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Electricity–gas multi-agent planning method considering users' comprehensive energy consumption behavior

Wentao Liu[1], Baorong Zhou[2], Mingyu Ou[1], Wenmeng Zhao[2], Guanglei Huang[1]* and Tian Mao[2]

[1]Shenzhen Power Supply Company, China Southern Power Grid, Shenzhen, China, [2]Electric Power Research Institute, China Southern Power Grid, Guangzhou, China

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EDITED BY
Zhengmao Li,
Aalto University, Finland

REVIEWED BY
Lu Nan,
Sichuan University, China
Zhihao Xu,
Nanchang Institute of Technology, China

*CORRESPONDENCE
Guanglei Huang,
✉ l15897554402@163.com

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With the advent of the energy Internet and the swift growth of unified energy systems, the comprehensive energy demand of users has gradually become a problem that cannot be ignored for the planning of integrated energy systems. Aiming at this problem, this paper suggests a multi-agent planning approach for electricity and gas, considering users' holistic energy consumption behavior. First, utilizing a combined subjective and objective weighting method, this study establishes a utility model for users' energy consumption characteristics. The analysis of comprehensive energy consumption behavior is conducted through an evolutionary game. On this basis, the planning revenue model for electricity grid and gas network investors is formulated, and the game mechanism of different investors is analyzed. A dynamic game model of electricity–gas multi-agent planning considering comprehensive energy consumption behavior is proposed. Ultimately, the model is resolved using an iterative exploration approach. The validity and efficacy of the proposed method are confirmed through a simulation example.

KEYWORDS

comprehensive energy network, analysis of energy consumption patterns, complete information dynamic game, joint planning, iterative exploration

1 Introduction

Given the growing prominence of environmental issues and the scarcity of energy resources, the unified energy system, capable of overcoming diverse energy obstacles and enhancing energy efficiency, has developed rapidly in recent years (Sheng et al., 2019; Wu et al., 2019; Zang et al., 2022). Within the unified energy framework, on one hand, users have more choices of energy use, and various energy systems are more closely linked (Dou et al., 2020a; Huang et al., 2020a; Yang et al., 2022a). At this time, neglecting users' comprehensive energy usage behavior makes it challenging to guarantee the economic, safety, and reliable aspects of the planning scheme (Chen et al., 2021; Zhang et al., 2022). On the other hand, due to the existence of multiple investors such as power generators, transmission companies, and natural gas operators, it is difficult for the current planning method to take into account the interests of each investor in the market (Shen et al., 2021; Li et al., 2023). Therefore, there is an immediate need to conduct research on the multi-agent planning method for electricity and gas, taking into account the overall energy utilization patterns of users.

At present, several researchers have explored the cooperative planning of an integrated electricity–gas energy system involving multiple agents (Wang et al., 2023; Zhang et al., 2023). Hu et al. (2017) filled in the blank of the research on the joint planning problem of the electricity–gas integrated energy system in China. By linearizing the gas flow constraints of the non-linear natural gas pipeline, the initial intricate non-linear non-convex programming problem is converted into a more manageable mixed-integer linear programming challenge. Unsihuay et al. (2010) built an electricity–gas joint planning model, considering electricity market and natural gas market transactions on an energy engineering simulation platform. A planning model encompassing multiple stages for electricity generation, the natural gas network, and power grid is outlined in Barati et al. (2015).

Nevertheless, within an actual integrated energy system, different investors may undertake the investment and construction of the power network and the natural gas network. These investors have independent interest demands, and their decision-making behavior is driven by individual rationality, leading to equilibrium outcomes in the gaming process (Fang et al., 2022; Xu et al., 2023; Yu et al., 2023). In this case, on one hand, the planning model, grounded in comprehensive rationality, struggles to adequately capture the prevalent multi-agent gaming dynamics in real-world integrated energy systems (Li Z. et al., 2020a; Yang et al., 2022b; Yu et al., 2022). Conversely, the comprehensive perspective in planning makes it challenging to consider the preferences of each market investor, consequently diminishing market vitality (Liao et al., 2018; Zheng et al., 2018; Yang et al., 2021). In view of the above problems, in Yang et al. (2020), each energy unit, along with electric and gas network companies, is treated as a distinct interest group, considers maximizing the annual net income as the optimization goal, and establishes a comprehensive non-linear programming model for wind-generating units, gas-generating units, and power-gas integrated systems involving electric-to-gas generators, transmission lines, and natural gas pipelines. A cooperative planning approach for an electricity–gas system is suggested, utilizing non-cooperative game theory. Dai et al. (2023) established planning models for power network and natural gas network investors individually, scrutinized the game dynamics among diverse investors, and put forth a dynamic gaming model for collaborative planning in an integrated electricity–natural gas energy system.

