Internal benefit optimization model of gas-thermal power virtual power plant under China's carbon neutral target

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**Abstract**
China's “14th Five-Year Plan” proposes that “carbon peak” is the basic prerequisite for achieving “carbon neutrality.” To achieve the “carbon neutrality” goal, the key is promoting the use of clean, low-carbon energy and building a diversified clean energy supply system on the energy supply side. Wind energy, photovoltaics, and other clean energy sources are increasingly relying on electrification (P2G) technology to achieve utilization, and this phenomenon can help China achieve carbon neutrality goals as soon as possible and realize the carbon cycle.

This article first aggregates combined heat and power (CHP), wind power, photovoltaics, P2G equipment, and gas storage devices into virtual power plants (VPPs), and the natural gas and electricity trading market are linked. We then take the virtual power plant operating profit maximization as the objective function considering the P2G device operating costs, carbon capture and storage costs. The optimization model is solved by particle swarm algorithm. Finally, the specific operating data of a gas-thermal power virtual power plant system were selected to verify the feasibility of the proposed optimization model. We got some relevant conclusions. (1) The optimal scheduling of gas-thermal power virtual power plant considering multiple energy markets can smooth the power load curve and improve the overall system benefit. (2) There is a negative correlation between the income of gas-thermal power virtual power plant and the confidence level effectively. (3) The optimization model effectively increases the amount of carbon capture, which proves that the gas-thermal power virtual power plant is effective for achieving China’s carbon neutrality goal, it can be developed on a larger scale in future. The above results verify that the optimal operation mode of the gas-thermal power virtual power plant is effective for achieving carbon neutrality.

**KEYWORDS**
carbon neutral, gas-thermal power virtual power plant, optimal dispatch model, power-to-gas
1 | INTRODUCTION

1.1 | Literature review

China’s 14th Five-Year Plan puts forward the goal of achieving “carbon neutrality”. China believes that it is necessary to accelerate the replacement of fossil energy with clean energy and achieve a balance between carbon emissions and carbon absorption through carbon capture, utilization and storage technologies. To achieve this goal, the key is to build a diversified clean energy supply system on the energy supply side and fully promote electrification and energy conservation on the energy consumption side.

Many scholars have studied in-depth of CO2 capture, CO2 utilization and CO2 storage. C. Tregambi et al.1 have long been committed to researching and capturing carbon dioxide from coal-fired power plants. The chemical principle is as follows. Hydrogen is obtained by electrolysis of water, and methane can be generated by reacting hydrogen with CO2. The results of the calculation example show that the CO2 capture amount ranges from 30% to 85%. K. Xiao et al.2 invented the liquefaction-coupled energy-efficiency hydrogen production technology. The thesis research shows that this technology reduces the carbon dioxide emitted during the hydrogen production process of the refinery and improves the resource utilization rate. M. Sedaghat et al.3 proposed least-squares support-vector machine (LSSVM) to be used to predict carbon dioxide capture. The results show that the proposed algorithm is reliable for estimating the amount of impure CO2 captured. M. Koh et al.4 reviewed the overall understanding of CCS by the Korean public and systematically summarized the actual bill and how the Korean public commented on the CCS Integration Act. V. Sick et al.5 used life-cycle assessment and technical economic assessment to study the environmental and economic impacts of carbon dioxide capture technology and further clarified the environmental benefit indicator system of carbon capture and utilization. M. Babar et al.6 used the golden section search technology to capture the pressure-temperature conditions of low-temperature carbon dioxide to generate a low-temperature carbon dioxide–methane mixture. Under a given atmospheric pressure, the cost of the carbon dioxide capture system was optimized, and finally, the optimal temperature for the system to capture low-temperature carbon dioxide under a given atmospheric pressure was obtained.

