IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received May 12, 2021, accepted May 19, 2021, date of publication May 25, 2021, date of current version June 7, 2021.

Digital Object Identifier 10.1109/ACCESS.2021.3083272

Research on System Planning of Gas-Power Integrated System Based on Improved Two-Stage Robust Optimization and Non-Cooperative Game Method

YANG LIU AND TIANYU LIU
College of Electrical Engineering, Shanghai Dianji University, Shanghai 201306, China

Corresponding author: Tianyu Liu (54097909@qq.com)

This work was supported by the National Natural Science Foundation of China under Project 61973209, the fault diagnosis and intelligent maintenance for offshore wind turbine pitch systems.

ABSTRACT The power to gas (P2G) technology can realize the large-scale storage of electric energy in the form of natural gas, so that the power system and the natural gas system have the ability to flow energy, and the degree of coupling between the power system and the natural gas system is deepened. As the coupling between the power system and the natural gas system continues to increase, an integrated energy system (IES) with the power grid as the core has emerged. However, under uncertain conditions, the current planning methods still cannot guarantee the optimal interests of each manufacturer, so a collaborative planning method for gas-electric systems based on non-cooperative game theory is proposed. With each energy unit and electricity and gas network companies as independent interest groups, and with the maximum annual net income as the optimization goal, establishing a comprehensive non-combination of wind turbines, gas turbines, electric-to-gas turbines, transmission lines and natural gas pipelines in the gas-electric integrated system linear programming model. Aiming at the uncertainty of wind power and load, an improved two-stage robust optimization method is proposed. Finally, the modified IEEE 39-node power system and 20-node natural gas system gas-electric network verify the application value of the model and algorithm.

INDEX TERMS IES, game theory, P2G, collaborative planning, robust optimization.

I. INTRODUCTION

The development of renewable energy such as wind power and photovoltaics is an important countermeasure to solve the fossil energy crisis and environmental degradation. However, with the expansion of the installed scale of wind power and photovoltaic power generation, the randomness and intermittentness of the grid will affect the grid during the process of grid connection. Safety, stability and operation scheduling have brought many hazards, and have also led to increasingly serious problems of abandonment of wind and solar, restricting the large-scale application of new energy power generation [1]. In the first half of 2016, wind power curtailment alone reached 32.3 billion kW·h, and Xinjiang and Gansu curtailed wind power as high as 45% and 47%. The contradiction between the rising number of new energy installed capacity and the curtailment of wind and solar power is extremely prominent [2].

The associate editor coordinating the review of this manuscript and approving it for publication was Zhouyang Ren.

Traditional power grids have adopted various solutions on the supply side and demand side for the consumption of intermittent renewable energy such as wind power. The use of conventional peak shaving power and energy storage to cope with the intermittent and volatility of renewable energy has a significant effect, but the configuration and operation cost of the two are too high, and the large-scale configuration is inefficient [3]; the response solution using demand-side management has low cost advantages, but was affected by the lack of project promotion and the uncertainty of the load itself, the response capability and response reliability need to be improved, and there are many participants, the benefit transmission method is complex, the policy mechanism requires high, and the conditions for large-scale application are not available in the short term [4]. To alleviate environmental pollution and improve the efficiency of end-use energy, the integrated energy system has become an important direction for multi-country energy structure adjustment.

In recent years, with the continuous increase in the scale of gas-electricity installations and the maturity of

P2G technology, the coupling relationship between power and natural gas systems has deepened. When the wind power output is surplus, the opening of the P2G device not only provides a new solution for the large storage and transportation of abandoned wind power, but also realizes the two-way flow of energy between the electricity and gas subsystems. Therefore, the electricity-gas interconnection system with P2G has become one of the important trends in the development of the energy field in the future.

Literature [5] analyzed the principles of P2G technology in detail and studied the application of P2G technology in integrated energy networks. Literature [6] regards wind farms and electricity-gas interconnection systems as two interest groups, and establishes a two-layer model to configure the capacity of P2G equipment. Literature [5], [6] mainly studies the operation planning of P2G equipment. Literature [7] proposed a peak-shaving and valley-filling model for gas turbines and P2G devices to reduce the fluctuation of power load in the system and increase the consumption of surplus wind power output. The above researches result paying more attention to the advantages and reliability problems brought by P2G technology to the power system, and do not consider the impact of P2G technology on the surplus output of wind power. The surplus output was transformed into natural gas, and coordinated planning research was carried out on the power and natural gas network.

Literature [6] considered the uncertainty of the output of new energy sources such as wind power and photovoltaics at the power generation end, and established a new energy micro-grid economic operation optimization model, which reduces the operating cost of the micro-grid. Literature [8] analyzed the relationship between different stakeholders on the basis of considering the uncertainty of new energy at the power generation end, and constructed a dynamic/static game planning model. Literature [9] studied the master-slave game relationship between microgrid operators and the microgrid operation plan driven by electricity prices, and established a corresponding optimization model. The above researches result paying more attention to the uncertainty brought about by the integration of new energy into the integrated energy system and the interest relationship between all stakeholders under the cooperative game. However, in the actual microgrid operation process, due to the different cost-benefit identification directions among the main stakeholders involved, sometimes it is not necessary to consider only the operation scheduling plan under the cooperative game mode.

Literature [10] studied the distribution network planning model containing natural gas, in which the natural gas power plant is regarded as a kind of distributed power source. Literature [11] proposed a large-scale multi-cycle generator, transmission line, and natural gas network expansion planning method. Based on the simulation of Iran's large-scale power-natural gas system, the effectiveness of the proposed method was verified. In order to improve the resilience of the power grid under extreme conditions, literature [12] proposed a comprehensive planning algorithm for power and natural gas transportation systems. Although the focus on the above research is different, it is basically based on the overall rational thinking, using a unified multi-objective optimization model to make planning decisions, and does not consider the individual rational behavior of different investment entities. However, in the actual integrated energy system, the power network and the natural gas network may be invested and constructed by different investment entities. These investors' interest appeals are independent of each other, and their decision-making behaviors are based on individual rationality and are formed in the process of gaming. Balanced results. Under this circumstance, the above-mentioned planning model based on overall rationality cannot effectively describe the widespread multi-agent game phenomenon in the actual integrated energy system; on the other hand, the planning method based on the overall perspective is difficult to consider every market in the market. The interest appeals of investment entities, thereby reducing market vitality.

The above documents all simply attribute the comprehensive cost and benefits to the gas-electric integrated system, and do not analyze each subject under uncertainty. Therefore, this paper proposes a comprehensive energy game planning method that takes into account uncertain factors such as wind power load, and converts the surplus output of wind power photovoltaic into natural gas through P2G devices, and conducts collaborative planning research on power and natural gas networks. Establishing a multi-interest group model and listing the benefit function of each interest group. In order to be more suitable for the power system planning market model, an improved non-cooperative game strategy is used for planning. For each uncertain parameter in the model, an improved two-stage robustness is adopted. Optimization. Compared with the traditional method, this article is oriented to the planning of the electricity-natural gas integrated energy system, fully considering the game relationship between different investment entities, and conducting a collaborative planning study on the electricity and natural gas network, which can be viewed from the overall gas-electric integrated energy system. From a perspective, it can ensure the economy, safety and reliability of planning decisions; it can also ensure that each market entity maximizes its own profits in the game process, thereby enhancing the market vitality of the integrated energy system and the effectiveness of planning decisions. The feasibility and effectiveness of the method proposed in the paper are verified by the IEEE 39 node and the planning of a 21-node natural gas network in Belgium.

