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Research on joint planning method of supply and demand considering users' comprehensive energy consumption behavior and policy orientation

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Given the recent escalation of the energy and environmental crises, it is crucial to consider the evolution of various energy systems from a macro perspective in order to increase the overall efficiency of energy use and improve the environment. In order to tackle this issue, a wide-area integrated energy system planning method that takes into account consumers' comprehensive energy consumption behavior (CECB) and policy recommendations is provided in this study. First of all, according to the analysis of users' CECB, the decision-making model of regional users' energy supply transformation is established. A game model is constructed to explore cooperative planning of an integrated electricity-natural gas energy system based on the profit models of various market participants. The government is considered as the main body of planning and decision-making, and the evaluation model of government's pollution emissions from both supply and demand sides is established. A two-level dynamic game planning model for the wide-area IES is then created as a result of the examination of the game mechanism between users, the government, the integrated energy system (IES), and other market players. Finally, the model is solved using an iterative search approach. Results from simulations are used to validate the suggested method's accuracy and efficacy.

KEYWORDS

wide area integrated energy system planning, comprehensive energy use behavior of users, weak coupling, government planning, game theory

1 Introduction

The development of various types of energy systems from to improve the overall energy efficiency has become an unanimous opinion of all nations in the world in recent years as the energy and environmental crises become worse (Zhu, 2003; Li et al., 2021a; Dai et al., 2021; Zhang et al., 2021; Li et al., 2023a). In this context, the traditional idea of planning different energy systems separately has become unable to meet the needs of today's energy development. It is of great academic and engineering significance to break the barriers between heterogeneous energy systems and study the joint planning theory for wide-area various heterogeneous energy systems (Yang et al., 2022a; Zhang et al., 2022; Li et al., 2023b).

The IES planning methodology is currently the subject of some works, which primarily consider the coupling characteristics of various energy sources in the IES (Li et al., 2020; Chen et al., 2021; Shen et al., 2021). By studying the conversion relationship among various energy sources and focusing on minimizing the investment and operation cost or maximizing the income (Wang et al., 2017; Qu et al., 2018; Zhang and Lv, 2018), planning models that consider the mutual influence among various energy systems are built, and the related algorithms are used to solve them (Yang et al., 2018a; Hao et al., 2018; Liu et al., 2018). The regional integrated energy systems are the main focus of this type of planning models (Yang et al., 2018a; Liu et al., 2018; Zhang and Luo, 2018; Yang et al., 2021a). On the one hand, integrated energy systems involve relatively small range of energy supply, mostly industrial parks or towns, and generally does not involve large-scale energy transmission between provinces, and on the other hand, its energy coupling nodes are generally concentrated on the energy supply side, such as gas turbines, gas boilers, air energy heat pumps, etc., and there is a physical coupling between different energy types (Yang et al., 2019; Ding et al., 2021; Ma et al., 2021; Wang et al., 2022). Therefore, its energy conversion relationship is clear and explicit and it can be considered that the existing IES planning methods are more for rigid and strong coupling regional IES.

In fact, from the macro point of view of the whole society, in the process of energy consumption, people can choose more and more energy forms, such as natural gas, electricity, coal and so on (Yang et al., 2018b; Fang et al., 2022). In a larger time scale, influenced by market environment, policy orientation, and other factors, users' choice of different forms of energy is not unchanged, and users' energy consumption demand tends to be relatively stable (Xu et al., 2023; Yu et al., 2023). Therefore, from the standpoint of energy demand, the energy load may be distributed among various forms of energy over the course of the medium and long term. Additionally, this implies that several heterogeneous energy source types will be connected on the user side (Yu et al., 2022). Therefore, it is different from the traditional regional IES that emphasizes the rigid strong coupling of physical nodes on the energy supply side. From a macro point of view, the energy system of the whole society is based on the comprehensive energy consumption behavior of users on the demand side, and has flexible weak coupling between different forms of energy, which can be called flexible weak coupling wide area IES. For this kind of energy system, the traditional planning method of regional IES that is oriented to rigid and strong coupling is no longer applicable, which mainly displays in the following two aspects:

- (a) The research objects in the wide-area integrated energy system consist of two main bodies: users and integrated energy systems. This is in contrast to the traditional regional IES, which can directly construct its energy conversion model based on the physical characteristics of the coupling nodes on the energy supply side (Yang et al., 2022b). Not only the strong coupling relationship between source sides in traditional IES is considered, but also the correlation between source charges is considered (Yang et al., 2020; Gao et al., 2021). In other words, a flexible weak coupling relationship between different energy forms is formed by the comprehensive energy consumption behavior (CECB) on the user side. At present, most of the works on regional IES are based on the analysis of strong coupling between different energy systems on the supply side (Wang et al., 2021). However, there are limited research findings on the investigation of weak coupling mechanisms between supply and demand sides from the perspectives of source and load combined with the CECB of users. A joint optimization strategy for both the supply and demand sides is presented in reference (Zheng et al., 2018). It considers the behavior analysis of demand-side customers. The joint planning of users and energy systems has not been well investigated. To this end, this study mainly focuses on addressing the joint planning between the supply side and the demand side from the standpoint of system operation optimization.
- (b) The CECB of demand-side users and the investment and construction of various energy companies on the supply side are affected by the government's policy guidance. Especially in projects such as power supply transformation and electric energy substitution, the role of the government is particularly significant. Many of the existing works also adequately account for the impact of various environmental policies. As is shown in reference (Zheng et al., 2018), a decentralized scheduling model of multi-regional IES in account of carbon trading costs is built. Reference (Zhou and Zhao, 2013) considers environmental protection as one of the indicators for the evaluation of the microgrid in the park and establishes a multi-criteria evaluation system for the IES. The above studies simply deal with the relevant policy standards formulated by the government as the basic parameters in the model, and then evaluate the social and environmental benefits of the planning scheme (Liao et al., 2018; Wang et al., 2023; Zhang et al., 2023). There are limited works consider the government as an independent decision-making body, giving full play to the initiative of the government, and optimize the planning of various policy standards (Yang et al., 2021b; Fu et al., 2023; Zhu et al., 2023).

To sum up, this paper deeply analyzes the comprehensive energy use behavior of users, and considers the government as the decision-making body into the planning model, and proposes a wide-area IES planning method based on game theory, which considers the comprehensive energy use behavior of users and policy guidance (Li et al., 2021b). Firstly, by analogy with the regional IES with rigid and strong coupling characteristics, a wide-area IES with users' integrated energy consumption behavior as weak coupling nodes is proposed, and the users' integrated energy consumption behavior is analyzed. Then, the planning benefit models of various market players in the IES are constructed respectively, and the government's assessment model of pollution emissions from both supply and demand sides is established based on the environmental benefits of energy supply transformation. On this basis, a two-level dynamic game planning model for wide-area IES is created based on the analysis of the game mechanism involving users, the government, IES, and various market players. Finally, the model is solved using the iterative search approach. In comparison to current studies, this paper's primary contributions are as follows:

- (a) The concept of wide-area IES is proposed, which reveals a weak coupling relationship between various forms of energy

based on the link of integrated energy consumption behavior of users. It is based on research of traditional regional IES and the analysis of integrated energy consumption behavior of demand-side users.

- (b) A wide-area IES planning method considering users' integrated energy use behavior is proposed, and the utility model of users' energy use decision-making is used to evaluate the level of all kinds of new load in the region, so as to guide the planning and construction of IES.
- (c) In the planning of wide-area IES, the government should be considered as the main body of planning and decision-making, and users should be guided to carry out energy supply transformation by adjusting the energy subsidy standards of users, so as to effectively improve the environmental benefits in the region.

2 Wide area integrated energy system

The wide-area integrated energy system couples many energy types, including electric, heat, and natural gas energy, in the production and consumption of energy. This system not only has strong coupling characteristics of various energy systems on the source side based on various energy conversion equipment, but it also includes various energy systems on the source-load side based on users. As shown in Figure 1.

2.1 Analysis of strong coupling characteristics of integrated energy system

At present, the analysis of the coupling relationship of the system containing electricity, gas and heat has been widely used in the related research of various integrated energy systems, and the concept of energy hub is introduced to depict the coupling

relationship between different forms of energy at the source side, reflecting the static relationship between energy transmission and conversion. The energy hub can be equivalent to an energy multi-input and multi-output conversion structure. The input end is the energy vector $P = [P_1, P_2, \dots, P_N]^T$, the output is the load vector $L = [L_1, L_2, \dots, L_N]^T$, and C is the energy conversion matrix:

$$L = PC \tag{1}$$

Because the coupling coefficient matrix C depends on the parameters of various energy conversion elements, once the coupling elements are selected, the energy conversion relationship is uniquely determined. Therefore, this paper calls it a strong coupling relationship between various forms of energy in the IES.

2.2 Analysis of weak coupling characteristics based on user's comprehensive energy consumption behavior

The CECB of users, which displays the connection between the source and load sides, is the foundation upon which the coupling relationship between various kinds of energy is built in the wide-area integrated energy system. Because the CECB of users is affected by the energy price, there is a certain game relationship between the CECB of users and the pricing behavior of the energy system. Therefore, this coupling characteristic in the wide-area IES reflects the steady-state relationship between the production and consumption of energy.