Virtual Power Plant (VPP) technology uses advanced communication technology to integrate traditional fossil energy and new energy into a whole, coordinate and optimize the output of each unit, which can avoid the adverse impact on the grid when new energy generation is connected to the grid. It provides new ideas for wind power consumption. M. Jasinski et al7 studied a VPP in Poland, which included hydroelectric power stations and energy storage systems. The power quality problem is analyzed in detail, and finally, the impact of VPP on the power quality level is evaluated. Y. Zhou et al8 studied the impact of energy market prices and ancillary service market prices on the integrated community energy system. At the same time, they used the Gaussian process method to predict the uncertainty of wind power and photovoltaic power generation. Finally, a day-ahead scheduling optimization model of the system is constructed and a case study is carried out. F. Fang et al9 proposed a multidistributed energy profit distribution method coexisting with the virtual combined thermal power plant. The innovative concept of combined heat and power VPP system can coordinate heat and power dispatch, resulting in greater flexibility in decision-making and huge monetary benefits. They proposed and realized an improved Sharpley value method to achieve optimal profit distribution. F. Luo et al10 analyzed the function of VPP in coordinating the distribution system and DER, and a two-stage dispatching model based on VPP-based distribution system load peak shaving and valley filling was proposed. Li, B et al11 considered the VPP trading environment, and a two-layer optimization model was established to determine the best location and capacity. Z. Yi et al12 considered the price of active power and reactive power and proposed a two-level planning method for active distribution network (ADN) collaborative management with multiple VPP. It can effectively improve the safety of multiple VPP and economic performance. E. Mashhour et al13 modeled the VPP system’s structure, supply–demand balance constraints, safety constraints, etc., firstly. The constructed model belongs to a kind of nonlinear mixed integer programming, so it is solved by loading genetic algorithm. O. Arslan et al14 infiltrate plug-in hybrid electric vehicle into the grid on a large scale and made the extensive use of distributed energy. In order to study the comprehensive cost and carbon emission reduction of plug-in hybrid vehicles in the VPP system, a new VPP resource scheduling model was constructed. P. Olivella-Rosell et al15 proposed a novel operation model to optimize the distribution system, which can dispatch flexible energy resources. Through the simulation of local market test cases, its performance is tested, and the effectiveness of the proposed solution is proved. O. Sadeghian et al16 developed a decision-making procedure for effectively placing and adjusting the energy storage system (ESS) in the VPP site under the condition of uncertain market prices. The main purpose is to minimize the overall cost of VPP within a fixed time frame. Finally, case studies and comprehensive cost-benefit analysis...
prove the effectiveness of the proposed risk-based optimization method. M. Shabanzadeh et al\textsuperscript{17} proposed an optimization-based daily and weekly dispatch decision-making tool in the uncertain environment of the electricity market. An effective MILP model based on a robust optimization method was proposed, which can make wise decisions under different degrees of uncertainty. The efficiency and applicability of this method were analyzed through different scenarios.

Carbon storage electrification technology has been proven to effectively solve the problem of the absorption of low-carbon intermittent energy sources such as wind energy and photovoltaics, and has been adopted on a large scale in recent years. At the same time, the application and promotion of power-to-gas (P2G) are conducive to the absorption of CO2 emitted by the system. Therefore, this technology can accelerate the realization of the carbon neutral goal proposed by China. Z. Yang et al\textsuperscript{18} studied the problem of energy conversion efficiency between electrolyte, steam methane reformer, gas-fired equipment and gas-fired equipment. On this basis, a flexible day-ahead scheduling optimization model of the gas–electric interconnection system is established. The results prove that the P2G energy conversion method can alleviate the shortage of natural gas, improve energy efficiency, reduce carbon emissions and also have higher economic value. The P2G energy conversion method provides a new idea for China's energy utilization transition. Z. Cao et al\textsuperscript{19} believed that the integrated power–gas system can reduce carbon dioxide emissions, thereby helping to alleviate the global warming crisis. To this end, they have integrated electricity-to-gas, carbon capture systems and electric vehicles to build a coordinated integrated electricity–gas system structure. In the construction of the model, the goal is to minimize the total operating cost and carbon emissions of the system. At the same time, the cost of CO2 processing and the penalty cost of wind power deviation are considered in the operating cost of the system. The results also show that, compared with other situations, the total operating cost and carbon emissions of the integrated power–gas system are effectively controlled. X. Zhang et al\textsuperscript{20} believed that coal-to-gas and carbon capture are important technologies to reduce carbon emissions. Therefore, they coupled P2G technology and carbon capture power plants and finally built an integrated energy system including electricity, heat and gas, and then proposed a dispatch model under wind power integration. It proves that after the coupling of P2G technology and carbon capture power plant, most of the CO2 emitted by the system can be captured and sent to P2G facilities to synthesize natural gas. Z. Li et al\textsuperscript{21} proposed a multiobjective environmental economic dispatch model in view of the serious air pollution in coastal areas in recent years, which incorporated air pollutants into the dispatch model of the power–gas interconnected system. On the basis of minimizing system economic costs and carbon emissions, the contribution of pollutant concentration is used as one of the optimization goals. G. Yao et al\textsuperscript{22} studied the technical and economic feasibility of carbon capture technology for achieving carbon neutrality. By comparing carbon capture configurations under 9 different conditions at the same time, it is found that the system using carbon capture technology and combined with energy storage equipment has the highest economic and environmental benefits. Y. Yang et al\textsuperscript{23} believed that large-scale use of renewable energy, such as wind power and photovoltaic power generation, is necessary to achieve carbon emission reduction targets. Therefore, they proposed a power grid expansion planning model based on low-carbon goals, aiming to plan that traditional coal-fired power plants will be gradually replaced by renewable energy-distributed power generation equipment. During the research, they combined P2G technology with hydrogen turbines. This energy system can quickly store electricity generated by renewable energy and reduce resource waste. The results of calculation examples prove that this system can effectively reduce carbon dioxide emissions, but the economic benefits are not high. J. Liu et al\textsuperscript{24} proposed a new low-carbon economic environment dispatch strategy and then took into account all the constraints in the gas and electricity systems. Aiming at the problem of complex coupling constraints, a solution method combining the effective redundancy method, the trust zone method and the Levenberg-Marquardt method is applied. The results of the case study illustrate the benefits of P2G to the operation of low-carbon, economic and environmentally improved integrated systems. P. Costamagna et al’s\textsuperscript{25} first principle model of the alkaline electrolytic cell and the cooled isothermal packed-bed Sabatier reactor was established to evaluate the function of the power–gas system. Taking into account the advantages provided in carbon capture and utilization, the feasibility of P2G was evaluated.