II. INTEGRATED ENERGY SYSTEM

A. INTRODUCTION TO INTEGRATED ENERGY SYSTEM

The IES contains electricity, heat, and gas which consist of a power system, a thermal system, a natural gas system and multi-energy conversion equipment as a coupling link distributed in a region, as shown in Figure 1. The power network transmits electric energy from the power supply side to the load side; the thermal system is composed of a heat

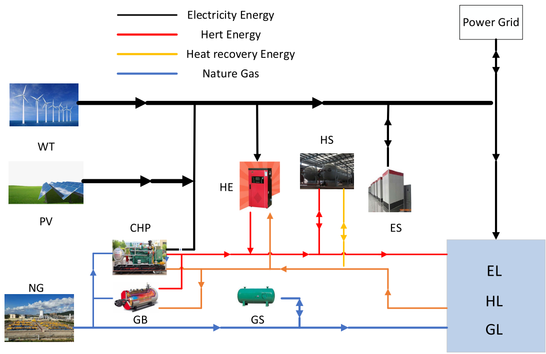

FIGURE 1. **IES contains electricity, heat and gas.**

source, a heating network, a heat recovery network and a heat load. The high-temperature hot water transports heat from the heat source to the heat load through the heating pipe, and the heat is transferred through the radiator. After the heat energy transmitted to the user, it is transformed into low-temperature hot water, and then flows back to the heat source through the heat recovery pipeline; the natural gas system is composed of a gas source, a gas supply pipeline, a compressor and a load, and a compressor driven by a gas turbine or an electric motor is used to increase the gas supply pressure to ensure the air supply. CHP units, electric boilers, gas boilers and other equipment can realize the conversion between different energy sources according to demand. In addition, in order to improve economy and operational flexibility, electric energy storage, thermal energy storage and gas storage equipment are also installed in the system. The comprehensive dispatch, coordination and optimization of multiple energy sources under the IES framework are of great significance to meet the increasing energy demand of mankind and reduce carbon emissions. Therefore, it has good universality and broad promotion prospects. Countries are pursuing policies in the energy field. At the time of its formulation, the emphasis on it has gradually increased.

B. P2G TECHNOLOGY

The multi-energy coordinated operation scheme involves the largest amount of energy, flexible energy conversion methods, and the widest range of energy transmission is the coordinated operation of the power grid and the gas grid, and the power-to-gas (P2G) technology as its energy conversion hub is also receiving increasing attention. P2G technology mainly includes 2 types [13]: 1) Electro-hydrogen technology, which decomposes water into oxygen and hydrogen through electrolysis. 2) Electric conversion to methane technology, that is, water is first decomposed into oxygen and hydrogen through electrolysis, and then hydrogen and carbon dioxide are reacted to synthesize methane [14], [15]. The reaction efficiency of electricity-to-hydrogen technology is higher than that of electricity-to-methane technology, but hydrogen cannot be injected into natural gas pipelines on a large scale (hydrogen injection into existing natural gas pipelines will cause pipeline hydrogen embrittlement and permeation), but methane can be directly injected into natural gas pipelines and storage devices to achieve Large-scale storage and long-distance transportation of energy. The electricity-to-gas technology introduced in this article specifically refers to electricity-to-methane technology, which provides a new idea for the large-scale storage and utilization of renewable energy: P2G equipment converts surplus electricity into man-made natural gas, and injects it into the natural gas network for storage and transmission, By coordinating the operation between the power system and the natural gas network, improve the system's ability to accept intermittent renewable energy power generation [16].

Features of P2G technology:

1) IMPACT ON THE POTENTIAL CONSUMPTION CAPACITY OF RENEWABLE ENERGY

1) Long-distance energy transportation when the transmission network is insufficient.

2) Realize large-scale storage of electric energy in the form of gas.

2) REDUCE CARBON EMISSIONS AND ENHANCE ENVIRONMENTAL BENEFITS

P2G technology mainly includes two processes in converting surplus power generation into natural gas for storage [17]. First, renewable energy or power grids are used to decompose water into hydrogen and oxygen through electrolysis. The hydrogen produced then reacts with carbon dioxide. The two gases are converted into methane through the sabatier catalytic reaction, and the heat energy released can be used in cascades. The increase in carbon dioxide emissions is an important cause of global warming. The development of P2G technology provides technical support for the large-scale power generation of renewable energy, which can indirectly reduce the use of fossil fuels for power generation. At the same time, P2G consumes a large amount of carbon dioxide resources during the operation, which further reduces carbon emissions, thereby improving environmental benefits. The specific reaction process is shown in Figure 2. There are many sources of CO2, the reactant of the methanation reaction, so the electricity-to-gas can be co-produced with other projects such as biogas plants, sewage treatment plants, breeding farms, coal-fired power plants, etc., effectively saving investment and realizing comprehensive benefit optimization.

3) IMPACT ON FLEXIBILITY AND RELIABILITY OF GAS-ELECTRIC SYSTEM

The impact of P2G technology on the gas-electric system is shown in Figure 3. Through the mutual conversion of electricity and gas, P2G technology can not only solve the problem of grid connection of renewable energy, improve the utilization rate of renewable energy, but also promote the coordination of electrical systems. Operation increases the flexibility of the gas-electric coupling system. The operation process is also an environmental protection process to eliminate carbon.

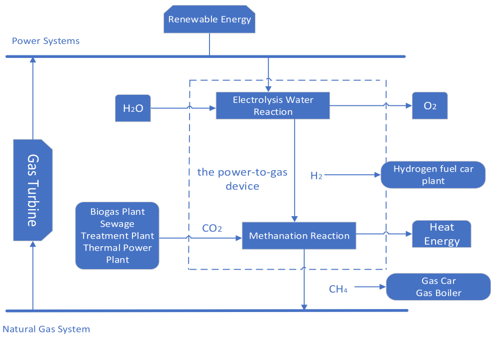

FIGURE 2. Power to gas process.

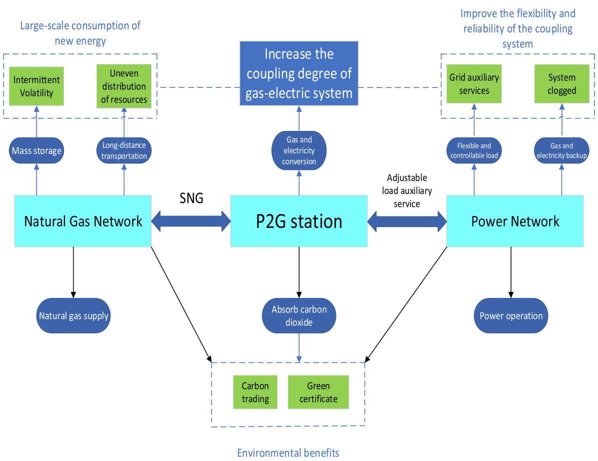

FIGURE 3. Influence of P2G technology on gas-electric coupling system.

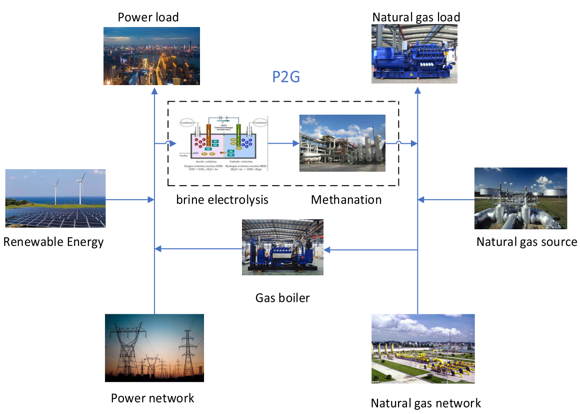

FIGURE 4. Gas-electricity interconnected integrated energy system.

C. GAS-ELECTRICITY INTERCONNECTED INTEGRATED ENERGY SYSTEM

The maturity of the electricity-to-gas technology and the cooperation with gas turbines have realized the circulation of energy between the power grid and the natural gas network, and increased the coupling of the electricity-gas network. Together, the electricity-to-gas unit and the gas turbine have become a pivotal component of the gas-electric integrated network [18]. The schematic diagram of the gas-electric integrated energy system is shown in Figure 4.

III. MULTI-AGENT NON-COOPERATIVE GAME FRAMEWORK

A. THE BASIC ELEMENTS OF NON-COOPERATIVE GAMES

The basic elements of non-cooperative games generally include participants, strategies and benefits [19]. In order to promote the promotion and application of non-cooperative game theory, non-cooperative games have formed two typical purely mathematical normative expression forms. The two forms are standard (strategy) games and mixed strategy games. The difference between the former and the latter lies in the simultaneity of decision-making, which is applicable to static and dynamic games respectively. This article adopts dynamic game, and the mathematical expression of dynamic game is introduced below.

Definition 3.1: Mixed strategy game, the game contains three basic elements:

(1) Player in independent game: N = {1,2,...,n-1,n}

(2) The mixed strategy of game participant i, the strategy set $\sigma = \{\sigma_1^m, \sigma_2^m, \ldots, \sigma_{n-1}^m, \sigma_n^m\}$;

(3) The expected return under the law of probability density distribution is as follows: $u_i(\sigma_i, \sigma_{-i}) = \sum_{s_{-i}\in S_{-i}} \sum_{s_{-i}\in S_{-i}} u_i(s_i, s_{-i})\sigma_i(s_i)\sigma_{-i}(s_{-i})$

The mathematical form of the mixed game is: $\Gamma = \{N, \sigma, u\} = \{N; \sigma_1^m, \sigma_2^m, \ldots, \sigma_{n-1}^m, \sigma_n^m; u_1, u_2, \ldots, \ldots, u_n\}$

B. DEFINITION OF NON-COOPERATIVE GAME EQUILIBRIUM AND THEORY OF EXISTENCE

The equilibrium of non-cooperative games is the Nash equilibrium. This equilibrium was proposed by John Nash and has been unified for academic circles and engineering applications and has been retained to this day.