The above research has effectively solved the multi-agent gaming dynamics widely existing within the unified energy framework (Fu et al., 2023), but with the increasing diversification of energy types available for people during energy utilization, the user's selection of comprehensive energy use has gradually become a factor that cannot be ignored for the design of an integrated electricity–gas energy system (Zhou and Zhao, 2013; Wang et al., 2021; Zhu et al., 2023). Failure to consider the holistic energy consumption patterns of users will reduce the accuracy and effectiveness of the planning scheme (Gao et al., 2021; Li et al., 2021). Based on the data-driven idea, Li J. et al. (2020b) proposed a method for analyzing user energy consumption behavior by introducing the method of deep learning. Dou et al. (2020b) examined the node energy cost by formulating the node energy equilibrium equation and quantified the valuation of user energy consumption in the node area based on the node energy price and the user market consumption surplus so as to analyze the energy usage patterns of the user. Huang et al. (2020b) developed a utility model using a method that combines subjective and objective factors, considering the user's energy consumption traits and comfort preferences. This approach is used to assess the energy utilization patterns of diverse users. The above studies have analyzed the amalgamated energy usage patterns of users, but they have not considered the planning of a unified energy system. At present, there is limited research on designing integrated energy systems that account for the comprehensive energy usage patterns of users.

In view of this, this paper proposes a collaborative planning approach for an integrated electricity and gas energy system using multi-agent methods combined with game theory under the background of user integrated energy consumption. First, using a combined subjective and objective weighting approach, a model is developed to capture the energy consumption traits of users, and an evolutionary game is used to assess the overall energy consumption behavior of users (Huang et al., 2016; Li et al., 2019; Murty and Kumar, 2020; Zhu et al., 2021). On this basis, a profit model for investors in the electricity and natural gas networks is formulated, the game mechanism of different investors is analyzed, and a dynamic game model of electric-gas multi-agent planning considering the holistic energy usage patterns of users is proposed. Finally, the model is solved using an iterative search approach.

The key contributions of this paper include the following:

Compared with the traditional methods, to enhance the dependability of the planning outcomes, this paper focuses on the combined electricity and gas energy system planning problem under the background of the comprehensive energy consumption of users. By constructing the model capturing users' energy characteristic consumption characteristics, the all-encompassing energy usage patterns of users is analyzed by using the evolutionary game. On this basis, the game relationship between different investors is fully considered, which can not only ensure the economy and safety of planning and decision-making from the overall perspective of the integrated energy system combining electricity and natural gas but also ensure the security and dependability of the planning and decision-making. It also guarantees that every participant optimizes their gains throughout the gaming process, thus boosting the market dynamism of the integrated energy system and the efficiency of planning and decision-making. The simulation outcomes demonstrate the validity and efficacy of the proposed approach.

2 Analyzing the holistic energy usage patterns of users

In this paper, examining users' holistic energy usage patterns, the user utility model is studied by selecting the energy utility evaluation index and analyzing the energy usage traits of residential, extensive industrial, and commercial user segments.

2.1 Construction of the utility index

In order to reflect users' utility objectively and truly, based on the aforementioned literature, this paper comprehensively and systematically selects users' utility indicators from three dimensions of economic benefits, social benefits, and security benefits. Through further analysis, the four indexes affecting the user's behavior of choosing the energy supplier are obtained as follows: economic benefit (comprehensive energy cost A_1), social benefits (energy supply occupancy A_2 and user comfort A_3), and safety benefits (energy supply reliability A_4).

(1) Comprehensive energy expenditure

In this paper, the life cycle cost (LCC) theory is introduced to describe the index (Fang, 2008), which mainly considers the system investment, installation, and ongoing maintenance expenses. Then, the life cycle cost can be written as

$$LCC = IC + \mathrm{OC} + DC, \tag{1}$$

where LCC represents the life cycle cost; IC denotes the initial capital outlay; OC stands for the operational and maintenance expenses; and DC is the residual value.