From the perspective of mathematical modeling, the equipment and network in the integrated energy system are nonlinear, leading to the optimal dispatch of the integrated energy system will also be a nonlinear problem.\textsuperscript{26} Therefore, foreign scholars have conducted a lot of research on the solution method of the optimized scheduling model constructed. Dufo-López R\textsuperscript{27} studied the multiobjective algorithm for solving the integrated energy system, and the advantages and disadvantages of various algorithms such as genetic algorithm and biological simulation algorithm are evaluated. Finally, genetic algorithm is considered to have higher general application performance. Dufo-López R\textsuperscript{28} studied the structure...
and control strategy of the hybrid light-diesel-hydrogen storage-hydrogen system. In order to solve the model, he solved it through an optimized genetic algorithm and obtained the optimal solution. Lee Ty applied the same genetic algorithm to the hybrid photovoltaic diesel system optimization model based on the literature, and the optimal solution was also output, which solved the difficult problem of solving the multiobjective optimization model. Hakimi S studied the mathematical modeling process of particle swarm optimization firstly, and then, it was applied to the optimal power purchase scheme of industrial users under the time-of-use electricity price. Moghaddam A A constructed an optimal operation model of the island hybrid power generation system with the goal of minimizing the total cost of the system. In order to solve the model, the optimal solution of the model is output smoothly through the optimized particle swarm algorithm. Zeng J considered that the output solution of the traditional particle swarm algorithm may only be a local optimal solution, and an improved adaptive multiobjective particle swarm algorithm is proposed. Specifically, the particle swarm algorithm was improved by using the chaotic local search mechanism and fuzzy adaptive structure. Finally, they applied it to the solution of the optimal operation model of the microgrid and got a more optimized output. Arun P improved the GA algorithm and realized the operation optimization of the whole life cycle of the hybrid renewable energy power generation system.

When the electricity price is low, the use of power-to-gas devices will consume CO\textsubscript{2}. Synthetic natural gas participates in natural gas market transactions, which reduces system carbon storage costs, increases power plant revenue, and realizes optimal allocation of resources.

2. When considering internal operation mode, the randomness of electricity price and wind output should also be considered. Otherwise, the dispatching plan is too conservative and cannot fully tap the economic benefits brought by the random units in the gas-thermal power virtual power plant.

3. Study the system operation optimization problem under the uncertainty of market electricity price. The proposed model does not aim at the maximum declared power but aims at maximizing the economic benefits of the gas-thermal power virtual power plant, so that the virtual power plant can fully take into account the randomness, and the profit is increased by optimizing the power of each internal output unit.

4. Considering the goal of maximizing the economic benefits of the system, the carbon capture and storage device can use a small amount of energy in the system to capture and store the CO\textsubscript{2} emissions of the gas-thermal power virtual power plan. The recycling of CO\textsubscript{2} of the system can reduce carbon emissions, which is beneficial to effectively realize China’s carbon neutrality goal.

1.2 Contribution

1. Due to price fluctuations in the electricity and natural gas trading market, take gas-thermal power virtual power plant as a research subject in trading market.

1.3 Layout of this paper

The layout of this paper is as follows. Section 2 designs the basic structure of the gas-thermal power virtual power plant and the output power model of each unit;
Section 3 builds the internal benefit optimization model of the gas-thermal power virtual power plant; Section 4 analyzes an example to verify the model effectiveness and practicality; Section 5 elaborates the conclusion of this article.