By analogy with the energy conversion relationship in the IES, in the wide-area IES, since the total load of various users on the user side is relatively stable, the load demand of various types in the region depends on the proportional coefficient x of various energy supply modes selected by users.

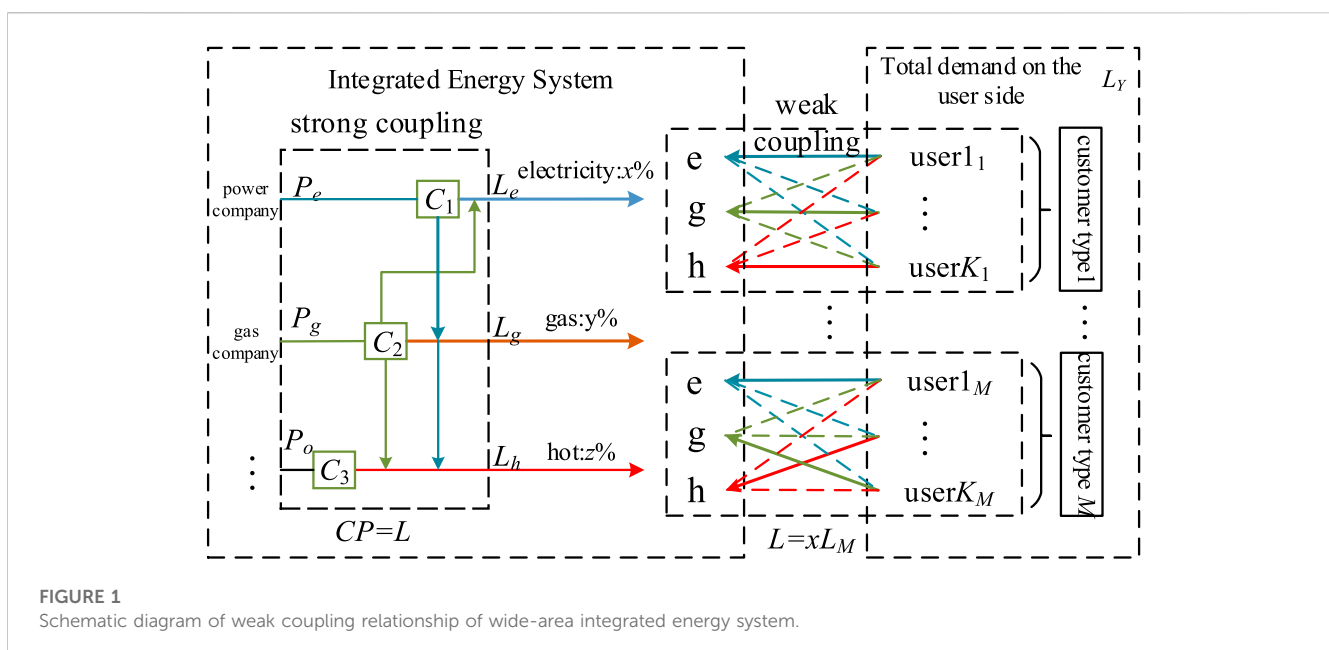


FIGURE 1 Schematic diagram of weak coupling relationship of wide-area integrated energy system.

$$L = xL_M \tag{2}$$

In (2):

$$x = \begin{bmatrix} x_1^1 & x_1^p & \dots & x_1^M \\ x_q^1 & x_q^p & \dots & x_q^M \\ \vdots & \vdots & & \vdots \\ x_N^1 & x_N^p & \dots & x_N^M \end{bmatrix} \tag{3}$$

In (3): M is the number of user types; p represents different user types; q indicates different modes of energy supply and can be taken as e , g , c , which indicates that the energy is supplied by electric energy, natural gas and coal respectively when representing the energy supply mode, and indicates that the load is electric load, natural gas load and coal load respectively when representing the load; x_q^p is the proportion of selecting the energy supply mode q from the users of p type.

Because the user’s behavior of choosing the way of energy supply is influenced by the user’s own characteristics and external factors such as energy prices, policy guidance and so on, and there is a game behavior between the user and the energy system, the proportional coefficient has a certain volatility, and this paper calls different forms of energy as a flexible weak coupling relationship linked by the user’s comprehensive energy use behavior.

2.3 Analysis of comprehensive energy use behavior of users

When selecting the energy supply mode, the user usually hopes to use the energy supply mode with the minimum energy cost and the maximum utility value while ensuring the user’s comfort. Therefore, this section makes a quantitative analysis and calculation of the energy cost and comfort under various energy supply modes, so as to calculate the deterministic utility value of each energy supply mode, and then incorporate the ambiguous usefulness in the user’s behavior in making choices. The utility model for deciding how much energy to utilize is established.

2.3.1 Economic indicators

The cost of various energy supply modes, including investment costs and energy consumption costs, as well as energy prices, government subsidies, and user energy consumption levels, are all included in the economic index.

$$C_q = C_q^I + C_q^O \tag{4}$$

$$\begin{cases} C_q^I = \frac{r}{1 - (1 + r)^{-T_{heat}^q}} C_q^{inv} \\ C_q^O = (\lambda^q - \delta_q) \cdot \sum_t W_q^t \end{cases} \tag{5}$$

In (5): e , g , c can be used, which means that the energy is supplied by electric energy, natural gas and coal respectively when it represents the energy supply mode, and the load is electric load, natural gas load and coal load respectively when it represents the load; C_q^Y , C_q^{YI} , C_q^{YO} are respectively the total cost, investment cost and energy consumption cost of various energy supply modes in the total demand of class k load the region p ; C_{pq}^{inv} is the present value of investment cost; T_{heat}^q is the

service life of various energy supply equipment; λ^q and δ_q are the market price and government subsidy of fuel used by various energy supply modes respectively; W_q^t is energy consumption; r is the discount rate.

2.3.2 Comfort index

This section uses an exponential function that takes into account environmental elements to characterize the comfort of various energy supply modes for the user:

$$v_q = \alpha(\beta e^{-x_q^p} / t + k) \tag{6}$$

In (6): v_q is the user’s comfort income; α is the coefficient of user’s comfort income; β is the energy utilization coefficient of the user; k is a random quantity related to external factors.

The energy utility of users is modeled using the analytical hierarchy process (AHP). According to their own energy preferences, different types of users score the importance of various factors to obtain the weight value of each index (Zhang et al., 2021), so as to calculate the deterministic utility value of various energy supply modes selected by various types of users, and set the modified utility ξ_{pq} for the uncertain factors in user selection behavior. It reflects the random preference of decision makers and represents a contingency of user’s choice behavior. Then the utility value function U_q^p of the user of type p for the energy supply mode q is:

$$U_q^p = (k_C^p C_q^I + k_v^p v_q^I) + \xi_q^p \tag{7}$$

In (7): C_q^I and v_q^I are respectively the normalized values of the economic index and the comfort index after dimensionless treatment.

According to the utility maximization decision criterion, combined with the Logit model, the calculation method of probability distribution function can be used to deduce and calculate the probability of p -type users choosing energy supply mode q . The specific derivation process is detailed in literature (Ma et al., 2021). In this paper, ∂_{kpq} is used to characterize the proportion of energy supply mode q in p -type users.

$$x_q^p = \partial_q^p = \frac{e^{V_q^p}}{\sum_{q=1} e^{V_q^p}} \tag{8}$$

Based on the above analysis of energy consumption behavior of users, the proportional coefficient x of various energy supply modes selected by various users is determined, and then various load levels are determined in combination with the basic load in the region, so as to guide the planning and construction of the IES.

3 Planning model

This paper views the government as an independent decision-making body and collaborates on wide-area integrated energy system planning with the two main groups of users and integrated energy systems because the subsidy standard of government decisions will significantly influence the user’s choice of energy supply mode, further affecting the user’s load level and the planning and construction of various energy systems.

3.1 Integrated energy system planning model

The market investors in the IES will renovate, expand, and build new facilities for the energy supply system against the backdrop of energy substitution by demand-side users, to meet the demand of new electricity load and natural gas load in the region and respond to the requirements of energy saving and emission reduction. Power generation firms, grid firms, and natural gas firms are among the major IES investors taken into account in this study. To get the most out of gas-fired units, power production businesses want to minimize their investment, operation, and environmental expenses while maximizing their revenue from electricity sales. For grid firms, minimizing network loss of lines and investment costs will maximize benefits. In order to lower pipeline investment expenses and system operating costs, boost gas sales revenue, and maximize revenue are the goals of natural gas firms.