1) Initial investment cost (IC):

$$IC = IC^{m}_{n,\mathrm{inv}} = \phi^{\mathrm{m}}_{0,\mathrm{n}} \cdot x^{m}_{0n}, \tag{2}$$

where $IC^{m}_{n,\mathrm{inv}}$ represents the initial investment and installation expenses for choosing the energy type n for the user type m; $\phi^{m}_{0,n}$ stands for the initial investment and installation cost of equipment for the energy type n; and x^{m}_{0n} denotes the initial energy supply utilization rate chosen by the user.

2) Operation and maintenance cost (OC):

$$\begin{aligned} OC &= OC^{m}_{\mathrm{n,op}} + OC^{m}_{\mathrm{n,tr}} \\ &= \sum_{t=2}^{\mathrm{T}} \left[p_n(t) \cdot L^{m}_{n}(t) + \gamma^{\mathrm{m}}_{c,\mathrm{n}} \cdot \Delta x^{m}_{n}(t) \right], \end{aligned} \tag{3}$$

$$\Delta \mathrm{x}^{m}_{n}(t) = \mathrm{x}^{m}_{n}(t) - \mathrm{x}^{m}_{n}(t-1), \Delta \mathrm{x}^{m}_{n}(t) > 0, \tag{4}$$

where $L^{\mathrm{m}}_{\mathrm{n}}(t)$ represents the real energy usage load of the energy type n selected by the user of the type m during the time period t; $OC^{m}_{\mathrm{n,op}}$ is the energy use cost of selecting the energy type n for m-type users; $OC^{m}_{\mathrm{n,tr}}$ indicates the equipment transformation and maintenance cost caused by the transformation of other energy forms of energy-using equipment on the user side; $\gamma^{m}_{c,n}$ stands for the expense incurred in dismantling the old equipment and installing and maintaining the new equipment after the shift in the energy type from c to n; $x^{m}_{n}(\mathrm{t})$ represents the energy supply utilization rate of the energy type n chosen by the users of type m during the time period t; $\Delta \mathrm{x}^{m}_{n}(t)$ takes the positive value of the change in the energy supply occupancy rate before and after, that is, $\Delta \mathrm{x}^{m}_{n}(t) > 0$.

3) Scrap disposal cost (DC)

DC covers the cost and income of the disposal of scrapped equipment, which is selected according to the residual value rate of energy equipment, and takes into account the correction of various economic factors, so the LCC formula is shown in Formula 5. Assuming that the study period is T, if the user category m selects the energy type n in the study period, the mathematical model of the user category m selecting the energy type n calculated by LCC is shown in Formula 6:

$$LCC = IC + \mathrm{OC}\frac{(1+\mathrm{i})^{y} - 1}{(i+1)^{y}} + DC(1+\mathrm{i})^{-y}, \tag{5}$$

$$A_1 = \frac{LCC}{\sum_{t=1}^{\mathrm{T}} L^{m}_{n}(t)}, \tag{6}$$

where y is the number of years in the economic life cycle and i is the discount rate.

(2) Occupancy of energy supply

In this paper, the categorization is based on the user type and load usage, with the specific formula as follows:

$$A_2 = \left(\sum_{\mathrm{m}=1}^{M} \mathrm{x}^{m}_{n} \mathrm{D}^{\mathrm{m}} \right) \Big/ \sum_{\mathrm{m}=1}^{M} \mathrm{D}^{\mathrm{m}}. \tag{7}$$

In the above equation, D^{m} represents the aggregate load of users in category m throughout the research period.

(3) User comfort

In this research, we use an exponential function to represent the user comfort index, incorporating the influence of environmental factors. The specific formula is detailed below:

$$A_3 = \zeta\left(\beta \mathrm{e}^{-\mathrm{x}^{m}_{n}} / t + \delta\right), \tag{8}$$

where ζ is the user comfort benefit coefficient; β represents the user's energy experience coefficient; x^{m}_{n} is the energy supply utilization rate of the energy type n chosen by users of type m; and δ is a stochastic variable associated with external factors, $\delta \in (0, 1)$.

(4) Reliability of energy supply

In this paper, the user's effective energy supply time ratio to the overall study period is utilized as the metric for assessing the reliability of energy supply, and the precise formula is provided as follows:

$$A_4 = 1 - \frac{\chi_{\mathrm{n}}}{\mathrm{H}_{n}} \times 100\%, \tag{9}$$

where χ_{n} denotes the mean downtime of the chosen energy type n, measured in hours for the user type, and H_{n} is the duration of energy supply when selecting the energy type n, which is measured in hours.