2 | GAS-THERMAL POWER VIRTUAL POWER PLANT STRUCTURE

2.1 | Gas-thermal power virtual power plant structure

The gas-thermal power virtual power plants proposed in this paper are mainly composed of wind power plant (WPP), photovoltaic power generation (PV), combined heat and power plants (CHP), power-to-gas (P2G), carbon capture and storage (CCS), and gas storage tank (GST) integration. As shown in Figure 1.

P2G and GST belong to the coupling equipment in the system, which can adjust WPP, PV, CHP, and other power generation equipment to meet the power load demand on the user side of the system. Firstly, P2G can use the excess wind power and photovoltaic power in the system to convert CO₂ into natural gas for storage, which is conducive to reducing carbon emissions and achieving China’s carbon neutrality goal. Second, CCS can use a small amount of energy in the system to capture CO₂ emissions from the storage system. Comprehensive consideration of the electricity and gas prices in different time periods, when the electricity price is low, use P2G device to synthetic natural gas and sale it in natural gas market, which can reduce the cost of carbon storage, and increase the revenue of gas-thermal power virtual power plant.

2.2 | The output power model of each unit

2.2.1 | CHP

In this paper, a thermal power plant composed of coal-fired units supplies electrical and thermal energy of the gas-thermal power virtual power plant, which is determined by the load demand. Properly adjusting the heat-to-electricity ratio can realize the optimal operation of the system, and the operating cost $f_1$ of the CHP can be expressed as follows:

$$f_1 = aP_{G_t}^2 + bP_{G_t} + c \quad (1)$$

$$P_{G_t} = P_{Ge,t} + P_{Gh,t} \quad (2)$$

$$\lambda_t = \frac{P_{Gh,t}}{P_{Ge,t}} \quad (3)$$

where $P_{Ge,t}$ and $P_{Gh,t}$ are the electricity output and heat output of the combined heat and power system; $\lambda_t$ is the heat and power ratio of the combined heat and power system; $a, b, c$ are the unit energy consumption coefficient after fitting the energy consumption function of the coal-fired unit to the quadratic function.

2.2.2 | WPP output power model

The output power of the wind turbine is determined by the rated wind speed, cut-in wind speed, and cut-off wind speed. The output power characteristic curve of the wind turbine is shown in Figure 2.
When the wind speed \( v \) is lower than cut-in wind speed \( v_{in} \), the fan output is 0, when the wind speed is higher than the cut-in wind speed \( v_{in} \), the wind speed reaches the rated wind speed, the fan starts to run, and as the wind speed increases, the output power continues to increase, when the wind speed reaches the rated wind speed \( v_r \). After that, the fan maintains a constant output power \( P_r \), but when the wind speed exceeds the cut-out wind speed \( v_{out} \), the fan stops running to protect the safety of the equipment. Therefore, the power generation model of the wind turbine can be approximated by the following formula:

\[
P_{WPP} = \begin{cases} 
0 & v \leq v_{in} \\
\frac{v^3 - v_{in}^3}{v_r^3 - v_{in}^3}P_{WPP,rate} & v_{in} \leq v \leq v_r \\
P_r & v_r \leq v \leq v_{out} \\
0 & v \geq v_{out}
\end{cases}
\]  

where \( P_{WPP} \) is the actual output of the wind turbine; \( P_{WPP, rate} \) is the rated power of the fan.

2.2.3 | PV output power model

There are many external environmental factors affecting the output power of photovoltaic modules, mainly radiation intensity and temperature. The power characteristics under different conditions are shown in Figure 3.

In order to simplify the model, assuming that the photovoltaic output is only related to the light intensity and ambient temperature, the generated power of the photovoltaic array can be expressed by the following formula:

\[
P_{PV} = f_{PV}P_{PV, rate} \left( \frac{I_T}{I_S} \right) \left[ 1 + \alpha_P (T_{cell} - T_{cell,S}) \right]
\]

where \( P_{PV} \) is the actual output power of photovoltaics; \( f_{PV} \) is the derating factor of the photovoltaic array, that is, the ratio of the actual power generation of the photovoltaic array to the rated power generation, used to display the loss of the photovoltaic panel itself, usually 0.9. \( P_{PV, rate} \) is the rated capacity of the photovoltaic array; \( I_T \) and \( I_S \) respectively indicate the actual light intensity and the light intensity under the standard test environment; \( T_{cell} \) and \( T_{cell,S} \) respectively, indicate the actual temperature of the photovoltaic panel and the temperature under standard test conditions.