Definition 3.2: For the gam $\Gamma = \{N, \sigma, u\} = \{N; \sigma_1^m, \sigma_2^m, \ldots, \sigma_{n-1}^m, \sigma_n^m; u_1, u_2, \ldots, \ldots, u_n\}$, existence strategy response set $\sigma^* = \{\sigma_1^{m^*}, \sigma_2^{m^*}, \ldots, \sigma_{n-1}^{m^*}, \sigma_n^{m^*}\}$, satisfy $\forall s_i' \in S_i, s_i' \neq s_i^*, \forall i \in N$ following:

$$u_i(\sigma_1^*, \ldots, \sigma_{i-1}^*, \sigma_i^*, \sigma_{i+1}^*, \ldots, \sigma_n^*) \geq u_i(\sigma_1^*, \ldots, \sigma_{i-1}^*, \sigma_i', \sigma_{i+1}^*, \ldots, \sigma_n^*)$$

Then, $\sigma^* = \{\sigma_1^{m^*}, \sigma_2^{m^*}, \ldots, \sigma_{n-1}^{m^*}, \sigma_n^{m^*}\}$ is Nash equilibrium.

Based on the above definition, it is easy to know that the existence of a Nash equilibrium solution needs to meet certain specific conditions. For the existence of equilibrium, Nash, Debru, Glicksberg, Fan1, Dasgupta, Maskin and others have conducted in-depth discussions and proposed four existences. Theorems and the four theorems all inherit the ideas of Kakutani's fixed point theorem to some extent, and expand on this basis [20]. This article only describes an existence theorem involved in the following.

Definition 3.3: For any game with limited strategies, there must be an equilibrium solution.

IV. RESEARCH ON MODELING OF GAS-ELECTRIC COUPLING SYSTEM BASED ON P2G COUPLING

P2G technology can promote the integration of power systems and natural gas systems, but bring new challenges to the operation of energy systems. Modeling a gas-electric coupling system based on P2G coupling is a fundamental key issue for the safe and economic operation of the gas-electric coupling system under the high penetration rate of intermittent renewable energy and the P2G planning and configuration. The existing gas-electric coupling system research is shown in Figure 5, involving the modeling of P2G's own equipment, power generation and transmission network modeling, natural gas network modeling, and the construction of loads and renewable energy with forecast uncertainties. Model to form a more complete gas-electric coupling system model with P2G devices.

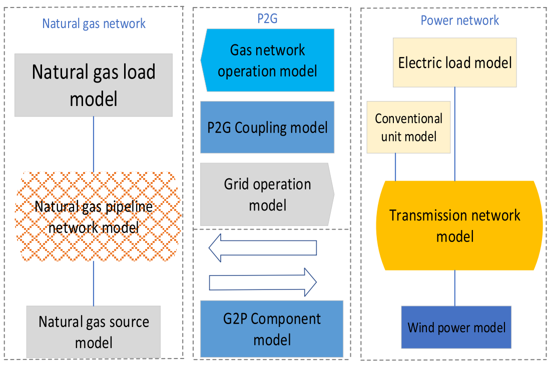

FIGURE 5. Gas-electric coupling system model.

A. P2G DEVICE MODELING

When wind abandonment occurs in the electricity-gas interconnection system, the surplus wind power can be converted into natural gas by turning on the P2G device and injected into the gas pipeline of the natural gas system for storage and transportation. Therefore, the following relationship between the power consumption of the P2G device and the injected air flow can be established:

$$F_{P2G,K} = \begin{cases} \frac{\eta_{P2G,k} P_{P2G,k}}{GHV}, & \sum_{i=1}^{N_W} \Delta P_{W,i} > 0 \\ 0, & \sum_{i=1}^{N_W} \Delta P_{W,i} > 0 \end{cases}, k = 1, 2, 3, \ldots, N_c \tag{1}$$

where $P_{P2G,k}$, $F_{P2G,k}$, $\eta_{P2G,k}$ respectively are the power consumption, injection airflow and conversion efficiency of P2G device k; GHV is the high heating value of natural gas; Nw and Nc are the total number of wind farms and P2G installations respectively.

B. GAS UNIT MODEL

Gas generating units and gas-fired cogeneration units are common gas-fired units in the electricity-gas interconnection system. The latter generally adopts the operation mode of "power by heat" in China, and the output power of the unit is determined according to the heat demand and the heat-to-power ratio. The following equations are satisfied between the air flow consumption and the output electric power of the above two gas-fired units:

$$F_{GAS,k} = \frac{[\alpha_k + \beta_k P_{GAS,k} + \gamma_k (P_{GAS,k})^2}{GHV}, \times k = 1, 2, 3, \ldots, N_a \tag{2}$$

$$F_{CHP,k} = P_{CHP,k}/(\eta_{CHP,k} GHV), \quad k = 1, 2, 3, \ldots, N_b \tag{3}$$

$$P_{CHP,k} = H_{CHP,k}/v_{CHP,k}, \quad k = 1, 2, 3, \ldots, N_b \tag{4}$$

where $P_{CAS,k}$, $F_{CAS,k}$ respectively are the active power output and the consumed air flow of the gas generator set k; α_k, β_k, γ_k is the consumption coefficient of gas generator set k; $P_{CHP,k}$, $F_{CHP,k}$, $H_{CHP,k}$, $v_{CHP,k}$, $\eta_{CHP,k}$ are the active power, air consumption, heat load, heat-to-electricity ratio, and conversion efficiency of gas-fired cogeneration unit k; Na and Nb are the total number of gas-fired generating units and gas-fired cogeneration units, respectively.

C. NODE INJECTION POWER AND AIRFLOW EQUATION

The calculation formula for the injected active and reactive power at node i of the power system and the injected air flow at node m of the natural gas system is as follows:

$$P_i = V_i \sum_{j=1}^{N_e} V_j (G_{ij} \cos\theta_{ij} + B_{ij} \sin\theta_{ij}), \quad i = 1, 2, \ldots, N_e \tag{5}$$

$$Q_i = V_i \sum_{j=1}^{N_e} V_j (G_{ij} \sin\theta_{ij} - B_{ij} \cos\theta_{ij}), \quad i = 1, 2, \ldots, N_e \tag{6}$$

$$F_m = V_i \sum_{r=1}^{N_1} A_{mr} L_r + \sum_{r=1}^{N_p} E_{mr} C_r + \sum_{r=1}^{N_p} T_{mr} \tau_r, \times m = 1, 2, \ldots, N_m \tag{7}$$

where Vi is the voltage amplitude of node i in the power system; θ_{ij} is the voltage phase angle difference between nodes i and j of the power system; G_{ij} and B_{ij} are the real and imaginary parts of the elements in the i-th row and j-th column of the nodal admittance matrix; L_r, C_r and τ_r are the flow through the gas pipeline r, the compressor branch r, and the flow consumed by the compressor branch r in the natural gas system, The specific calculation formula can be found in the literature [21]; A_{mr}, E_{mr} and T_{mr} are the node-pipe correlation matrix A, the node-compressor correlation matrix E, and the node-compressor inlet node correlation matrix T in the mth row and rth column elements respectively; N_l, N_p is the total number of gas pipelines and compressor branches respectively.

