off in China’s Coal Power Industry 48 11082–9

Zhang X, Liu J and Tang Y 2017 China’s coal-fired power plants impose pressure on water resources Journal of Cleaner Production 161 1171–79