2.2.4 | P2G and CCS

The CCS system is used to collect part of the CO\(_2\) produced by the coal-fired unit and provide it to the P2G device. The P2G device produces CH\(_4\) through the process of water electrolysis. This process reduces CO\(_2\) emissions, and the natural gas produced at the same time can participate in natural gas market transactions.

(1) P2G equipment operating cost.

Considering personnel management, unit start-up and shutdown, technical cost, etc., the operating cost of P2G equipment is as follows:

\[
f_{21} = C_{P2G}P_{P2G,t}
\]

\[
Q_{gas,t} = \frac{\alpha_P P_{P2G,t}}{H_g} \Delta t
\]
where $C_{P2G}$ is the operating equipment cost factor of P2G equipment; $P_{P2G,t}$ is electric power consumed by P2G; $Q_{gas,t}$, $\beta_{P2G}$, respectively, indicate the amount of natural gas produced by the P2G equipment and the conversion efficiency; $\Delta t$ is the period length; $H_g$ is the calorific value of natural gas; $\alpha$ is the conversion coefficient between electric energy and heat.

(2) The cost of carbon capture and storage is as follows:

$$P_{CCS,t} = P_{CCS}' + \delta_{CO_2,t}Q_t P_{CO_2}$$

$$Q_{sto,t} = \delta_{CO_2,t} Q_t - Q_{CO_2,t}$$

$$f_{22} = C_{e,t} P_{CCS,t} + \eta \sqrt{Q_{sto,t}/280}$$

where $P_{CCS}'$ is basic energy consumption for carbon capture devices; $C_{e,t}$ is the on-grid electricity price at time $t$; $P_{CO_2}$ is electric power consumed by the CO2 capture unit; $\delta_{CO_2,t}$ is the carbon capture rate; $\eta$ is the total production of CO2; $Q_{sto,t}$ is the amount of carbon sequestration; $\eta$ is the cost coefficient of carbon storage, which is taken as 107.94 in this article.

Consider the operating cost of P2G equipment $f_{21}$, the cost of carbon capture and storage $f_{22}$; then, the operating cost of the P2G-CCS system $f_2$ is as follows:

$$f_2 = f_{21} + f_{22}$$

2.2.5 | GST

Because GST can realize real-time storage of natural gas synthesized by P2G in the gas-thermal power virtual power plant, gas-thermal power virtual power plant can flexibly use this part of natural gas, transport natural gas synthesized by P2G in the gas-thermal power virtual power plant, gas-thermal power virtual power plant can fully reflect the overall output of the virtual power plant in the process of participating in the gas and power market; $C_{e,t}$, $C_{gas,t}$, $P_{grid,t}$ are planned declared power of the gas-thermal power virtual power plant and the amount of natural gas planned to be sold to the natural gas market, which fully reflect the overall output of the virtual power plant in the process of participating in the gas and power market; $C_{e,t}$, $C_{gas,t}$ are the on-grid electricity price and natural gas price respectively; $P_{heat,t}$ is the heat load power; $C_{heat,t}$ is the heat price.

3 | INTERNAL BENEFIT OPTIMIZATION MODEL OF GAS-THERMAL POWER VIRTUAL POWER PLANT

3.1 | Objective function

Optimized scheduling of gas-thermal power virtual power plant to output power from coal-fired units $P_{G,t}$, electric to gas power $P_{P2G,t}$, and carbon capture rate $\delta_{CO_2,t}$. As a decision variable, taking into account the operating cost of coal-fired units, the operating cost of the P2G-CCS system, and the operating cost of the combined heat and power system, with the goal of maximizing the operating revenue of the gas-thermal power virtual power plant, the established model is as follows:

$$\max F = F_1 - F_2$$

where $F, F_1, F_2$ are the net income, total income, and operating cost of the gas-thermal power virtual power plant. The above formula is a function of each decision variable and random variable:

$$F_1 = \sum_{i=1}^{T} C_{e,t}P_{grid,t}P_{grid,t} + C_{gas,t}Q_{gas,t} + P_{heat,t}C_{heat,t}$$

$$F_2 = \sum_{i=1}^{T} f_1 + f_2$$

3.2 | Constraints

In order to ensure the smooth operation of gas-thermal power virtual power plant, it is necessary to consider thermal and electric power balance constraints, coal-fired unit output constraints, unit climbing constraints, P2G-CCS system equipment constraints, cogeneration system thermoelectric ratio constraints, and spinning reserve constraints.
3.2.1 | Thermal and power balance constraints

\[
P_{\text{heat},i} = v P_{\text{GH},i} \\
P_{\text{grid},i} = P_{\text{WPP},i} + P_{\text{PV},i} + P_{\text{G},i} - P_{\text{P2G},i} - P_{\text{CCS},i}
\]  

(15)

where \( P_{\text{WPP},i} \), \( P_{\text{PV},i} \) are forecasting value of wind power and photovoltaic output; \( v \) is the heat transfer efficiency.