D. POWER SYSTEM CONSTRAINTS

The power system constraints mainly include: output constraints, node voltage constraints, line transmission power constraints, line power flow equation constraints, and network active power balance constraints, as shown in equations (9) to (12):

$$P_i^{W,\min} \le P_{i,h}^{W} + P_{i,h}^{P2G} \le P_i^{W,\max} \tag{8}$$

$$U_i^{\min} \le U_{i,h} \le U_i^{\max} \tag{9}$$

$$-P_L^{\max} \le P_{l,h} \le P_L^{\max} \tag{10}$$

$$\begin{cases} P_{i,h} - U_{i,h}\sum_{i=1}^{N} U_{j,h}(G_{ij}\cos\theta_{ij,h} + B_{ij}\sin\theta_{ij,h}) = 0 \\ Q_{i,h} - U_{i,h}\sum_{i=1}^{N} U_{j,h}(G_{ij}\sin\theta_{ij,h} + B_{ij}\cos\theta_{ij,h}) = 0 \end{cases} \tag{11}$$

$$P_{load,h} + P_{loss,h} + \sum_{i=1}^{N^{P2G}} P_{i,h}^{P2G} = \sum_{i=1}^{N^{MT}} P_{i,h}^{MT} + P_h^{grid} \tag{12}$$

where $P_i^{W,\max}$, $P_i^{W,\min}$ is the upper and lower limits of wind power output on node i; $U_i^{\max}$, $U_i^{\min}$ is the upper and lower limits of the voltage on node i; $P_L^{\max}$ is the transmission power limit of line ij; $P_{i,h}$, $Q_{i,h}$ are the injected active power and reactive power of node i in period h; $U_{i,h}$, $U_{j,h}$ are the voltage amplitudes of node i and node j under period h; G_{ij}, B_{ij} are the conductance and susceptance on the branch ij; $\theta_{ij,h}$ is the phase angle difference between node i and node j in period h.

E. NATURAL GAS SYSTEM CONSTRAINTS

Natural gas system constraints mainly include: gas source and gas storage device output constraints, natural gas pipeline flow constraints, network flow constraints and natural gas balance constraints, as shown in equations (13) to (17) respectively:

$$g_{i,\min}^{gs} \le g_{i,h}^{gs} \le g_{i,\max}^{ga} \tag{13}$$

$$g_{i,\min}^{stor} \le g_{i,h}^{stor} \le g_{i,\max}^{stor} \tag{14}$$

$$g_{ij,h} = \mathrm{sgn}(\rho_{i,h} - \rho_{j,h}) \cdot C_{ij}^2 \cdot (\rho_{i,h}^2 + \rho_{j,h}^2) \tag{15}$$

$$g_{ij,h,\min} \le g_{ij,h} \le g_{ij,h,\max} \tag{16}$$

$$g_{load,h} + \sum_{i=1}^{N^{MT}} g_{i,h}^{MT} - \sum_{i=1}^{N^{P2G}} g_{i,h}^{P2G} - P_h^{up} = 0 \tag{17}$$

where $g_{i,h}^{gs}$, $g_{i,h}^{stor}$ is the natural gas supply flow rate and the supply flow rate of the gas storage tank at the gas source point i in the period h; $g_{i,\max}^{ga}$, $g_{i,\min}^{gs}$ are the upper and lower limits of the natural gas supply flow at gas source point i; $g_{i,\max}^{stor}$, $g_{i,\min}^{stor}$ are the pipe flow from node i to node j in the h-th period, and the air pressure at node i and node j; C_{ij} is the pipeline coefficient, which is related to the length, diameter, and operating efficiency of the pipeline; $g_{ij,h,\max}$, $g_{ij,h,\min}$ are the upper and lower limits of pipe flow.

F. ELECTRIC-GAS COUPLING CONSTRAINT

$$P_i^{MT,\min} \le P_{i,h}^{MT} \le P_i^{MT,\max} \tag{18}$$

$$0 \le P_{i,h}^{P2G} \le P_i^{P2G,\max} \tag{19}$$

$$P_{i,,h}^{MT} = \mu^{MT} \times g_{i,h}^{MT} \tag{20}$$

$$P_{i,,h}^{P2G} = \mu^{P2G} \times g_{i,h}^{P2G} \tag{21}$$

where $P_i^{MT,\max}$, $P_i^{MT,\min}$ is the upper and lower limits of the gas turbine output on node i; $P_i^{P2G,\max}$ is the output upper limit of the P2G plant station on node i; μ^{MT} is the energy conversion efficiency of the gas turbine, μ^{P2G} is the energy conversion efficiency of the electric-to-gas unit.

V. COMPREHENSIVE ENERGY PLANNING MODEL BASED ON NON-COOPERATIVE GAME

A. MULTI-AGENT PLANNING INCOME MODEL

The multi-agents considered in this paper include the main body of the electric power network and the main body of the natural gas network. The main body of the electric power network is the power generation company and the grid company, and the main body of the natural gas network is the natural gas company. Different from the traditional integrated energy system planning problem with the power grid company as the core subject, this article involves multiple subjects and each subject has different interests. For power generation companies, they hope to reduce the investment and construction costs of gas generating units, and reduce operating costs and environmental costs, so as to maximize revenue; for power grid companies, they hope to reduce line investment costs and network losses, thereby maximizing revenue; For natural gas companies, they hope to rationally plan pipeline investment costs, reduce the operating costs of natural gas sources, increase gas sales income, and maximize their own interests. Different entities have different goals when participating in planning and making independent decisions. Therefore, the planning models of the above entities need to be constructed separately. Reference [22] provides the modeling idea of the revenue model in dynamic game planning. In this paper, the revenue is obtained by calculating the difference between the total network revenue and the total cost of the network, and considering the network security constraints, the power generation company, the power grid company and the natural gas company are constructed separately. Income model.

B. WIND POWER REVENUE FUNCTION

Analyzing the entire investment, construction and operation cycle of a wind power plant, it can be seen that its income roughly includes the parts of early investment, sale of electric energy, operation and maintenance, etc. The mathematical expression of F_i^W is as follows:

$$F_i^W = \sum_{h=1}^{S_h} P_{i,h}^W \times (c_h^{W,sw} + c^{W,bt}) + \sum_{h=1}^{S_h} P_{i,h}^{P2G} \times c_h^{P2G} - \frac{r(1+r)^{nW}}{(1+r)^{nW}-1} S_i^W \times c^{W,inv} \quad (22)$$

where N_h is the number of operating periods; T_h is the duration of the h-th period; $P_{i,h}^W$, $P_{i,h}^{P2G}$ are the actual grid power of the wind power at node i in the period h and the power provided to the P2G plant and station; $c_h^{W,sw}$ is the on-grid price of wind power in time period h; $c^{W,bt}$ is the government's new energy subsidies for wind power grids; c_h^{P2G} is the price of P2G power supply for wind power at time period h; $\frac{r(1+r)^{nW}}{(1+r)^{nW}-1}$ is the DWG's current value conversion coefficient of equivalent annual value, where, nW is the economic service life of the DWG, r is the discount rate; S_i^W is the rated capacity of WDG installed at the i-th node; $c^{W,inv}$ is the unit capacity investment cost of WDG.

C. REVENUE FUNCTION OF MICRO GAS TURBINE PLANT

Discuss the power generation characteristics of gas-fired power plants. The income F_i^{MT} includes the income from the sale of electric energy and related expenditures related to operation and maintenance. The specific mathematical expressions are shown below:

$$F_i^{MT} = \sum_{h=1}^{S_h} P_{i,h}^{MT} \times (c_h^{MT,sw} - c^{MT,m}) - \sum_{h=1}^{S_h} g_{i,h}^{MT} \times c_h^{g,s} - \frac{r(1+r)^{nMT}}{(1+r)^{nMT}-1} S_i^{MT} \times c^{MT,inv} \quad (23)$$

where $P_{i,h}^{MT}$ is the actual grid power of the gas turbine at node i in the period h; $c_h^{MT,sw}$ is the on-grid electricity price of the gas turbine in time period h; $c^{MT,m}$ is the maintenance cost of the gas turbine; $g_{i,h}^{MT}$ is the amount of natural gas required by the gas turbine at node i to generate power at $P_{i,h}^{MT}$ during period h; $c_h^{g,s}$ is the natural gas price at time period h; nMT is the economic service life of the gas turbine; S_i^{MT} is the rated capacity of the gas turbine installed at the i-th node; $c^{MT,inv}$ is the investment cost per unit capacity of the gas turbine.

D. P2G PLANT REVENUE FUNCTION

The income of the P2G plant comes from the electricity-to-gas sales income, and the cost includes the investment cost of the electricity-to-gas device and the cost of electricity. The income function F_i^{P2G} is as follows:

$$F_i^{P2G} = \sum_{h=1}^{S_h} g_{i,h}^{P2G} \times c_h^{g,sw} - \sum_{h=1}^{S_h} P_{i,h}^{P2G} \times (c_h^{P2G} + c^{P2G,m}) - \frac{r(1+r)^{nP2G}}{(1+r)^{nP2G}-1} S_i^{P2G} \times c^{P2G,inv} \quad (24)$$

where $g_{i,h}^{P2G}$ is the actual gas supply volume of the electric-to-gas device at node i during the period h; $c_h^{g,sw}$ is the gas supply price for the electricity-to-gas device at time period h; $P_{i,h}^{P2G}$ is the amount of electricity required by the electric-to-gas device on node i to supply gas $g_{i,h}^{P2G}$ during time period h;

c_h^{P2G} is the maintenance cost of the gas turbine; $nP2G$ is the economic service life of the electricity-to-gas device; S_i^{P2G} is the rated capacity of the electric-to-gas device installed at the i-th node; $c^{P2G,inv}$ is the investment cost per unit capacity of the electricity-to-gas device.