The revenue function of the generation company is as follows:

$$\left\{ \begin{aligned} I_F &= \sum_{T=1}^{\Omega_T} (C_S^F - C_{BG}^F - C_I^F - C_O^F - C_E^F)(1+r)^{-T} \\ C_S^F &= \sum_{i=1}^{\Omega_E} \sum_{t=1}^{\Omega_t} P_{i,t}^D \lambda_{i,t}^e \\ C_{BG}^F &= \sum_{i=1}^{\Omega_E} \sum_{t=1}^{\Omega_t} Q_{i,t}^{BG} \lambda_{i,t}^g \\ C_I^F &= \frac{r}{1 - (1+r)^{-T_{GT}}} \left(\sum_{a=1}^{\Omega_{XG}} x_a C_a^{GT} \right) \\ C_O^F &= \sum_{t=1}^{\Omega_t} \left(\sum_{g=1}^{\Omega_{GT}} C_g^O P_{gt} + \sum_{m=1}^{\Omega_{MT}} C_m^O P_{mt} \right) \\ C_E^F &= \sum_{t=1}^{\Omega_t} \left(\sum_{g=1}^{\Omega_{GT}} C_g^E P_{gt} + \sum_{m=1}^{\Omega_{MT}} C_m^E P_{mt} \right) \end{aligned} \right. \quad (9)$$

In (9): I_F is the total revenue of the generating company; C_S^F is the power generation company's revenue from selling electricity; C_I^F is the price of new gas-fired units as an investment; C_{BG}^F is the price of buying gas for the gas-fired units; C_O^F is the operating cost of the unit; C_E^F is the environmental cost of unit sewage discharge; Ω_T represents the planning cycle; Ω_E is a set of power system nodes; $P_{i,t}^D$ is the electrical power at node i at time t ; $Q_{i,t}^{BG}$ is the gas purchasing power at node i at time t ; T_{GT} is the duration of the new gas-fired units' service life; Ω_{XG} is the set of gas-fired units to be selected; x_a is the 0-1 variable for the construction of the gas-fired unit a to be selected; C_a^{GT} is the investment costs of the gas-fired unit a to be selected; C_g^O and C_m^O are running expenses for coal- and gas-fired units under unit power; P_{gt} and P_{mt} are the output of both the coal-fired and gas-fired units at time t ; C_g^E and C_m^E are the environmental cost of gas-fired units and coal-fired units under unit power; Ω_{GT} and Ω_{MT} refer to the both the operational set of coal-fired units and the set of gas-fired units.

The revenue function of the grid company is as follows:

$$\left\{ \begin{aligned} I_E &= \sum_{T=1}^{\Omega_T} \left(\left(\sum_{l=1}^{\Omega_L} \sum_{t=1}^{\Omega_t} (C_{Sl,t}^E - C_{Ol,t}^E - C_{El,t}^E) \right) - C_I^E \right) (1+r)^{-T} \\ C_{Sl,t}^E &= (C_{Ml,t}^E \times 0.4) + \frac{P_{l,t}^{flow}}{P_l^{cap}} (C_{Ol,t}^E) \\ C_{El,t}^E &= \theta_{es} \cdot EENS_{l,t} = \theta_{es} \cdot \sum_{b=1}^{\Omega_b} \lambda_b \cdot \sum_{n=1}^{\Omega_n} P_{n,t}^{load} \\ C_I^E &= \frac{r}{1 - (1+r)^{-T_{EL}}} \left(\sum_{b=1}^{\Omega_{XL}} y_b \cdot C_b^{EL} \right) \end{aligned} \right. \quad (10)$$

In (10): I_E is the total revenue of the power grid company; $C_{Sl,t}^E$ is the income of the grid company; Ω_L is the set of transmission lines; $C_{Ol,t}^E$ is the operation cost of line l in time period t ; $C_{El,t}^E$ is the reliability cost of line l in time period t ; C_I^E is the upfront expense of installing new transmission lines; $C_{Ml,t}^E$ is the operation cost of power grid company; $P_{l,t}^{flow}$ is maximum power value flowing through line l ; P_l^{cap} is the capacity of line l ; θ_{es} represents unit outage losses; $EENS_{l,t}$ is the expected value of the power shortage of the line l in the time period t ; T_{EL} is the transmission line's useful life; Ω_{XL} is the set of transmission line to be selected; y_b is the construction 0-1 variable for the construction of the transmission line b to be selected; C_b^{EL} is the transmission line b 's investment cost that will be chosen.

The natural gas company's revenue function is as follows:

$$\left\{ \begin{aligned} I_G &= \sum_{T=1}^{\Omega_T} (C_S^G - C_O^G - C_I^G)(1+r)^{-T} \\ C_S^G &= \sum_{j=1}^{\Omega_C} \sum_{t=1}^{\Omega_t} G_{j,t}^D \cdot \lambda_{j,t}^g \\ C_O^G &= \sum_t \sum_h C_h^O G_{ht} \\ C_I^G &= \frac{r}{1 - (1+r)^{-T_{GL}}} \left(\sum_{c=1}^{\Omega_{GL}} z_c \cdot C_c^{GL} \right) \end{aligned} \right. \quad (11)$$

In (11): I_G is the total revenue of the natural gas company; C_S^G is the income of the natural gas company; C_O^G is the expense of maintaining the natural gas network; C_I^G is the investment cost of new gas transmission pipeline; Ω_C is a node set of the natural gas network; $G_{j,t}$ is the natural gas power at node J at time t ; Ω_h is a collection of air source points; C_h^O is the operating cost per unit power at source point h ; G_{ht} is the natural gas power at time t at gas source point h . T_{GL} is the gas transmission pipeline's lifespan; Ω_{GL} is a set of gas transmission pipeline to be selected; z_c is the investment variable 0-1 of gas transmission pipeline c ; C_c^{GL} is the price of the chosen gas transmission pipeline as an investment.

Power balance constraints, power flow constraints, transmission capacity limitations for lines and pipelines, and output restrictions for units and gas source points are the main constraints of each subsystem in the IES. For more information, see reference (Yang et al., 2019). The relevant restrictions of gas-fired units serving as IES coupling nodes must also be taken into account.

(a) Gas-fired unit output constrain

$$P_{Gg}^{\min} \leq P_{Gg} \leq P_{Gg}^{\max} \quad \forall u \in S_{GF} \quad (12)$$

In (12): P_{Gg}^{\max} and P_{Gg}^{\min} indicates the upper and lower limits of the output of the gas-fired unit g ;

(b) Coupling node power balance constraint

$$f_{ig}^E + \Theta f_g^G = f_{og}^E + E_{Lg} \quad (13)$$

In (13): f_{ig}^E is the electric current entering the coupling node; f_g^G is the coupling node's natural gas power input; Θ is the conversion coefficient of the gas-fired unit; f_{og}^E is the electrical power flowing out of the coupling node; E_{Lg} is the load of the coupling node.

3.2 Government decision-making model considering environmental benefits

Users and integrated energy systems focus on economic benefits when making planning decisions, while the government pays more attention to social and environmental benefits. Taking the government as the main body of decision-making can comprehensively evaluate the environmental benefits brought about by the transformation of users' energy supply mode, so as to make planning decisions more reasonable. In this paper, a government planning model considering environmental benefits is constructed, which takes the minimum emission of user side and supply side as the optimization objective, and takes the transformation subsidy and the scale of energy supply transformation of user side affected by construction conditions as the constraints.

$$R(\delta_E, \delta_G) = \sum_T \sum_{d=1}^{\Omega_d} Q_d (R_d^{YM} W_T^{YM} + R_d^{YG} W_T^{YG} + R_d^{FM} W_T^{FM} + R_d^{FG} W_T^{FG}) \quad (14)$$

In (14): R is the total emission of the user and the energy system in the formula; δ_E and δ_G are decision-making variables for the government: electricity price and gas price subsidy standards; R_d^{YM} , R_d^{YG} , R_d^{FM} and R_d^{FG} are the amount of pollution d emitted by the unit gas consumption of gas-fired units, the unit coal consumption of coal-fired units, the unit gas consumption of gas-fired units, and the unit coal consumption of gas-fired units, respectively; W_T^{YM} , W_T^{YG} , W_T^{FM} and W_T^{FG} are respectively the consumption of coal and gas by users who use coal and gas, as well as the consumption of coal and gas by coal- and gas-fired units in power plants. Q_d is the emission weight factor of the pollutant d ; Ω_d is the type of pollutant.

The constraints to be considered when the government decides on the subsidy standard are as follows:

(a) Government subsidy constraint

$$\begin{cases} \delta_E^{\min} \leq \delta_E \leq \delta_E^{\max} \\ \delta_G^{\min} \leq \delta_G \leq \delta_G^{\max} \end{cases} \quad (15)$$

In (15): δ_E^{\max} and δ_E^{\min} are respectively the upper and lower limit of electricity price subsidy; δ_G^{\max} and δ_G^{\min} are respectively the upper and lower limit of gas price subsidy.

(b) Constraints on the scale of energy supply transformation at the user side

$$\varphi^{\min} \leq \varphi \leq \varphi^{\max} \quad (16)$$

In (16):

$$\varphi = \frac{\sum_p P_p \cdot (\partial_{p,e} + \partial_{p,g})}{\sum_p P_p} \quad (17)$$

In (17): φ is the proportion of energy supply transformation completed in the region; φ^{\max} and φ^{\min} are respectively the upper and lower limits of the scale of energy supply transformation for users in the region.