3.2.2 | The output constraints of coal-fired units

\[
p_{\text{min},G,i} + \Delta P_{\text{down},G,i} \leq P_{G,i} \leq p_{\text{max},G,i} - \Delta p_{\text{up},G,i}
\]  

(16)

where \( p_{\text{max},G,i} \), \( p_{\text{min},G,i} \) are the upper and lower limits of coal-fired unit output; \( \Delta p_{\text{up},G,i} \), \( \Delta P_{\text{down},G,i} \) are the upper and lower spare capacity of coal-fired units.

3.2.3 | Crew climbing constraints

In order to extend the service life of the system unit and reduce maintenance costs, the difference between the output of the unit in two adjacent time periods should be less than the maximum climbing power of the unit:

\[
|P_{G,i} - P_{G,i-1}| \leq \Delta P_G
\]  

(17)

\[
|P_{\text{P2G},i} - P_{\text{P2G},i-1}| \leq \Delta P_{\text{P2G}}
\]  

(18)

where \( \Delta P_G \), \( \Delta P_{\text{P2G}} \) are the maximum climbing power of gas turbine and P2G device respectively.

3.2.4 | P2G-CCS system equipment constraints

The electric power consumed by P2G is restricted as follows:

\[
p_{\text{P2G},i}^{\text{min}} \leq P_{\text{P2G},i} \leq p_{\text{P2G},i}^{\text{max}}
\]  

(19)

The \( CO_2 \) consumed by P2G in the process of methanation to synthesize natural gas all comes from carbon capture devices, so the constraint is as follows:

\[
0 \leq Q_{\text{CO}_2,i} \leq \delta_{\text{CO}_2,i} Q_i
\]  

(20)

The upper and lower limits of the carbon capture rate are as follows:

\[
\delta_{\text{CO}_2,i} \leq \delta_{\text{CO}_2,i} \leq \delta_{\text{CO}_2,i}
\]  

(21)

where \( \delta_{\text{CO}_2,i} \), \( \delta_{\text{CO}_2,i} \), \( \delta_{\text{CO}_2,i} \) are the upper and lower limits of the carbon capture rate, which are, respectively, 0.9 and 0.1 in this paper.

3.2.5 | Thermal-to-power ratio constraint of cogeneration system

\[
\lambda_{t}^{\text{min}} \leq \lambda_{t} \leq \lambda_{t}^{\text{max}}
\]  

(22)

where \( \lambda_{t}^{\text{max}} \), \( \lambda_{t}^{\text{min}} \) are the upper and lower limits of the heat-to-electricity ratio, which are taken as 2.0 and 0.8 in this paper.

3.2.6 | Spinning reserve constraints

The coal-fired unit in the electricity–heat–gas virtual power plant can provide spinning reserve to cope with the impact of system uncertainty, so as to ensure stable output to the outside world during the dispatching process, and introduce the concept of chance-constrained planning confidence to describe the system. Spinning reserve can be expressed as follows:

\[
Pr\left\{ \left( P_{\text{G},i}^{\text{max}} - P_{\text{G},i} - \Delta P_{\text{up},G,i} \right) - \left( \delta_{\text{WPP},i} + \delta_{\text{PV},i} \right) \geq 0 \right\} \geq \xi_1
\]  

(23)

where \( \delta_{\text{WPP},i} \), \( \delta_{\text{PV},i} \) are, respectively, the forecast errors of wind power and photovoltaic power; \( \xi_1 \) are the confidence levels of the upper and lower spinning reserve constraints, and both are taken as 0.9 in this paper.

4 | CASE ANALYSIS

4.1 | Particle swarm algorithm

In the particle swarm optimization algorithm, the unknown solution of each optimization problem can be used as a point in the search range, that is, the particle. Each particle corresponds to a fitness value that depends on the function to be optimized. The direction and distance of all particles are determined by their speed, and all particles in the group follow the optimal particle to search in a plane solution domain. The update principle of each speed and position is as follows:

\[
v_{ij}^{k+1} = \omega v_{ij}^k + c_1 r_1 \left( P_{ij}^{k} - x_{ij}^k \right) + c_2 r_2 \left( P_{ij}^{k} - x_{ij}^k \right)
\]

\[
x_{ij}^{k+1} = x_{ij}^k + v_{ij}^{k+1}
\]  