E. GRID COMPANY REVENUE FUNCTION

The income of the power grid comes from the sales of electricity, and the cost includes the investment cost of the transmission line, the cost of network loss and the cost of electricity purchase. The income function F^E is shown in formula:

$$F^E = \sum_{h=1}^{S_h} P_{load,h} \times c_h^{p,s} - \sum_{i=1}^{N^W} \sum_{h=1}^{S_h} P_{i,h}^W \times c_h^{W,sw} - \sum_{i=1}^{N^{mt}} \sum_{h=1}^{S_h} P_{i,h}^{MT} \times c_h^{MT,sw} - \sum_{h=1}^{S_h} P_h^{grid} \times c_h^{grid} - \sum_{h=1}^{S_h} P_{loss,h} \times c_h^{p,s} - \frac{r(1+r)^{n^{ij}}}{(1+r)^{n^{ij}}-1} \sum_{ij\in\varphi l} x_{ij} \times c_{ij} \times l_{ij} - \sum_{ij\in\varphi l} x_{ij} \times c_{ij}^m \times l_{ij} \quad (25)$$

where $P_{load,h}$ is the power load demand in h period; $c_h^{p,s}$ is the average price of electricity sold by the residents of the power grid during period h; N^W, N^{mt} are the nodes to be installed for wind power and gas turbines; P_h^{grid} is the power purchased by the distribution network from the upper-level grid for the period h; c_h^{grid} is the electricity purchase price of the distribution network from the upper-level grid for the time period h; $P_{loss,h}$ is the network loss of time period h; n^{ij} is the economic service life of line ij; x_{ij} is a 0-1 variable, if the line is added to the line ij, it is 1, if it is not installed, it is 0; c_{ij} is the investment cost per unit length of line ij; l_{ij} is the length of circuit ij; c_{ij}^m is the maintenance cost per unit length of the line.

F. NATURAL GAS COMPANY REVENUE FUNCTION

The income of natural gas companies comes from the sales of gas, and the cost includes the investment cost of the gas pipeline and the operating cost of the natural gas source. The income function F^G is as follows:

$$F^G = \sum_{h=1}^{S_h} g_{load,h} \times c_h^{g,s} + \sum_{i=1}^{N^{MT}} \sum_{h=1}^{S_h} g_{i,h}^{MT} \times c_h^{g,s} - \sum_{i=1}^{N^{P2G}} \sum_{h=1}^{S_h} g_{i,h}^{P2G}$$

$$\times c_h^{g,sw} - \sum_{h=1}^{S_h} g_h^{gp} \times c_h^{gp} - \frac{r(1+r)^{n^{gp}}}{(1+r)^{n^{gp}}-1} \times \sum_{ij\in\varphi_{gp}} x_{ij} \times c^{gpij} \times l_{ij}^{gp} \quad (26)$$

where $g_{load,h}$ is the natural gas load demand in period h; $c_h^{g,s}$ is the average price of gas sold by residents in period h; N^{P2G} is the node to be installed of the electric-to-gas device; g_h^{gp} is the power purchased by the distribution network from the upper-level grid for the period h; c_h^{gp} is the electricity purchase price of the distribution network from the upper-level grid for the time period h; N^{gp} is the economic service life of the pipeline; x_{ij} is a 0-1 variable, if pipe is installed in ij, it is 1, and if it is not installed, it is 0; c^{gpij} is the investment cost per unit length of pipeline ij; l_{ij}^{gp} is the length of pipe ij.

G. CONSTRUCTION OF NON-COOPERATIVE GAME MODEL OF INTEGRATED GAS AND ELECTRICITY SYSTEM UNDER UNCERTAINTY

A non-cooperative game contains three necessary components. For the non-cooperative game model under uncertainty established in this chapter, the corresponding components are:

(1) Independent game player. The players in the bureau include power generation companies (wind power plants, micro gas turbine plants), power grid companies and natural gas companies, and power-to-gas plant plants, forming a multi-agent non-cooperative game.

(2) The strategies of the players in the game. The strategy set in this chapter is the plans of each subject under their corresponding constraints, that is, the strategies of wind power plants, micro gas turbine plants, and electricity-to-gas plant plants are their respective capacities; the strategies of grid companies and natural gas companies are expansion plans for grids and natural gas pipelines; Under the condition that some parameters are uncertain, each participant makes a decision to maximize his own profit based on the information he has mastered.

(3) Participants' income. The income function of multiple participants is the annual net income of the difference between annual income and cost;

(4) Uncertain parameters. Uncertain parameters include wind power output, electricity load and natural gas load;

H. GAME RELATIONSHIP

In the joint planning of the gas-power integrated energy system, the main bodies are power generation companies, natural gas companies and grid companies. The planning decision of the power generation company is the new construction of gas generating units, the planning decision of the power grid company is the construction of new transmission lines, and the planning decision of the natural gas company is the construction of new pipelines. The above-mentioned multiple entities indirectly influence each other's decision-making through the electric-gas mixed power flow model. In the process of decision-making, natural gas companies can decide on the structure of natural gas pipelines, which will affect the investment and construction of gas generators and the income of electricity sales of power generation companies; grid companies can make decisions on the grid and seek to minimize investment, which will affect the investment and construction of gas generators of power generation companies and the income of electricity sales. Power generation companies can make decisions about the investment of gas generating units, thereby affecting the investment and construction of grid company grids and the gas sales income of natural gas companies; grid companies and natural gas companies can also indirectly affect each other's network topology through the power flow information transmitted by coupling nodes. Multiple subjects make independent decisions, but influence each other to form a game relationship.

Due to the need to jointly complete the planning and construction of the power-natural gas integrated energy system under the premise of independent decision-making, power grid companies, power generation companies, and natural gas companies have each other's strategic information in the planning process. Based on this, in the game process, when any one of the power generation company, the power grid company, and the natural gas company changes strategy and cannot obtain more benefits, the game reaches an equilibrium state.

I. PROOF OF THE EXISTENCE OF GAME EQUILIBRIUM

Nash equilibrium is the solution of the non-cooperative game recognized by the academic circles and the engineering application circles. Its existence needs to satisfy one or more of the four existence axioms. Analyzing the output characteristics of each subject shows that its output is continuously adjustable, and the adjustment range is determined, that is, the strategy set is a continuous strategy space on R^3, and the game scheduling model in this chapter is a finite game. Combining with Theorem 3.3 of this paper, we can see that the game model in this paper must have a corresponding equilibrium solution.

VI. IMPROVED TWO-STAGE ROBUST OPTIMIZATION MODEL

Renewable energy output, load, etc. all have forecast deviations, and it is difficult to ensure the economics of dispatch by using a deterministic optimization model. In order to avoid the optimization scheme being too aggressive and risky, this paper takes into account the uncertain factors in the optimization model, and solves it by improving the two-stage robust optimization model. It is explained as follows: The basic idea of the classic two-stage robust optimization model is that as long as the system output plan can withstand the disturbance in the most extreme scenario, it must meet the disturbance in any other scenario, which improves the robustness of the system to a certain extent. It is great, but the probability of extreme scenarios is low. It only pursues the lowest system operating cost under extreme conditions, the system backup cost is relatively high, and the solution obtained is relatively conservative. Aiming at the shortcomings of the classic two-stage robust optimization model, the article proposes an improved two-stage robust optimization model. The basic idea is that the system output plan is optimal in the desired scenario and can withstand fluctuations in any scenario. The corresponding robust risk appetite is:

$$\min_{x}[c^T x + \max_{u\in U} \min_{x_0\in(x,u_0)} b^T \Delta x_0] \tag{27}$$

$$\begin{cases} Dx \geq d \\ Gx = 0 \\ D(x+\Delta x_0) \geq d \\ G(x+\Delta x_0) = 0 \\ D(x+\Delta x) \geq d \\ G(x+\Delta x) = 0 \end{cases} \tag{28}$$

where x is the decision variable in the first stage; Δx_0 is the amount of change in wind power output and load in the desired scenario; u_0 is the expected value in the expected scenario; u is the variable cost amount in the desired scenario; $b^T \Delta x_0$ is the first stage decision variable obtained; $G(x + \Delta x_0) = 0$, $D(x + \Delta x_0) \geq d$ are the equality and inequality constraints that need to be met in the expected scenario of wind power output and load change; Δx is the actual wind power output and load change when the uncertainty set U fluctuates; $G(x + \Delta x_0) = 0$, $D(x + \Delta x) \geq d$ respectively represents the equality and inequality constraints that need to be satisfied when the wind power output and load change are. That is to say, the meaning of the entire formula is to seek the optimal value in the desired scenario, while being able to resist fluctuations in any scenario.