3.3 Wide-area integrated energy system joint planning model based on two-level game

3.3.1 Game relationship analysis

The user, the government, and the IES are the decision-making subjects in the collaborative planning of a wide-area integrated energy system taking the influence of the government into consideration. The user can decide the way of energy supply transformation, the IES can decide the topology of each energy network and various energy prices, and the government can decide the subsidy standard for transformation. They include several power generation corporations, power grid companies, and natural gas companies, as well as other investors in the energy market. The transitive relationship of each subject in planning and decision-making is shown in Figure 2. In the planning and decision-making process of the outer wide-area IES, the user decides the energy supply transformation scheme according to the energy price determined by each energy company and the energy price subsidy of the government, and transmits the transformation result to the government, and feeds back various load increments to each energy company at the same time. According to various load data from the user side, each energy company in the IES determines the expansion, new construction, and pricing scheme of each energy system, transmits energy price information to the user, and reports to the government the pollution discharge situation of each energy company. The decisions of the new units of the power generating company and the new lines of the grid company in the source side and the grid side of the power system immediately affect each other during the inner IES decision-making process. The decision of the natural gas company to build a pipeline may have an impact on the new construction scheme of the gas-fired unit of the power generation company. Additionally, the node marginal gas price set by the IES's economic and safe dispatch may have an impact on the power generation company's plan to purchase gas. On the other side, the choice of the natural gas company to build a pipeline may be influenced by the newly constructed gas-fired unit of the gas generation company. The mixed power flow data sent by gas units has an indirect impact on the decision-making of power grid enterprises and natural gas corporations. As a result, the three energy market investors in the IES make their own decisions on their own, independently of one another, and have an influence on one another.

According to the pollution discharge of users and energy systems in the region, the government makes a comprehensive evaluation of the environmental benefits of the renovation project, and revises the subsidy standard to guide users and

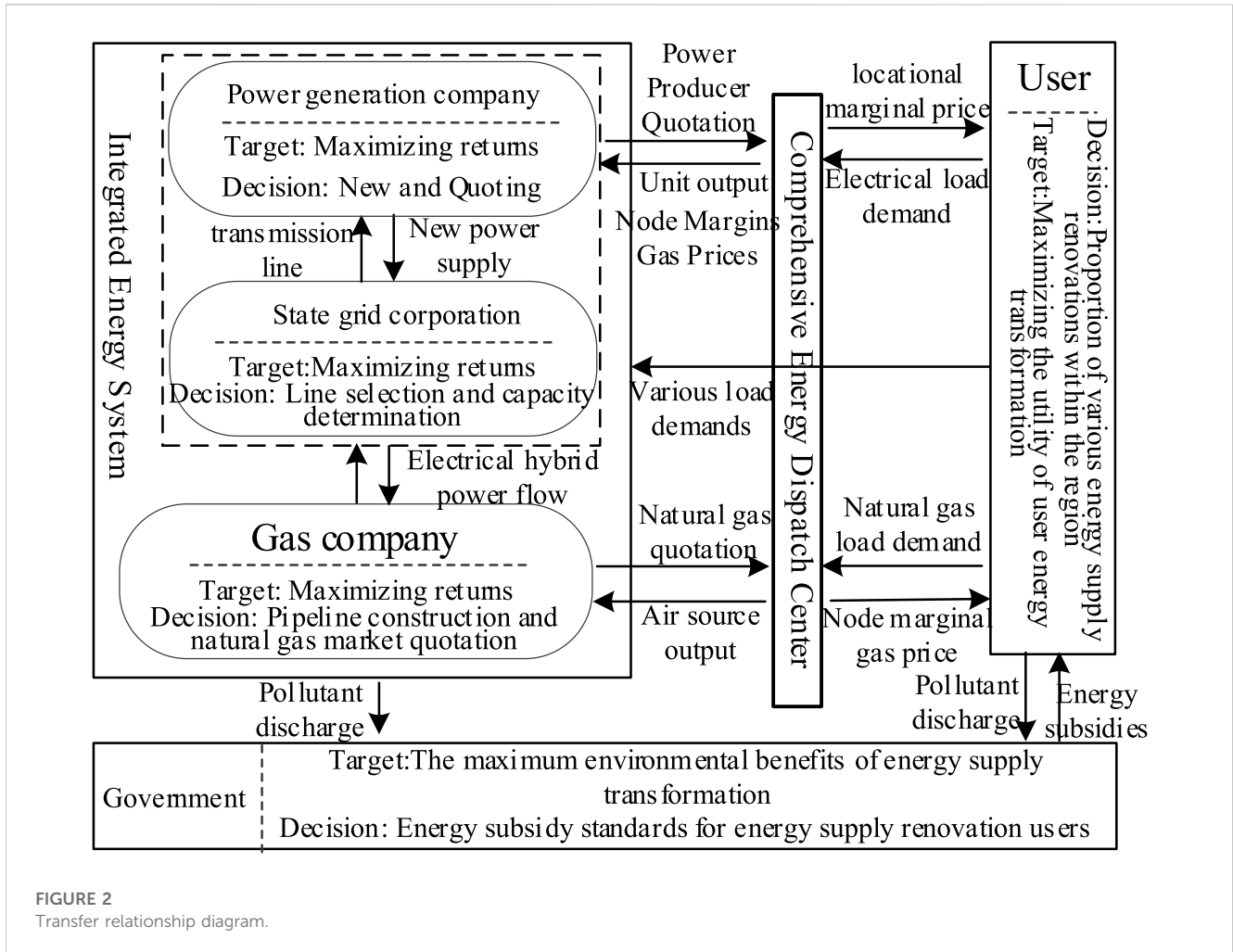


FIGURE 2 Transfer relationship diagram.

energy systems to make more reasonable planning decisions. The environmental benefits of the renovation project are comprehensively evaluated and the subsidy standards are revised to guide the users and the IES to make more rational planning and decision-making. Therefore, the user, the IES and the government make decisions independently and influence each other, which also constitutes a game relationship. Therefore, in this paper, the multi-agent in the wide area IES planning considering the influence of the government constitutes a two-level game framework.

3.3.2 Game behavior analysis

In the planning process, the electricity generating company, the grid company, and the natural gas company can all understand all of the strategic information of other firms. The user, the government, and the IES can all understand the strategic information of each other. This is because the planning and decision-making of the wide-area IES must be completed jointly under the premise of independent decision-making. In the planning of energy supply transformation project, the government should first formulate the subsidy standard, then the user decides the way of energy supply transformation according to the current energy price and policy, and finally the energy company decides the planning and construction of the system based on the load level, so the main body of the outer layer gives the decision-making scheme successively.

The electricity-gas mixed power flow is computed using the sequential solution approach in this study for the IES planning. Before calculating the natural gas network power flow based on data from gas-fired units and natural gas businesses, the power network power flow is first computed using data from power generation companies and grid companies. As a result, each investor makes their decisions in the inner IES one at a time. Therefore, all participants in the wide-area IES in this paper constitute a two-tier complete information dynamic game pattern. The game behavior diagram is shown in Figure 3.

In an outer game round, the government first evaluates the environmental benefits of the current renovation project, adjusts the subsidy standard for energy supply renovation, and gives a decision X_R^n to reduce the discharge of pollutants in the area; Then the information is transmitted to the user, and the user determines the energy supply transformation mode according to the energy price and its subsidy standard, and gives a decision X_U^n , which makes the expenditure cost of the user side minimum; Next the load information is transmitted to the IES. In an inner game round, the power generation company selects the location and capacity of the new power source according to the power load demand of the user and the natural gas network information at the coupling node, and gives a decision X_{IP}^{nm} , to maximize the revenue of the power generation company; Then according to its own planning scheme, the power grid company determines the new construction