(24)
where \( i = 1, 2, \ldots, m \) (\( m \) is the population size); \( j = 1, 2, \ldots, D \) (\( D \) is the number of unknowns); \( c_1 \) and \( c_2 \) are the learning factor; \( v_{ik}^k \) and \( v_{ik}^{k+1} \) are, respectively, particles \( i \) corresponding to \( j \) variables in the first \( k \) sequence \( k \) and \( k + 1 \) corresponding speed during the second correction; \( x_{ij}^k \) and \( x_{ij}^{k+1} \) are, respectively, particles \( i \) corresponding to \( j \) variables in the first \( k \) sequence \( k \) and \( k + 1 \) corresponding position at the time of the second correction; \( p_{ij}^k \) is particles \( i \) corresponding to \( j \) variables in the first \( k \) optimal position of the individual at the time of the second correction; \( p_{ij}^{g,k} \) is the whole group \( j \) variables in the first \( k \) global optimal position during the second correction; \( r_1 \) and \( r_2 \) are uniformly distributed random numbers between 0 and 1. In the classic particle swarm optimization algorithm, the inertia weight uses a linear decreasing correction method to update the weight value. The specific correction mode is as follows:

\[
\omega^{k+1} = \omega^k - (\omega_{\text{max}} - \omega_{\text{min}}) / K_{\text{max}}
\]

where \( \omega^k \) versus \( \omega^{k+1} \) are, respectively, for the particles in the first \( k \) and first \( k + 1 \). The inertia weight value corresponding to the second optimization; \( \omega_{\text{max}} \) is the maximum inertia weight, usually the empirical value is 0.9; \( \omega_{\text{min}} \) is the minimum inertia weight, and the usual experience is 0.4; \( K_{\text{max}} \) is the preset maximum number of iterations.

Considering that the particle swarm algorithm has been proved by many scholars to have the advantages of
fast solution convergence and high accuracy of output results, it has certain advantages in solving the problems raised by the model in this paper. Its detailed principle and solution process are referenced in. The flow of the optimization algorithm is as follows:

1. The important parameters of the virtual power plant: initial parameters such as wind power, photovoltaic, load demand curve, wind and solar forecasting output and other variables are input into the algorithm;
2. Initialize the number of particles and the number of iterations to start generating the first generation of particles;
3. Initialize the local optimal solution and the global optimal solution of the particle;
4. Calculate and output the objective function value corresponding to each particle;
5. Iterate continuously to update the local optimal solution and the global optimal solution of the particle;
6. Judging the cut-off condition and the algorithm is cut-off, then go to final step and output the result. If it is not cut-off, automatically adjust the position and speed of each particle and then return to step 4;
7. Output the final calculation result.

The solution flow chart is shown in Figure 4.

### 4.2 Basic data

Assume that the gas-thermal power virtual power plant is composed of coal-fired units, wind turbines, photovoltaic units, electricity-to-gas equipment, and carbon capture devices. Set a dispatch period of 24 h and a unit dispatch period of 1 h. The output curves of heat load, wind power, and photovoltaic are shown in Figure 5, and the average value of electricity price forecast is shown in Figure 6. System-operating parameter settings are shown in Table 1.

### 4.3 Simulation results and analysis

From formula (9), capture capacity of the system $Q_{cap,t}$ can be expressed as follows:

$$Q_{cap,t} = \delta_{CO_2,t} Q_t$$

Under the condition that the confidence level is 0.95, the article model is solved by the particle swarm algorithm, and the optimal scheduling scheme of the gas-thermal power virtual power plant is obtained. The operating results are shown in Table 2.

The heat–electricity ratio and carbon capture rate are shown in Figure 7, and the output and P2G power of coal-fired units are shown in Figure 8.

During 01:00–04:00 and 22:00–24:00, the electricity price is at a low period, the gas price is higher than the electricity price, and the carbon capture rate is above 0.8. Natural gas participates in the natural gas market; during the period of 04:00–07:00 and 15:00–17:00, the electricity...
price gradually increases, and the output of coal-fired units also gradually increases, and the heat-to-electricity ratio and carbon capture rate decrease; in the 17th period, the electricity price is at the peak point, but the reason why the output of coal-fired units has not reached the peak is the limitation of unit climbing; during the period of 17:00–21:00, the electricity price is in the falling stage, but the reason why the output of coal-fired units continues to increase is heat. The load demand continues to increase; during the 06:00–21:00 period, the electricity price is higher than the gas price (except during the 14:00–15:00 period), and the P2G power gradually decreases, and then gradually increases.