A. MODEL SOLVING

When optimizing the solution and improving the two-stage robust optimization model, this paper decomposes it into the main sub-problems, and uses interactive iteration to find the optimal value.

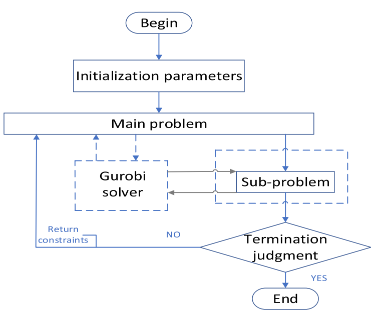

FIGURE 6. Flow chart of algorithm solution.

B. GAME MODEL SOLVING STRATEGY

Step 1: Input raw data and parameters. Initialize the required data, including the number of players in the game, the strategy set, the parameters of the profit function, the parameters related to the amount of uncertainty, etc.;

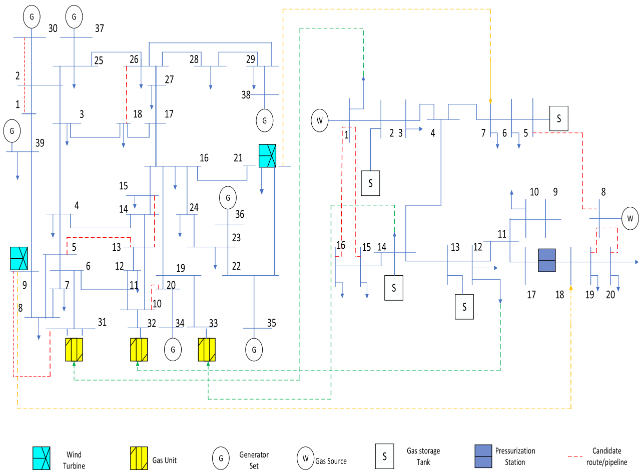

FIGURE 7. Interconnected IEEE 39-bus electric power system and 20-bus natural gas system.

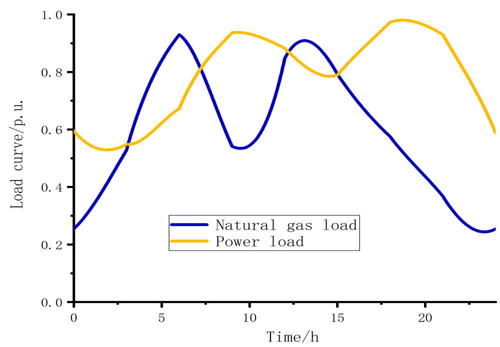

FIGURE 8. Typical daily load curve.

Step 2: Set the initial value of the equilibrium point. In this paper, the feasible initial value is randomly selected as the equilibrium point X* in the strategy set;

Step 3: Each game participant independently optimizes. Monte Carlo sampling is performed on wind power output, power load and natural gas load, and the power flow calculation is performed. According to the results of the previous round of optimization, each participant refers to the decisions made by other participants, and uses the improved two-stage robust optimization to obtain the optimal Strategy;

Step 4: Determine whether each participant has found the Nash equilibrium. If the results of each participant's iterative solution are the same for two consecutive times, it is considered that the equilibrium solution is found and the equilibrium solution is output; if the equilibrium solution is not found, information exchange is carried out, the decision of each participant is updated, and step 3 is returned to re-optimize.

VII. CASE ANALYSIS

In order to verify the effectiveness of the scheme proposed in this paper, based on the IEEE 39-node power system and a certain 20-node natural gas system in Belgium, the test case shown in Figure 2 was constructed with electric-to-gas unit and micro gas turbine unit as energy coupling units for

TABLE 1. Optimal planning scheme in four situations.

Program	Power line	Natural Gas Pipeline	Coupling unit
1	1-30	1-5,	$W_9(450)$
	5-13	1-16,	$W_{21}(550)$
	9-31	5-8	
	13-15	8-19	
2	1-30	1-5	$W_9(400)$,$W_{21}(450)$
	10-20	1-15	$P2G_9(40)$,$P2G_{21}(35)$
	13-15	1-16	$MT_{31}(300)$,$MT_{32}(300)MT_{33}(300)$
	18-26	5-8	
3	1-30	1-15	$W_9(450)$,$W_{21}(550)$
	5-13	1-16	$P2G_9(40)$,$P2G_{21}(40)$
	18-26	5-8	$MT_{31}(300)$,$MT_{32}(300)$,$MT_{33}(350)$

testing [23]. Among them, the power system includes 50 power load nodes, 7 power supply nodes and 46 transmission lines. In order to meet the estimated power demand, 2 candidate sites for wind turbines and P2G units, 3 candidate sites for micro gas turbine units and 6 candidate transmission lines are proposed. The natural gas system includes 9 natural gas load nodes, 2 gas source stations, 4 gas storage devices, 2 pressurization stations and 19 pipelines.

The coupling candidate nodes of power system and natural gas system include:

Power node 9 (natural gas node 18), power node 21 (natural gas node 7), power node 31 (natural gas node 1), power node 32 (natural gas node 12), power node 33 (natural gas node 14). As the operating cost of P2G is still relatively high, the P2G site is selected at the same location as the wind farm to absorb the surplus output of the wind farm and reduce the wind abandonment rate of wind power [24].

The following three schemes are designed in the article. Option 1: Independent planning of power network and natural gas network; Option 2: Direct integrated planning of power network and natural gas network without game strategy; Option 3: Comprehensive planning of power network and natural gas network through the proposed game strategy.

A. PLANNING RESULTS ANALYSIS

For the above three schemes, the optimal planning scheme obtained by the solution is shown in Table 1. Among them, the number in parentheses indicates the installed capacity, for example, W9 (450) indicates that the wind turbine generator set at node 9 is 450 MW.

It can be seen from Table 1 that in the planning of gas generating units: Scheme 1 selects the units at nodes 1, 5, 8, 16, and 19, and Scheme 2 selects the units at nodes 1, 5, 8, 15, and 16. Scenario 3 selects 1, 5, 8 and 16-node units; in the transmission line planning, the difference between the three schemes is that: scheme 1 has newly-built transmission lines on all branches to be selected, scheme 3 is in 9. −31 branch and 13-15 branch did not build a new transmission line, plan 2 did not build a new line in the 9-31 branch. The rest of the transmission lines are newly constructed in the same situation. From the above results, it can be seen that the planning results of Option 1 and Option 2 and Option 3 are different. The reason is that: Option 1 is an independent plan, and both Option 3 and Option 2 are joint planning. The independent planning method and the comprehensive planning method are in the planning. The idea of seeking optimal goals is different. Independent planning involves power generation companies, power grid companies, and natural gas companies separately planning the power network and natural gas network, and comprehensive planning is the overall planning of the power network and natural gas network from an overall perspective. Although both Option 2 and Option 3 are comprehensive planning, the planning results are different. The reason is that Option 2 is to make joint planning decisions with the goal of maximizing overall revenue, while Option 3 is based on individual rationality and through dynamic game. Seek an equilibrium state that can maximize the respective benefits of multiple market entities. Therefore, compared with the comprehensive planning in Option 2 that does not consider the game, the planning scheme will be different.

B. NECESSITY ANALYSIS OF COORDINATED PLANNING

Figure 9 shows the comparison of the operating cost values of the power grid and the gas network under the three optimization scenarios. Option 1 represents the result of independent optimization of the power grid and the natural gas network for their own operating costs. From the figure, we can see that although the grid or natural gas grid alone can optimize its own goals, it can reduce its own operating costs, but the operation mode that ignores the other's interests will greatly increase the other's operating costs. The result of the game strategy planning we adopted can weigh the interests of both parties, so as not to make the other party suffer huge losses due to the preference of one party.