2.2 User utility analysis based on the combination weighting method

Building the user utility function requires the consideration of various indicators, each exerting a distinct impact on the user utility index system. This study uses the concept of combined weighting to compute the weight index (Guo et al., 2017), that is, the weight values for the user utility index, considering both subjective and objective factors, are calculated by AHP and the variation coefficient method respectively, and the combination weight value is finally obtained according to the energy preference coefficient α. Moreover, then a user utility function model is constructed.

2.2.1 Subjective weight calculation based on AHP

As a commonly used subjective weighting method, AHP is used to solve the subjective weights of the four indicators in this paper. The procedural steps are outlined as follows.

(1) The above four indicators are evaluated according to expert experience, b_h and b_{h+1} are compared with the "nine-level scale method," and the corresponding scale value of j_h is recorded at this moment.
(2) The remaining elements in the matrix are determined by the transitivity of the index importance degree, and the judgment matrix (four-order square matrix) is obtained.

$$\boldsymbol{J}_{\mathbf{h}}' = \begin{bmatrix} 1 & j_1 & j_1 j_2 & j_1 j_2 j_3 \\ \frac{1}{j_1} & 1 & j_2 & j_2 j_3 \\ \frac{1}{j_1 j_2} & \frac{1}{j_2} & 1 & j_3 \\ \frac{1}{j_1 j_2 j_3} & \frac{1}{j_2 j_3} & \frac{1}{j_3} & 1 \end{bmatrix}. \tag{10}$$

(3) After the consistency test, the subjective weight value $r^m_{1\mathrm{T,h}}$ is obtained.

$$\begin{cases} M_h = \prod_{p=1}^{4} J'_{hp}, \\ G_h = \sqrt[4]{M_h}, \\ r^m_{1T,h} = \dfrac{G_h}{\sum_{h=1}^{4} G_h}, \end{cases} \tag{11}$$

where M_h is the product of each row element of the judgment matrix J'_h; G_h is the fourth root of M_h; and $r^m_{1T,h}$ is the subjective weight value of m m-type users about the index h.

2.2.2 Calculation of objective weight based on the variation coefficient method

Considering the dynamic characteristics of A_1, A_2, A_3, and other indicators, the coefficient of variation approach is used to solve the objective weight value. In this method, the weight value is proportional to the degree of variation, which can quantitatively measure the importance of indicators. The calculation steps are as follows.

(1) Standardizing each index

It is assumed that the four evaluation indexes before and after the user's decision are b_{hj} (h = 1, 2, . . . , 4); j = 1, 2 indicates before and after the user changes the decision. After normalizing b_{hj}, b_{hj} is obtained.

$$b'_{hj} = \frac{b_{hj} - \mathrm{b}_{hj,\min}}{\mathrm{b}_{hj,\max} - \mathrm{b}_{hj,\min}} \quad h = 1, 2, \cdots, 4, \tag{12}$$

where $\mathrm{b}_{hj,\min}$ and $\mathrm{b}_{hj,\max}$ represent the lowest and highest values of the h index before and after the decision alteration, respectively.

(2) Solving the coefficient of variation V_h

$$\begin{cases} \bar{b}_h' = \frac{1}{2}\left(b'_{h1} + b'_{h2}\right), \\ s_h = \sqrt{\frac{1}{2}\left[\left(b'_{h2} - \bar{b}_h'\right)^2 + \left(b'_{h1} - \bar{b}_h'\right)^2\right]}, \\ V_h = \dfrac{s_h}{\left|\bar{b}_h'\right|}, \end{cases} \tag{13}$$

where $\bar{b}_h'$ stands for the mean value of the h index; s_h represents the standard deviation of the h index; and V_h denotes the coefficient of variation of the h index.

The objective weight value $r^m_{2\mathrm{T,h}}$ of m-type users about the index h is determined.

$$r^m_{2\mathrm{T,h}} = \frac{V_h}{\sum_{h=1}^{4} V_h} \quad h = 1, 2, \cdots, 4. \tag{14}$$

2.2.3 Determination of combination weight values

The combined weight value is calculated as follows:

$$r^m_{\mathrm{T,h}} = \alpha \cdot r^m_{1\mathrm{T,h}} + (1 - \alpha) \cdot r^m_{2\mathrm{T,h}}, \tag{15}$$

where $r^m_{1\mathrm{T,h}}$ and $r^m_{2\mathrm{T,h}}$ are the subjective weight value and objective weight value of m-type users about the h-item index, respectively; α represents the energy preference coefficient.