4.3.1 | Sensitivity analysis

To study how the confidence level $\beta$ impact on the simulation results, respectively, set deterministic conditions $\beta = 0.80, 0.85, 0.90, 0.95, 1.00$ as comparative analysis of the 5 scenes. Table 3 shows the comparison of running results at different confidence levels.

| $\beta$ | Total revenue | Electricity sales revenue | Gas sales revenue | Heat sales revenue | Coal-fired unit cost | P2G-CCS unit cost | $Q_{inj}/m^3$ | Risk tolerance |
|--------|---------------|---------------------------|------------------|------------------|--------------------|-------------------|--------------|---------------|
| 0.80   | 145.77        | 191.11                    | 19.27            | 101.43           | 99.82              | 66.22             | 1239.01      | excellent     |
| 0.85   | 145.01        | 190.23                    | 20.21            | 100.11           | 97.53              | 68.01             | 1239.43      | strong        |
| 0.90   | 141.54        | 187.52                    | 16.11            | 100.79           | 95.41              | 67.47             | 1240.53      | medium        |
| 0.95   | 139.51        | 188.84                    | 17.74            | 99.32            | 96.02              | 70.37             | 1241.26      | poor          |
| 1.00   | 138.27        | 185.41                    | 17.98            | 99.63            | 94.52              | 70.23             | 1241.93      | very poor     |

Comparing Table 3, it can be seen that under certain conditions, the income of the gas-thermal power virtual power plant is about 1,382,700 yuan, and the income expectation of the gas-thermal power virtual power plant under the uncertainty is higher than the income under certainty. When the system considers the forecasting deviation, the gas-thermal power virtual power plant can optimize resource allocation and have more opportunities to obtain higher economic benefits.

4.3.2 | Convergence analysis

In order to illustrate the effectiveness of the particle swarm algorithm in processing the model proposed in this paper, this paper draws the convergence curve of the particle swarm algorithm under different confidence levels as shown in Figure 9.

It can be seen from the convergence curve in Figure 9 that the simulation program under 4 different confidence levels can effectively solve the optimal solution of the model after 200 iterations. The curves in Figure 9 all
appear to be stable and then rise again, indicating that better solutions are continuously found as the iteration progresses, which reflects the ability of particle swarm optimization to improve the ability to jump out of the local optimal solution, thus verifying the particle swarm. The algorithm is effective in dealing with the model proposed in this article.

5 | CONCLUSION

In order to achieve a balance between carbon emissions and carbon absorption and to accelerate the realization of China’s carbon neutral goal, this article combines the basic structure of gas-thermal power virtual power plant to construct a unique operation optimization model that participates in natural gas and electricity trading market. In order to verify the feasibility of the model, a gas-thermal power virtual power plant composed of coal-fired units, wind turbines, photovoltaic units, power-to-gas devices, and carbon capture devices is taken as an example. In the end, the output of the model brings us some relevant conclusions and results.

1. When we actively design a reasonable confidence level for the model, the output of the optimized model is as follows. The system revenue from electricity sales is 188.84, gas sales revenue is 17.74, heat sales revenue is 99.32, coal-fired unit costs are 96.02, and P2G-CCS system costs are 70.37. The carbon capture capacity is 1,241.26m³. Therefore, under the optimization results, the total revenue of the system is 139.51.

2. In a dispatch cycle, when the price of electricity in multiple energy markets is lower than the price of gas, coal-fired units are mainly used for heating, and P2G also converts electricity into natural gas for sale. It can be found that the carbon capture rate is relatively high during this period; when the electricity price is higher than the gas price, the P2G power gradually decreases.

3. Sensitivity analysis shows that the income expectation under low confidence is higher than at high confidence level in most of the time. It shows that the smaller the confidence, the greater the income, so the income is negatively correlated with the confidence level. Convergence analysis proves that under various confidence levels, no matter which operating scheme is adopted, the system can effectively solve the optimal solution of the model, which proves that the particle swarm algorithm adapts to the model, and can effectively solve the global optimal solution of the model in this paper.

This paper mainly studies the structure of the gas-thermal power virtual power plant and solves the optimal operation problem of a gas-thermal power virtual power plant system in the natural gas and electricity trading market based on the research ideas of this paper. The limitation of this article is that it only considers the logical relationship between the gas, thermal and electric energy subnetworks. At the same time, we must also study more in-depth on algorithm-solving problems to improve algorithm accuracy. Therefore, the next step of the research is to consider the uncertainty of system operation, and to further improve the economic operation model and scheme of the virtual power plant and solution algorithms.

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CONFLICTS OF INTEREST
The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS
In this research activity, all authors were involved in the data collection and preprocessing phase, model constructing, empirical research, results analysis and discussion, and manuscript preparation. All authors have approved the submitted manuscript.

DATE AVAILABILITY STATEMENT
The data used to support the findings of this study are included within the article.

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