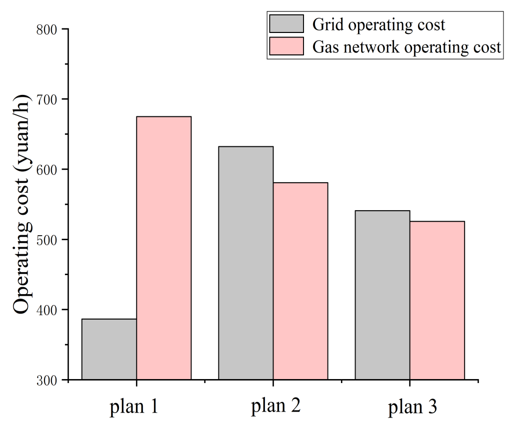

FIGURE 9. Operating costs of the power grid and gas network for the three options.

C. ANALYSIS OF THE NECESSITY OF MULTI-AGENT GAME

This paper verifies the necessity of considering the multi-agent game in this paper by comparing the costs and benefits of grid companies, power generation companies and natural gas companies under scenario 2 and scenario 3. The specific results are shown in Table 2-4.

TABLE 2. Grid company costs and benefits.

Program	Total revenue/100 million yuan	Network loss cost/100 million yuan	cost of investment/100 million yuan	Power purchase cost/100 million yuan
2	30.13	3.07	0.25	5.03
3	29.67	2.87	0.23	5.02

TABLE 3. Power generation company costs and benefits.

Program	Total revenue/100 million yuan	Gas unit operating cost/100 million yuan	cost of investment/100 million yuan	Gas purchase cost/100 million yuan
2	140.03	2.62	0.87	6.32
3	138.94	3.28	0.87	5.65

TABLE 4. Gas company costs and benefits.

Program	Total revenue/100 million yuan	Operating cost/100 million yuan	cost of investment/100 million yuan
2	30.23	15.15	0.94
3	28.96	14.89	0.91

It can be seen from Table 2 that, compared with Option 2, the transmission line investment cost of Option 3 is reduced by 20 million yuan, and the cost of network loss is reduced by 20 million yuan. The reason is that after scheme 3 takes into account the multi-agent game, the grid company changed the line investment portfolio and did not expand the line on branch 13-15, so compared with scheme 2, the line investment cost and network loss cost are reduced.

It can be seen from Table 3 that, compared with Option 2, the investment cost of Option 3 is basically unchanged, the gas purchase cost has been reduced by 67 million yuan, and the operating cost of gas-fired units has increased by 66 million yuan. The reason is that after the multi-agent game is taken into account in Option 3, the grid company reduced the transmission line near one gas-fired unit, which led to a reduction in the gas purchase cost of the gas-fired unit.

It can be seen from Table 4 that, compared with Option 2, the natural gas network investment in Option 3 has been reduced by 3 million yuan. Because the natural gas company has reduced one natural gas pipeline, the operating cost has been reduced by 26 million yuan, and the income of the natural gas company has decreased by 127 million yuan. The reason is that after considering the multi-agent game, the reduction in the operating costs of gas-fired units in the grid will reduce the demand for natural gas, thereby reducing the operating costs of natural gas companies, and at the same time, reducing the total income of natural gas companies.

The net income of each interest group under each plan is shown in Figure 10. By comparing the income of wind farms

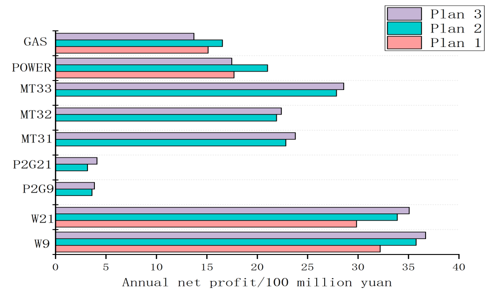

FIGURE 10. Economical comparison of three plans.

and P2G plants and stations in each scheme, the income of wind farms is much greater than that of P2G plants. Because the gas price of P2G plants is lower than that of wind farms, and the capacity of P2G plants is limited, the income of P2G plants is limited. The conversion efficiency of P2G is up to about 60%, so its revenue-to-cost ratio is lower than that of other plants.

It can be seen from Figure 10 that the net income of each vendor in Option 1 is less than that of Option 2 and Option 3. This is due to the fact that electricity and natural gas can be converted into each other through the coupling unit during collaborative planning. During the peak period of natural gas demand, during independent planning, new transmission lines and natural gas pipelines need to be built to meet the load demand; when coordinated planning, P2G plants are equivalent to gas sources, which can effectively reduce the number of additional natural gas pipelines and reduce costs. The same is true during peak power demand periods.

Among them, the total social benefit of Option 2 is 183. 8 billion yuan, the total social benefit of option 3 is 182. 1.1 billion yuan, and it is found from Figure 3 that the annual revenue of each distributed power plant in Option 2 is less than that of Option 3. The reason is that Option 2 is optimized to maximize the total social benefits. Among them, the maximum total revenue is at the expense of the benefits of the distributed power plants, which is completely inconsistent with the market mechanism. The game theory strategy adopted in Scheme 3 enables each subject to obtain the Nash equilibrium point after continuous gaming, that is, the optimal benefit that each subject can obtain. As an interest group, the distributed power plant will not choose a planning scheme with lower interest. Scheme 3 takes into account the benefits of all market entities and is more in line with the actual operation of the electricity market.

D. ANALYZE THE IMPACT OF THE COORDINATED PLANNING OF THE POWER SYSTEM AND THE NATURAL GAS SYSTEM ON THE AMOUNT OF WIND CURTAILMENT

Figure 11 shows the impact and comparison of Option 1, Option 2, and Option 3 on the wind turbine abandonment volume.

It can be seen from Figure 11 that the wind abandonment rate is high at night when the power consumption is low, as high as about 25%, and the peak time is around 10 o'clock

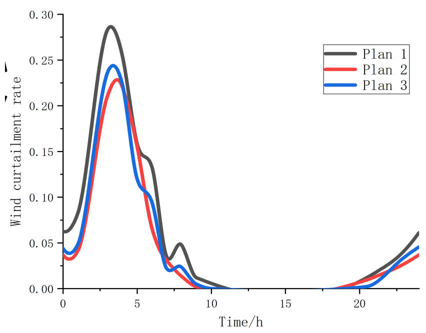

FIGURE 11. **Wind curtailment rate under each plan.**

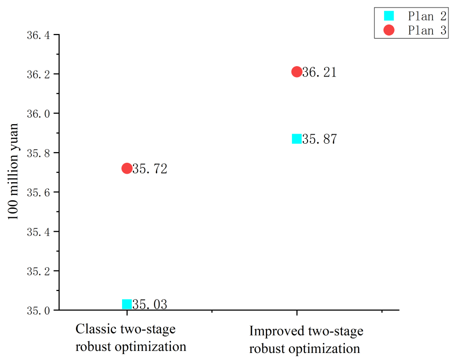

FIGURE 12. **Annual income of wind power plants under different optimization schemes.**

to 21 o'clock, and wind power is almost completely consumed. The total amount of wind curtailment in Option 2 is reduced by 13% compared with Option 1. In Option 1, no P2G units are built, and all wind power output is absorbed by the electrical load. In Option 2, Option 3, wind power is in addition to meeting power demand. The surplus output is used to supply P2G units, supply and store gas to the natural gas network. Therefore, the construction and operation of P2G generating units can effectively reduce the abandonment of wind turbines and improve energy efficiency. At the same time, comparing the wind abandonment rate of Option 2 and Option 3 in Figure 4, since the game strategy is adopted, the number of wind farms and P2G units will increase, and the amount of wind abandonment will also be reduced. Therefore, when the wind power penetration rate is high, it can be considered to connect to a certain amount of wind power. P2G devices with high capacity to effectively alleviate the phenomenon of ''abandoning wind and curtailing electricity'' in the system.

E. ROBUST OPTIMIZATION METHOD COMPARISON

In order to verify the effectiveness of the improved two-stage robust optimization model proposed in this paper, a comparative analysis is made with the classic two-stage robust optimization model.

The classic two-stage robust optimization is to find the solution with the highest annual comprehensive income in the worst scenario. Therefore, the planning must meet the robustness requirements when the wind power output, load and other uncertain factors fluctuate the most. Compared with the improvement of the two-stage robust optimization It is too conservative and unrealistic, resulting in a comprehensive income lower than the improved two-stage robust optimization scheme. For the classic two-stage robust optimization, the conservative planning method requires the construction of more lines and distributed power sources, resulting in waste of resources and reduced revenue, which is equivalent to sacrificing part of the economy in exchange for robustness. The improved two-stage robust optimization planning scheme finds the optimal scheme in the desired scenario, and the scheme can resist any scenario. Therefore, the planning scheme obtained by improving the two-stage robust optimization is more economical, as shown in Table 2.