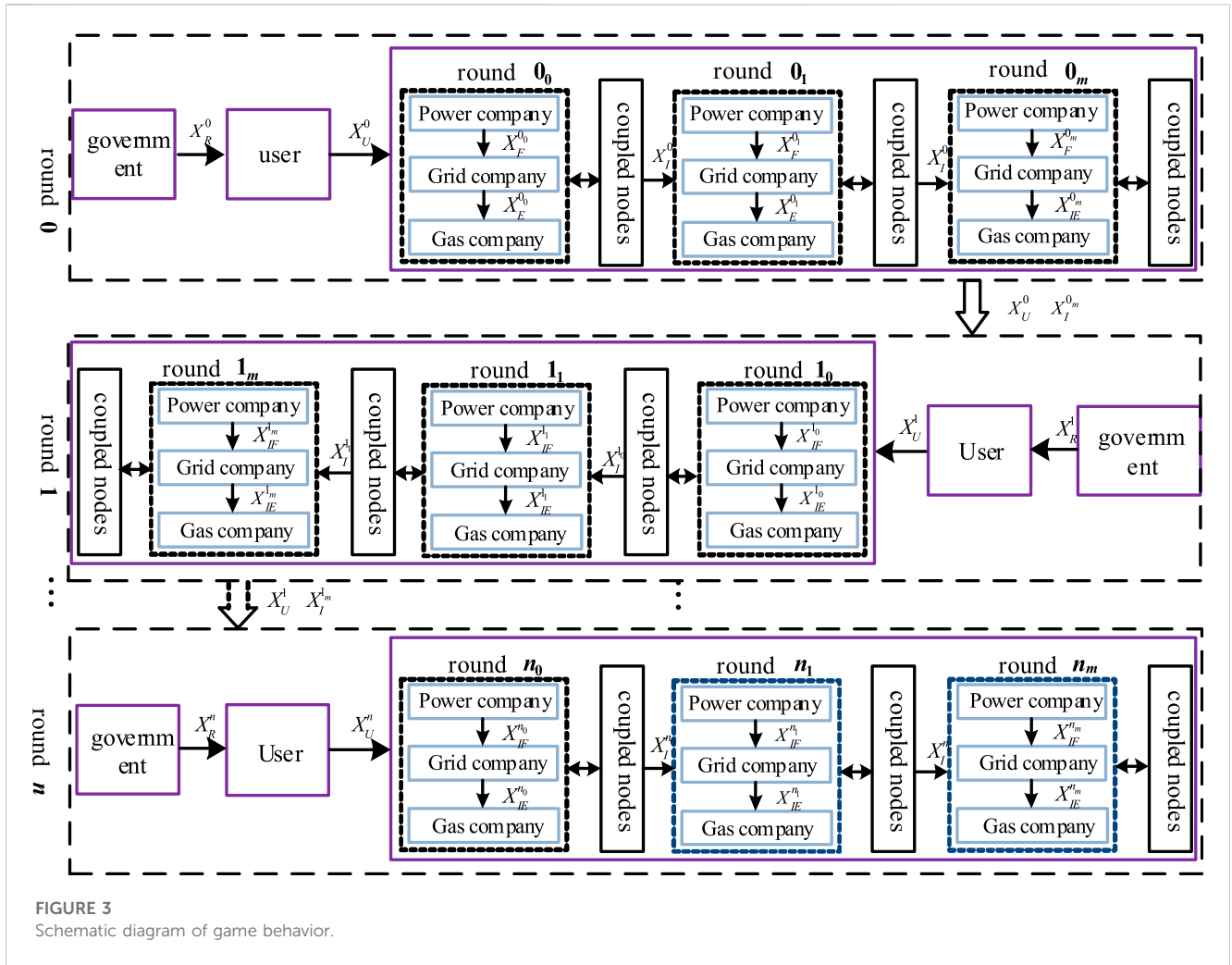


FIGURE 3 Schematic diagram of game behavior.

scheme of the transmission line and gives a decision X_{IE}^{nm} , to maximize the revenue of the its own company; After that, the power flow information on the coupling node is transmitted to the natural gas company, which adjusts the new construction scheme of the gas transmission pipeline according to the natural gas load demand of the user side, and gives a decision X_{IG}^{nm} , to maximize the profits of its own company; The decision-making scheme of the three investors makes the topology of the IES update and enter the next inner game round. The inner layer dynamic game equilibrium state forms and the decision X_I^n of the comprehensive energy system is made when neither the power generation company, the power grid company, nor the natural gas company can increase their profits by modifying their business models. At this time, the decision-making scheme of the three outer subjects updates the planning information of the wide-area IES and enters the next outer game round. When any party of the government, users and IES changes its strategy, it can not improve its own income, and an outer game equilibrium state is formed.

Among them, the game equilibrium state of each investor in the inner IES is described as follows:

$$\begin{cases} X_E^* = \operatorname{argmax} I_E(X_E, X_F^*, X_G^*) \\ X_F^* = \operatorname{argmax} I_F(X_F, X_E^*, X_G^*) \\ X_G^* = \operatorname{argmax} I_G(X_G, X_E^*, X_F^*) \end{cases} \quad (18)$$

The game equilibrium state of each participant in the outer wide-area IES is described as follows:

$$\begin{cases} X_U^* = \operatorname{argmax} U(X_U, X_I^*, X_R^*) \\ X_I^* = \operatorname{argmax} I(X_I, X_U^*, X_R^*) \\ X_R^* = \operatorname{argmax} R(X_R, X_U^*, X_I^*) \end{cases} \quad (19)$$

4 Model solving

The planning problem in multi-agent game environment is an independent optimization problem for each participant based on their own objectives, and it is hard to solve the problem by a unified optimization method. This study employs the iterative search approach to resolve the Nash equilibrium for the aforementioned game model, and Figure 3 illustrates the precise solution procedure. The following is a detailed presentation of the solution steps:

Step 1: Add the settings and raw data. Set up the necessary data, such as the load data, unit output data, and energy supply equipment data (price, energy consumption parameters, and sewage parameters).

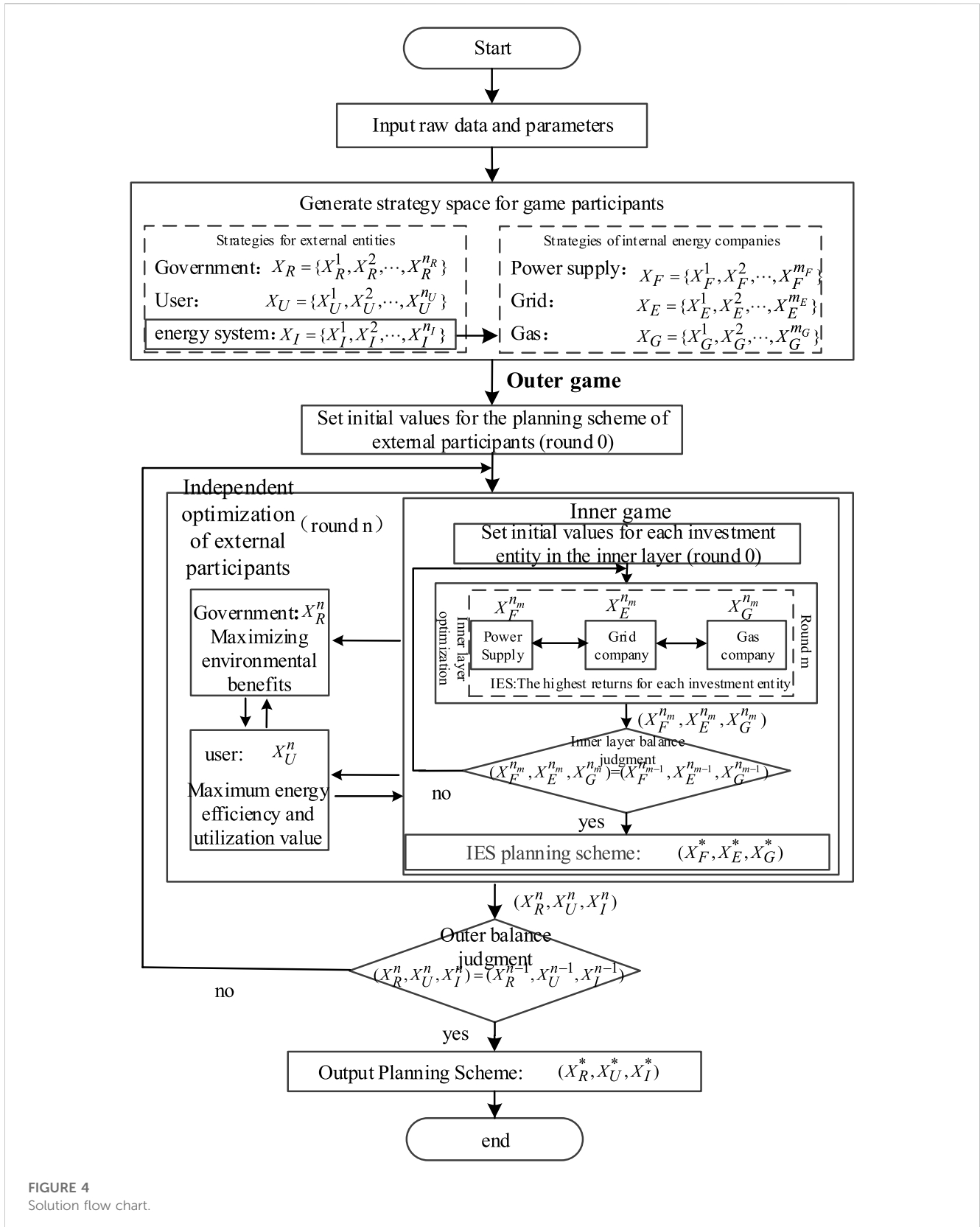


FIGURE 4 Solution flow chart.