The index values are calculated in combination with Formulas 1–14, and after the indexes are normalized, the index values are combined with the weight values of Formula 15 for weighting operation, thus deriving the utility function for the chosen energy type n by users of the type m.

$$\mathrm{U}^m_n = r^m_{\mathrm{T,1}} B^m_1 + r^m_{\mathrm{T,2}} B^m_2 + r^m_{\mathrm{T,3}} B^m_3 + r^m_{\mathrm{T,4}} B^m_4. \tag{16}$$

In the user utility function, A_1, A_2, and A_3 indexes are related to the user group characteristics and group status, that is, their values will be constantly updated in the dynamic evolution.

2.3 Decision-making regarding users' energy consumption behavior using evolutionary game theory

2.3.1 Evolutionary game model

The utility obtained by different types of users of the type m choosing the energy type is analyzed by the evolutionary game method. First, power providers and gas distributors disseminate relevant energy supply details to distinct user categories individually. Second, the user calculates the utility of selecting the energy type n according to Formula 16. Then, the utility model is evaluated to determine the three key elements in the evolutionary game, and based on this, the game strategy is updated. In addition, the energy supplier adjusts the energy supply utilization rate based on the current user group's selection status and communicates the updated rate to the three user types. Both parties reach the ultimate equilibrium state during the evolutionary game progression.

The in-area user population state can be represented by the matrix Y as

$$\boldsymbol{Y} = \begin{bmatrix} y_1^1 & \cdots & y_n^1 & \cdots & y_N^1 \\ \vdots & \ddots & & \therefore & \vdots \\ y_1^m & & y_n^m & & y_N^m \\ \vdots & \therefore & & \ddots & \vdots \\ y_1^M & \cdots & y_n^M & \cdots & y_N^M \end{bmatrix}. \tag{17}$$

When selecting the energy type, the user will revise the utility function according to the change in current index information and complete the optimization of adjusting their strategy based on the utility function. Hence, the introduction of the correction factor $\rho_{q,n}^m[\mathrm{U}^m(\boldsymbol{Y})]$ aims to describe the fraction of users of the type m transitioning from q to n during the evolution process. At any given moment, each user has the possibility of being proportionally shifted from policy q to n through $\rho_{q,n}^m[\mathrm{U}^m(\boldsymbol{Y})]$. Assuming that as all users adjust their respective policies, the dynamic transformation of the aforementioned user group state Y can be expressed through a differential equation, which is outlined as follows:

$$\frac{\partial y_{\mathrm{n}}^{\mathrm{m}}}{\partial t} = \sum_{\mathrm{q}=1}^{\mathrm{N}} y_q^m \rho_{q,n}^m[\mathrm{U}^m(\boldsymbol{Y})] - y_n^m \sum_{\mathrm{q}=1}^{N} \rho_{n,q}^m[\mathrm{U}^m(\boldsymbol{Y})]. \tag{18}$$

The initial and second terms on the right side of Formulas 17, 18 represent the percentage of users in category m transitioning from selecting alternative policies to policy n and from policy n to opting for alternative policies, respectively. Among them, $\rho_{q,n}^m[\mathrm{U}^m(\boldsymbol{Y})]$ is associated with the existing user utility function and the user group state. To establish the connection between the user group selection ratio and the optional strategy, this chapter uses the Logit discrete selection model, with the formula outlined as follows:

$$\rho_{\mathrm{q,n}}^m[\mathrm{U}^{\mathrm{m}}(\boldsymbol{Y})] = \frac{\exp[\mathrm{U}_{\mathrm{n}}^{\mathrm{m}}(\boldsymbol{Y})]}{\sum_{\mathrm{l}=1}^{N} \exp[\mathrm{U}_l^{\mathrm{m}}(\boldsymbol{Y})]}. \tag{19}$$

The dynamic transformation equation for the terminal user group is acquired by substituting the preceding equation into Formula 19 as follows:

$$\begin{aligned} \frac{\partial y_{\mathrm{n}}^m}{\partial t} &= \frac{\exp[\mathrm{U}_n^m(\boldsymbol{Y})]}{\sum_{\mathrm{l}=1}^{N} \exp[\mathrm{U}_l^m(\boldsymbol{Y})]} - y_n^m \\ &= \rho_{\mathrm{q,n}}^m[\mathrm{U}^{\mathrm{m}}(\boldsymbol{Y})] - y_n^m. \end{aligned} \tag{20}$$