VIII. CONCLUSION

The article introduces the electrical and electrical integrated energy network with P2G and gas turbine as the energy coupling unit, and proposes a comprehensive planning model considering the uncertainty of wind power and load, aiming at the uncertainty of wind power and load, and classical two-stage robust optimization For the conservative problem of, an improved two-stage robust optimization method is proposed, and the improved non-cooperative game is used as a strategy to solve the model. The following conclusions can be drawn in the analysis of the results of the calculation example:

(1) Gas-power coordinated planning can reduce the total cost, promote the absorption of wind power, relieve the pressure caused by peak power and gas load, reduce the investment and construction of new transmission lines and natural gas pipelines, and thus bring greater Economic benefits;

(2) The establishment and operation of P2G units can effectively absorb the excess wind power output in the system, and significantly improve the wind abandonment phenomenon of the system. The use of P2G units can convert surplus renewable energy into natural gas, store and transmit it through the natural gas network, and improve the utilization rate of renewable energy;

(3) The improved two-stage robust optimization is obviously better than the classic two-stage robust optimization, and the economy is better.

REFERENCES

[1] A. Quelhas, E. Gil, J. D. McCalley, and S. M. Ryan, "A multiperiod generalized network flow model of the U.S. Integrated energy system: Part I—Model description," *IEEE Trans. Power Syst.*, vol. 22, no. 2, pp. 829–836, May 2007.

[2] J. H. Zheng, J. J. Chen, Q. H. Wu, and Z. X. Jing, "Multi-objective optimization and decision making for power dispatch of a large-scale integrated energy system with distributed DHCs embedded," *Appl. Energy*, vol. 154, pp. 369–379, Sep. 2015.

[3] B. Chen, Y. Li, P. Li, and D. Wu, "Decentralized coordinated dispatch of multi-microgrid integrated energy system considering source-load uncertainty," *IOP Conf. Ser., Earth Environ. Sci.*, vol. 555, no. 1, 2020, Art. no. 012105.

[4] S. Clegg and P. Mancarella, "Integrated modeling and assessment of the operational impact of power-to-gas (P2G) on electrical and gas transmission networks," *IEEE Trans. Sustain. Energy*, vol. 6, no. 4, pp. 1234–1244, Oct. 2015.

[5] Z. Chen, D. Wang, H. Jia, W. Wang, B. Guo, B. Qu, and M. H. Fan, "Research on optimal day-ahead economic dispatching strategy for microgrid considering P2G and multi-source energy storage system," *Proc. CSEE*, vol. 37, no. 11, pp. 3067–3077, Jun. 2017.

[6] T. Ding, Z. Wu, J. Lv, Z. Bie, and X. Zhang, "Robust co-optimization to energy and ancillary service joint dispatch considering wind power uncertainties in real-time electricity markets," *IEEE Trans. Sustain. Energy*, vol. 7, no. 4, pp. 1547–1557, Oct. 2016.

[7] Z. Jinhui, W. Xu, J. Chuanwen, G. Kai, Y. Shuo, and Y. Meng, "Two-stage robust optimal scheduling of distribution network containing cogeneration units in new towns," *Automat. Electr. Power Syst.*, vol. 43, no. 23, pp. 155–163, 2019.

[8] P. Xiao, W. Hu, X. Xu, W. Liu, Q. Huang, and Z. Chen, "Optimal operation of a wind-electrolytic hydrogen storage system in the electricity/hydrogen markets," *Int. J. Hydrogen Energy*, vol. 45, no. 46, pp. 24412–24423, Sep. 2020.

[9] Y. Wang, Y. Yang, L. Tang, W. Sun, and B. Li, "A wasserstein based two-stage distributionally robust optimization model for optimal operation of CCHP micro-grid under uncertainties," *Int. J. Electr. Power Energy Syst.*, vol. 119, Jul. 2020, Art. no. 105941.

[10] J. Liu, W. Sun, and J. Yan, "Effect of P2G on flexibility in integrated power-natural gas-heating energy systems with gas storage," *Energies*, vol. 14, no. 1, p. 196, Jan. 2021.

[11] H. Chen, J. Shao, T. Jiang, R. Zhang, X. Li, and G. Li, "Situation awareness and security risk mitigation for integrated energy systems with P2G based on sensitivity analysis," *IET Renew. Power Gener.*, vol. 14, no. 17, pp. 3327–3335, 2020.

[12] Y. Li, Y. Du, K. Xiang, C. Lin, H. Lin, and Y. Yang, "Planning model of integrated energy system considering P2G and energy storage," in *Proc. IEEE 3rd Conf. Energy Internet Energy Syst. Integr. (EI2)*, Nov. 2019, pp. 1246–1251.

[13] Z. Yang, C. Gao, and M. Zhao, "The optimal investment strategy of P2G based on real option theory," *IEEE Access*, vol. 8, pp. 127156–127166, 2020.

[14] Y. Xu, G. Huang, and X. Qin, "Inexact two-stage stochastic robust optimization model for water resources management under uncertainty," *Environ. Eng. Sci.*, vol. 26, no. 12, pp. 1765–1776, Dec. 2009.

[15] M. Mohiti, H. Monsef, A. Anvari-Moghaddam, and H. Lesani, "Two-stage robust optimization for resilient operation of microgrids considering hierarchical frequency control structure," *IEEE Trans. Ind. Electron.*, vol. 67, no. 11, pp. 9439–9449, Nov. 2020.

[16] E. Kuznetsova, Y.-F. Li, C. Ruiz, and E. Zio, "An integrated framework of agent-based modelling and robust optimization for microgrid energy management," *Appl. Energy*, vol. 129, pp. 70–88, Sep. 2014.

[17] E. Kuznetsova, C. Ruiz, Y.-F. Li, and E. Zio, "Analysis of robust optimization for decentralized microgrid energy management under uncertainty," *Int. J. Electr. Power Energy Syst.*, vol. 64, pp. 815–832, Jan. 2015.

[18] S. A. Alavi, A. Ahmadian, and M. Aliakbar-Golkar, "Optimal probabilistic energy management in a typical micro-grid based-on robust optimization and point estimate method," *Energy Convers. Manage.*, vol. 95, pp. 314–325, May 2015.

[19] P. Aristidou, A. Dimeas, and N. Hatziargyriou, "Microgrid modelling and analysis using game theory methods," in *Proc. Int. Conf. Energy-Efficient Comput. Netw.*, 2010, pp. 12–19.

[20] L. Ali, S. M. Muyeen, H. Bizhani, and A. Ghosh, "Optimal planning of clustered microgrid using a technique of cooperative game theory," *Electr. Power Syst. Res.*, vol. 183, Jun. 2020, Art. no. 106262.

[21] J. Aguila-Leon, C. Chiñas-Palacios, E. X. Garcia, and C. Vargas-Salgado, "A multimicrogrid energy management model implementing an evolutionary game-theoretic approach," *Int. Trans. Elect. Energy Syst.*, vol. 30, no. 11, 2020, Art. no. e12617.

[22] F. Fang, Z. Zhu, S. Jin, and S. Hu, "Two-layer game theoretic microgrid capacity optimization considering uncertainty of renewable energy," *IEEE Syst. J.*, early access, Jul. 28, 2020, doi: 10.1109/JSYST.2020.3008316.

[23] P. Sangdon *et al.*, "A study on game theory methodology to distributed network environment for energy trading in micro grid," in *Proc. Symp. Korean Inst. Commun. Inf. Sci.*, Jun. 2017, pp. 5–6.

[24] M. Khojasteh, "A robust energy procurement strategy for micro-grid operator with hydrogen-based energy resources using game theory," *Sustain. Cities Soc.*, vol. 60, Sep. 2020, Art. no. 102260.

YANG LIU received the bachelor's degree in electrical engineering and automation from North China Electric Power University, in 2018, and the master's degree from Shanghai Dianji University, in 2019.

From 2019 to 2021, his main research interests include power system planning and optimal dispatch.

TIANYU LIU born in April 1978. He received the master's degree in control theory and control engineering from Xinjiang University, in 2003, and the Ph.D. degree in control theory and control engineering from Shanghai University, in 2007.

Since 2007, he has been working with Shanghai Dianji University, where he was appointed as an Associate Professor, in 2010. From 2010 to 2011, he was a Senior Foreign Visiting Scholar with Durham University, U.K. In 2016, he was hired as a Professor with Shanghai Dianji University. He is currently a master tutor.