Step 2: Generate the strategy space of the players in the inner and outer layer game. Wherein, strategy space of each participant in the outer layer: the government generates its planning strategy space

according to the set of transformation subsidies to be selected; The user generates an energy supply transformation strategy space according to the user energy supply transformation candidate set

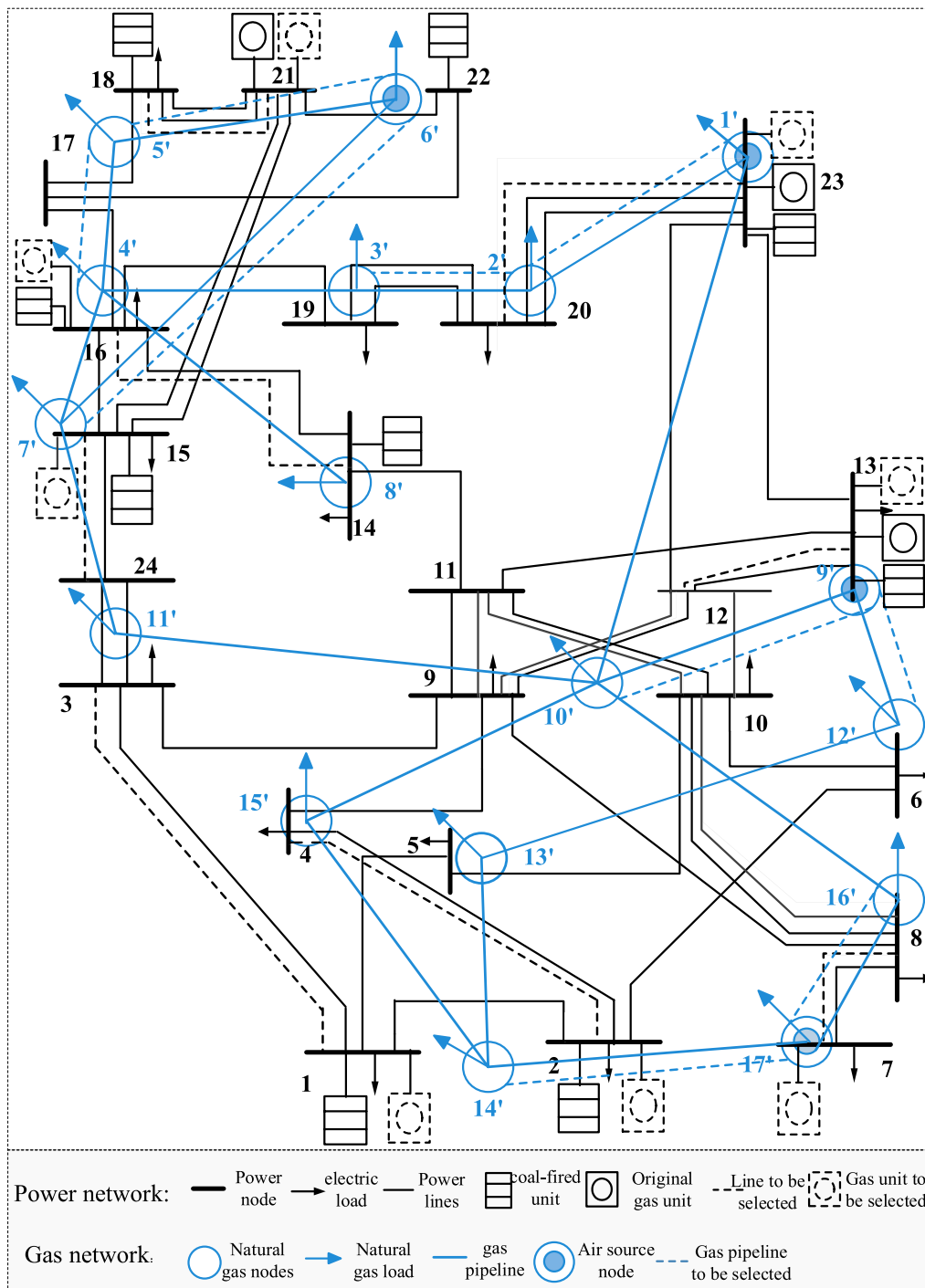


FIGURE 5
Topological structure diagram of integrated energy system.

TABLE 1 Weight coefficient of each type of user for each index.

User type	Economy	Comfortable
Residents	0.416	0.584
Business	0.308	0.692
Industry	0.759	0.241

in the whole region; The IES generates the system planning strategy space according to the set to be selected of new facilities construction and pricing of each energy company. Strategy space of each participant in the inner layer: the power generation company generates its strategy space according to the set of new units to be selected; Power grid company generates its strategy space according to the set of new transmission lines to be selected; The

TABLE 2 Planning results of each market investor in the integrated energy system.

Situation	Power generation company	Power grid company	Natural gas company
1	1,7,13,23	2-4,12-13,14-16,15-24,20-23	1'-2',5'-6',9'-10',14'-17'
2	1,7,13,16	1-3,7-8,12-13,14-16,20-23	1'-2',4'-5',5'-6',9'-10',14'-17'
3	1,7,13,16,21	1-3,7-8,12-13,14-16,18-21,20-23	1'-2',2'-3',5'-6',6'-7',9'-10',16'-17'

TABLE 3 Newly increased load of each area.

Region	1	2	3	4	5	6	7	8	9	10	13	14	15	16	18	19	20
Electrical load (MW)	31	26	48	30	12	25	20	45	42	35	20	27	33	98	24	33	17
Gas load (MW)	29	26	53	25	10	24	22	41	42	27	22	26	35	85	26	30	25

natural gas company generates its strategy space according to the set of the newly-built gas pipelines to be selected. $X_R^n, X_U^n, X_I^n, X_F^n, X_E^n$ and X_G^n are, in turn, the total number of elements in the strategy set of government, user, IES and generation company, grid company, gas company as shown in Figure 4.

Step 3: Set the initial value. Randomly pick a set of values (X_R^0, X_U^0, X_I^0) and (X_F^0, X_E^0, X_G^0) from the inner and outer strategy spaces, respectively, as the iterative initial values of the inner and outer layer game.

Step 4: Participants refine the plan. The government, the users, and the IES make decisions on their own planning schemes once more in the outer game round, and they calculate the ultimate benefits using the data from other players in the earlier round. The investors of the three companies alter the planning scheme in the inner game round based on information from other companies in the previous round and recalculate the final income based on the combined information on power flow and energy price.

Step 5: judge whether equilibrium state is reached. Outer equilibrium state: in the wide-area IES, the benefits of government, users and the IES are the same in two consecutive game rounds, that is, $(X_R^n, X_U^n, X_I^n) = (X_R^{n-1}, X_U^{n-1}, X_I^{n-1}) = (X_R^*, X_U^*, X_I^*)$; Inner game equilibrium state: all energy investment companies in the IES have the same returns in two consecutive inner game rounds namely, $(X_F^n, X_E^n, X_G^n) = (X_F^{n-1}, X_E^{n-1}, X_G^{n-1}) = (X_F^*, X_E^*, X_G^*)$.

Step 6: Output the final decision-making scheme (X_R^*, X_U^*, X_I^*) and its benefits of the three main bodies of the users, the government and the IES.

5 Example analysis

5.1 Parameter setting

A regional IES is made up of a modified IEEE24 power system (Ding et al., 2021) and a modified 17-node natural gas system (Wang et al., 2022), with the majority of the geographical overlap between the nodes of the two systems. And node 5', 6', 10', 11', 14' of that

natural gas network cover a plurality of electric pow network nodes as shown in Figure 5.

The power system has three gas-fired units, and Tables A1, A2 in the appendix, respectively, provide specific information on the gas-fired units and transmission lines to be chosen; 15 traditional natural gas loads and 4 natural gas sources make up the natural gas system. Table A5 in the Appendix displays the natural gas network's parameters. Table A3 in the appendix displays the information regarding the gas transmission pipeline that needs to be chosen as well as the pertinent natural gas network parameters. Among them, the transmission line's unit investment cost per km is 680,000 yuan, and the gas transmission pipeline's unit investment cost per km is 1.02 million yuan. If the area is divided into power nodes, the energy supply loads to be modified in each zone are shown in Table A4 of the Appendix. The electricity subsidy for users is 0.1 yuan/kw-h, and the gas subsidy is 1 yuan/m³. Different types of users have different preferences for the economy and comfort of energy supply modes. Based on the hierarchical structure of user utility, the judgment matrix is constructed, and the weights of various indicators for different types of users are obtained as shown in Table 1. The construction of judgment matrix and the determination of weight are analytic hierarchy process. The key to applying to the evaluation system. The steps of judgment matrix construction and weight solution are divided into. For the following sections:

Step 1: The problem is decomposed and combined to establish a hierarchical knot. Structure, clearly shows the relationship between the various levels.

Step 2: The three-scale method is used to compare the elements of the same layer. A comparison matrix A is established.

$$A = (\alpha_{ij}) = \begin{pmatrix} & c_1 & c_2 & \cdots & c_n \\ c_1 & \alpha_{11} & \alpha_{12} & \cdots & \alpha_{1n} \\ c_2 & \alpha_{21} & \alpha_{22} & \cdots & \alpha_{2n} \\ \vdots & \vdots & \vdots & \cdots & \vdots \\ c_n & \alpha_{n1} & \alpha_{n2} & \cdots & \alpha_{nm} \end{pmatrix} \quad (20)$$

Using the three-scale method, we can get:

$$\alpha_{ij} = \begin{cases} 2, & c_i \text{ is more important than } c_j \\ 1, & c_i \text{ is as important as } c_j. \\ 0, & c_j \text{ is more important than } c_i \end{cases} \quad (21)$$

TABLE 4 Scenarios 1 and 2 integrated energy system benefits.

Situation	Company	Total income (yuan)	Investment cost (yuan)	Cost of purchasing coal (yuan)	Gas purchase cost (yuan)	Reliability cost (yuan)	Operating cost (yuan)	Environmental costs (yuan)	Total revenue (yuan)
1	Power Generation Company	5.570×10^{10}	1.499×10^9	7.395×10^9	5.344×10^9	0	9.787×10^9	4.535×10^9	2.714×10^{10}
	Power Grid Company	1.361×10^{10}	1.489×10^8	0	0	1.208×10^9	0	0	1.225×10^{10}
	Natural Gas Company	2.695×10^{10}	3.682×10^8	0	0	0	1.467×10^{10}	0	1.191×10^{10}
2	Total	9.926×10^{10}	2.016×10^9	7.395×10^9	5.344×10^9	1.208×10^9	2.449×10^{10}	4.535×10^9	5.137×10^{10}
	Power Generation Company	5.597×10^{10}	1.499×10^9	7.235×10^9	5.465×10^9	0	9.802×10^9	4.495×10^9	2.747×10^{10}
	Power Grid Company	1.400×10^{10}	1.503×10^8	0	0	1.112×10^9	0	0	1.273×10^{10}
	Natural Gas Company	2.819×10^{10}	4.264×10^8	0	0	0	1.536×10^{10}	0	1.240×10^{10}
	Total	9.82×10^{10}	2.076×10^9	7.235×10^9	5.465×10^9	1.112×10^9	2.516×10^{10}	4.495×10^9	5.260×10^{10}

Step 3: Calculate the ranking index of the importance of each element of the comparison matrix. The comparison matrix is transformed into a judgment matrix.

In this paper, three scenarios are set up to solve the problem of wide-area IES planning considering the comprehensive energy use behavior of users and government participation in decision-making: scenario 1 is the IES planning without considering the analysis of comprehensive energy use behavior of users; Scenario 2 is the joint planning of wide-area IES considering the analysis of users' integrated energy consumption behavior; Scenario 3 is a wide-area IES planning that considers the analysis of users' integrated energy consumption behavior and the government's participation in planning and decision-making.

5.2 Planning results

Under the three scenarios, the planning results of the outer participant users, the IES and the government are shown in Table 1, and the planning results of the inner energy investor power generation companies, power grid companies and natural gas companies are shown in Table 2.

The planning outcomes for each investment company in the IES under the three scenarios are different, as shown in Table 1, and there are several reasons for this. The CECB of customers is not taken into account in Scenario 1, only the strong coupling properties between various energy sources in the total energy system. Scenario 2 and Scenario 3 plan the wide-area IES based on the CECB of users. On the basis of Scenario 1, the weak coupling characteristics between different forms of energy sources formed by the CECB of users are further considered. However, the planning schemes in scenario 2 and scenario 3 are also different. The reason is that compared with scenario 2, scenario 3 considers the government as the main body of planning and decision-making to participate in the planning of wide-area IES. In order to maximize the environmental benefits of energy supply transformation, the company guides users to carry out coal-fired transformation by adjusting the subsidies for electric energy and natural gas energy consumption. The planning decisions of each company in the IES are adjusted with the changes of various loads on the user side.

5.3 Necessity analysis of considering user's comprehensive energy use behavior

In order to validate the necessity of considering the CECB analysis of users in the wide-area IES planning, it is assumed that the total new load on the user side is the same in scenario 1 and scenario 2. In scenario 2, the analysis of customers' energy consumption patterns can be used to determine the new load for each zone, as shown in Table 3. A comparison of the benefits of the IES in Scenario 1 and Scenario 2 is shown in Table 4.

It can be seen from Table 3 that there is little difference among all kinds of new loads in each region, because compared with coal-fired energy supply, after considering government subsidies, the index values of electric energy and natural gas are more similar, and their comfort is better than coal-fired, but the economy is poor. Therefore, the proportion of electric energy and natural gas chosen

TABLE 5 Planning results of each participant in the outer layer.

Situation	User			Integrated energy system		Government	
	Electric power supply transformation size (%)	Transformation scale of gas energy supply (%)	Total transformation scale (%)	Average price of electricity (yuan/kw (H))	Average gas price (yuan/m ³)	Electricity price subsidy (yuan/kw (H))	Gas price subsidy (yuan/m ³)
2	30.06	28.57	58.63	0.556	2.35	0.100	1.00
3	33.15	28.03	61.18	0.556	2.31	0.108	0.97

by all types of users in each region is not much different. On the other hand, the new load in some areas is relatively high, such as node areas 3, 8 and 16, which is mainly due to the high coal load to be transformed, and is also affected by the energy price of each node to a certain extent.

The IES planning results under the two scenarios in Table 2 are further compared and analyzed in combination with Table 3. In Scenario 1 and Scenario 2, most of the new lines and pipelines are connected with gas-fired units, because the coupling characteristics of gas-fired units are considered, which effectively promotes multi-energy complementarity. Compared with Scenario 1, in Scenario 2, the power generation company adjusts Unit 23 to Unit 16, and the electrical load of Node 16 is higher; Some new lines 1-2, 7-8, 12-13 and 14-16 of the power grid company are connected with the new gas-fired units, and the natural gas company builds an additional pipeline 4'-5' to connect with Unit 16, which is the result of source-network coordination planning and is more conducive to the realization of economic dispatch of the IES. Scenario 2 takes into account the user's CECB analysis, fully considers the user's own characteristics, energy prices, subsidies and other factors, so as to make a reasonable assessment of the load level of each region, which can improve the effectiveness of guiding the planning and decision-making of the IES.

Table 4 illustrates how little has changed between scenario 2 and scenario 1 in terms of overall income and investment costs for the two power firms. This is due to the fact that the total demand for power is the same in both scenarios, despite an increase in the natural gas company's overall revenue of 1.24×10^9 yuan and an increase in investment costs of 5.82×10^7 yuan.

In Scenario 2, the gas purchases by the power production firm are increased, increasing the natural gas company's revenue from gas sales. In Scenario 2, a new gas transmission pipeline is built concurrently due to an increase in the demand for natural gas. This results in an increase in the investment cost for the natural gas firm, and the operation cost also rises as the supply of gas grows. The operating cost of the power generation company increased by 10^7 yuan. This is due to the fact that the cost of purchasing coal has decreased for the power generation firm, and some thermal power unit power generation jobs have also been transferred to gas power units, while the operating costs of gas units are greater than those of thermal power units. The environmental cost of power generation firms is also decreased because gas-fired units have a lower environmental cost than thermal power units. As far as the reliability cost of the grid company is concerned, although the new transmission distance in scenario 2 is slightly increased from the perspective of investment cost, the reliability cost is reduced because the planning of gas-fired units and lines in scenario 2 is more

reasonable. From the overall income point of view, the income of all investors has improved.

To sum up, comparing the planning results and the benefits of various subjects in scenario 1 and scenario 2, different from the traditional IES planning in scenario 1, which only considers the interaction of the source side and lacks the correlation analysis of source and load side, scenario 2 combines the CECB of users and takes into account the game behavior between users and various energy investors. In scenario 1, various loads on the demand side are reasonably evaluated and predicted, so as to guide the IES to carry out more refined planning and construction, and effectively enhance the income of each investor.

5.4 Analysis on the necessity of government participation in planning and decision-making

In order to validate that the method proposed considers the influence of the government's participation in the planning as a game subject in the wide-area IES planning considering the analysis of users' energy consumption behavior, the planning results of scenario 2 and scenario 3 are compared and analyzed in this paper. The planning results of each subject in scenario 2 and scenario 3 are shown in Table 5, and the benefits of the IES are shown in Table 6. The government's environmental benefits are shown in Table 7.

It can be seen from Table 5 that in Scenario 2 and Scenario 3, the energy supply transformation decisions of the main users, the pricing strategies of the IES and the government's subsidy standards are different. This is because Scenario 3 considers the government as the main body of planning and decision-making, which leads to the adjustment of the user's energy subsidy standards, thereby affecting the decision-making of users and energy systems.

According to Table 6, the total revenue in scenario 3 increases by 7.7×10^8 yuan in terms of IES compared to scenario 2, with the revenue of two power companies increasing, the revenue of the power generation company rising by 1.29×10^9 yuan, the revenue of the power grid company rising by 3.1×10^8 yuan, but the revenue of the natural gas company falling by 8.3×10^8 yuan. The reason is that, as shown in Table 5, the electricity price subsidy decided by the government is increased by 0.008 yuan/kw-h, and the gas price subsidy is reduced by 0.03 yuan/m³. Under this energy supply transformation subsidy policy, all energy companies choose the planning scheme that maximizes their gains or minimizes their losses in the equilibrium game process. The proportion of natural gas energy supply transformation only decreases by 0.54% as far as

TABLE 6 Scenarios 2 and 3 integrated energy system benefits.

Situation	Company	Total income (yuan)	Investment cost (yuan)	Cost of purchasing coal (yuan)	Gas purchase cost (yuan)	Reliability cost (yuan)	Operating cost (yuan)	Environmental costs (yuan)	Total revenue (yuan)
2	Power Generation Company	5.597×10^{10}	1.499×10^9	7.235×10^9	5.465×10^9	0	9.802×10^9	4.495×10^9	2.747×10^{10}
	Power Grid Company	1.400×10^{10}	1.503×10^8	0	0	1.112×10^9	0	0	1.273×10^{10}
	Natural Gas Company	2.819×10^{10}	4.264×10^8	0	0	0	1.536×10^{10}	0	1.240×10^{10}
	Total	9.82×10^{10}	2.076×10^9	7.235×10^9	5.465×10^9	1.112×10^9	2.516×10^{10}	4.495×10^9	5.260×10^{10}
3	Power Generation Company	5.909×10^{10}	2.017×10^9	6.811×10^9	6.747×10^9	0	1.019×10^{10}	4.557×10^9	2.876×10^{10}
	Power Grid Company	1.452×10^{10}	1.748×10^8	0	0	1.301×10^9	0	0	1.304×10^{10}
	Natural Gas Company	2.915×10^{10}	5.263×10^8	0	0	0	1.705×10^{10}	0	1.157×10^{10}
	Total	1.028×10^{11}	2.718×10^9	6.811×10^9	6.747×10^9	1.301×10^9	2.724×10^{10}	4.557×10^9	5.337×10^{10}

TABLE 7 Total user and government benefits for scenarios 2 and 3.

Situation	Discharge volume at the government side (ton)		
	User side	Supply side	Total sewage discharge
2	5.250×10^8	2.179×10^8	7.429×10^8
3	5.023×10^8	2.209×10^8	7.232×10^8

natural gas companies are concerned, and at the same time, it can also increase the demand of power generation companies for natural gas, as can be seen from the significant increase in the purchase cost of power generation companies. This decision is made on the basis of the decline of natural gas subsidies. Therefore, the income of natural gas companies increased by 9.6×10^8 yuan, but due to the expansion of investment and production, the corresponding increase in investment costs and operating costs, the overall income of natural gas companies has declined. As for the power companies, the costs of investment and operation of power generation businesses as well as the revenue from electricity sales have increased due to the increase in subsidies for the transformation of the power supply as well as the increase in power load demand on the user side. The cost of coal purchase decreased by 4.13×10^8 yuan while the cost of gas purchase increased significantly by 1.282×10^9 yuan after the natural gas company reduced the price of gas. As a result, the cost of coal purchase decreased while the cost of gas purchase increased significantly. At the same time, more gas-fired units are used to undertake the task of power generation, which can also effectively control the environmental cost. However, due to the increase of total power generation, the environmental cost still increases slightly. Therefore, on the whole, the income of power generation companies is further improved. As far as the grid company is concerned, due to the increase of power users, the level of electricity load has been improved, and the grid company needs to improve the transmission capacity of the power network, so the investment cost of transmission lines has increased by 2.45×10^7 yuan, and the transmission income has also increased by 5.2×10^8 yuan. Because the increase of transmission distance also increases the reliability cost by 1.89×10^8 yuan, the overall income of power grid companies has increased.

Table 7 shows that in the government's case, in comparison to scenario 2, the total pollutant discharge in the area in scenario 3 is reduced by 1.97×10^7 tons, with the pollutant discharge on the user side being reduced by 2.27×10^7 tons and the pollutant discharge on the supply side being increased by 3×10^6 tons. The reason is that the proportion of user-side electric energy supply and total energy supply transformation has increased, and more users choose pollution-free electric energy supply mode. On the other hand, from the environmental cost analysis of the above power generation companies, it can be seen that the increase in emissions on the supply side is not large, so the total emissions in the region can be reduced.

To sum up, Scenario 3 considers the government as the main body of the game to participate in the wide-area IES planning, and fully takes into account the impact of government policy guidance, which can effectively guide users to carry out energy supply transformation, thus improving the environmental benefits of user-side energy supply transformation. As far as the IES is concerned, under the adjustment of government subsidies, the investors effectively guarantee their own benefits or minimize losses through overall planning.

6 Conclusion

This article proposes a planning method for wide area IES, which considers the user's integrated energy consumption behavior and policy guidance. The income optimization models are built separately for the users, the government, and various market participants in the large-area IES. This serves as the foundation for the establishment of a two-level game model for the joint planning of the wide-area IES, and the iterative search approach is used to solve the model. Finally, the model is validated using a simulation example. The simulation's findings indicate that:

- Based on the correlation analysis of source and load side, this method fully considers the user's CECB in the wide area IES planning, reveals the flexible weak coupling relationship between different forms of energy based on the user's CECB as a link, and can realize the coordinated planning of users and IES. Based on the analysis of user's CECB, the various loads on the demand side are reasonably evaluated and predicted, so as to guide the IES to carry out more refined planning and construction, and effectively enhance the income of each investor.
- This method fully takes into account the initiative of the government in the wide area IES planning, and considers the government as the main body of planning and decision-making, which can effectively guide users to carry out energy supply transformation, thus enhancing the environmental benefits of energy supply transformation on the user side. In the IES, joint planning among the investors can ensure their own interests.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

JL: Methodology, Writing—original draft, Writing—review and editing. TW: Conceptualization, Software, Writing—review and editing. GH: Conceptualization, Writing—original draft, MO: Conceptualization, Writing—original draft. WZ: Methodology, Validation, Writing—review and editing. TM: Methodology, Software, Validation, Writing—review and editing.

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Conflict of interest

Authors JL, GH, and MO were employed by Shenzhen Power Supply Company.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Appendix

TABLE A1 Data of gas turbine units to be selected.

Node	Capacity(MW)	Investment fee with (10 ⁶ yuan)	Gas consumption rate coefficient of quadratic term (BTU/MW ²)	Gas consumption rate first-order coefficient (BTU/MW)
1	167.2	160.5	0.01131	12.145
2	167.2	160.5	0.01131	12.145
7	220	211.2	0.0122	17.924
13	833.4	800	0.0030	20.023
15	341	327.36	0.00392	8.919
16	341	327.36	0.0667	9.2706
21	880	844.74	0.0028	5.345
23	341	327.36	0.0028	5.345

TABLE A2 Data of transmission lines to be selected.

Line road	Capacity(MW)	Existing line number of roads	Maximum expansion number of exhibitions	Length (km)
1—3	175	1	2	55
2—4	175	1	2	33
7—8	175	1	2	16
12—13	500	1	2	66
14—16	500	1	2	54
15—24	500	1	2	72
18—21	500	1	2	36
20—23	500	1	2	30

TABLE A3 Existing and candidate pipeline data.

		Tube tao	Pipe constant	Number of existing pipes	Maximum number of extensions	Length (km)
Existing piping	New pipeline to be built	1'—2'	0.0320	1	2	85
		2'—3'	0.0128	1	2	72
		5'—6'	0.0320	1	2	82
		6'—7'	0.0214	1	2	95
		9'—10'	0.0320	1	2	96
		9'—12'	0.0214	1	2	70
		16'—17'	0.0320	1	2	86
	—	1'—10'	0.0214	1	2	70
		3'—4'	0.0103	1	2	69
		4'—5'	0.0128	1	2	75
		4'—7'	0.0103	1	2	75
		4'—8'	0.0130	1	2	86
		10'—11'	0.128	1	2	72

(Continued on following page)

TABLE A3 (Continued) Existing and candidate pipeline data.

		Tube tao	Pipe constant	Number of existing pipes	Maximum number of extensions	Length (km)
		10'—15'	0.0128	1	2	81
		10'—16'	0.0214	1	2	81
		12'—13'	0.0128	1	2	76
		13'—14'	0.0130	1	2	98

TABLE A4 Coal-fired load (MW) to be renovated for various types of users in each region.

Region	1	2	3	4	5	6	7	8	9	10	13	14	15	16	18	19	20
Residential load	60	0	162	0	0	75	0	38	55	106	0	0	100	80	0	0	77
Commercial load	20	64	0	0	0	0	0	90	67	0	0	0	0	180	97	0	0
Industrial load	0	0	0	118	47	0	95	0	0	0	105	127	0	0	0	120	0

TABLE A5 Relevant parameters of natural gas network.

Air net node	Electricity node	Gas load (10 ⁶ SCF/h)	Output of air source point (10 ⁶ SCF/h)	Minimum nodal pressure (psia)	Maximum nodal pressure (psia)	Air net node	Electricity node	Gas load (10 ⁶ SCF/h)	Output of air source point (10 ⁶ SCF/h)	Minimum nodal pressure (psia)	Maximum nodal pressure (psia)
1'	23	0	25.6	600	1200	10'	9	3.41	—	600	1200
2'	20	2.74	—	600	1200		10	3.71			
3'	19	3.15	—	500	1200		11	0			
4'	16	2.16	—	600	1000		12	0			
5'	17	0	—	600	1200	11'	3	3.52	—	500	1000
	18	5.39					24	0			
6'	21	0	30.9	600	1200	12'	6	2.98	—	600	1200
	22	0				13'	5	1.70			
7'	15	5.26	—	400	1000	14'	1	2.23	—	400	1000
8'	14	3.95	—	400	1000		2	2.06			
9'	13	4.56	22.0	600	1200	15'	4	1.82	—	500	1200
	22	0				16'	8	3.35			
						17'	7	2.68	26.3	600	1200