As the energy consumption ratio for extensive industrial and commercial users is constrained by actual production and the capacity for energy load absorption is restricted, the constraint conditions for selecting the proportion of users with the corresponding load are as follows Formulas 20, 21:

$$\begin{cases} y_2^2(t) \in [0, 0.3], \\ y_2^3(t) \in [0, 0.3], \\ y_3^3(t) \in [0, 0.3]. \end{cases} \tag{21}$$

3 Benefit model of each planning agent in the electricity–gas network

The power network is divided into two main bodies, namely, electricity generation firms and transmission grid companies, and the natural gas network mainly includes natural gas operators. The variance in total revenue from energy sales and the total cost of the above subjects is taken as the planning revenue function and constrained, and finally, the planning revenue model of each subject is constructed.

3.1 Generator planning revenue

Its income is mainly the electricity sales revenue B_{EGI} sold to the transmission network. Its cost covers the gas unit (GU) cost C_{GU}, which includes the investment cost C_{IGU}, gas purchase cost C_{BGU}, operation cost C_{OGU}, and pollution treatment cost C_{DGU}. Coal unit cost C_{CFU} (CU) includes the operation cost C_{OCFU} and pollution treatment cost C_{DCFU}. See Formulas 22–28 for the specific calculation of the above income and cost, and see Formula 29 for its income function F_{GC}:

$$\mathrm{B}_{\mathrm{EGI}} = \sum_{t=1}^{T} E_{\mathrm{P}t} {}^* s_{\mathrm{E}}, \tag{22}$$

$$C_{\mathrm{IGU}} = \frac{\mathrm{r}}{1-(1+r)^{-T_{\mathrm{GU}}}} \left(\sum_{i=1}^{N_{\mathrm{GU}}} x_i \mu_i \right), \tag{23}$$

$$C_{\mathrm{BGU}} = \sum_{t=1}^{T} \mathrm{G}_{\mathrm{P}t} {}^* s_{\mathrm{G}}, \tag{24}$$

$$C_{\mathrm{OGU}} = \sum_{t} \sum_{\mathrm{d}} h_{dt} (C_{\mathrm{OGUd}}) P_{\mathrm{CF}u}, \tag{25}$$

$$C_{\mathrm{DGU}} = \sum_{t} \sum_{d} h_{dt} (C_{\mathrm{DGU}d}) P_{\mathrm{CF}u}, \tag{26}$$

$$C_{\mathrm{OCFU}} = \sum_{t} \sum_{\mathrm{k}} h_{kt} (C_{\mathrm{CFUk}}) P_{\mathrm{Gk}}, \tag{27}$$

$$C_{\mathrm{DCFU}} = \sum_{t} \sum_{\mathrm{k}} g_{kt} (C_{\mathrm{DCFU}k}) P_{\mathrm{Gk}}, \tag{28}$$

$$\begin{cases} F_{\mathrm{GC}} = \mathrm{B}_{\mathrm{EGI}} - C_{\mathrm{GU}} - C_{\mathrm{CFU}}, \\ C_{\mathrm{GU}} = C_{\mathrm{IGU}} + C_{\mathrm{BGU}} + C_{\mathrm{OGU}} + C_{\mathrm{DGU}}, \\ C_{\mathrm{CFU}} = C_{\mathrm{OCFU}} + C_{\mathrm{DCFU}}, \end{cases} \tag{29}$$

where t is the horizontal year; T is the horizontal annual total; and $\mathrm{G}_{\mathrm{P}t}$ and $E_{\mathrm{P}t}$ are, respectively, the electricity quantity and gas quantity purchased by power generation companies and transmission network companies in the t-period. s_{E} is the electricity price sold by the generator; s_{G} represents the cost of natural gas; N_{GU} is the set of GU to be selected; x_i and μ_i are the investment 0/1 variable and investment amount of the i-th GU, respectively; r stands for the interest rate on funds; TGU is the equipment input life of GU. The GU number is d; hdt and hkt are, respectively, the running time of unit d and unit k in the t-period; $P_{\mathrm{CF}u}$ and P_{Gk} are the active power of unit d and unit k respectively; C_{OGUd} and $C_{\mathrm{DGU}d}$ represent the operational and pollution treatment expenses for unit d per unit of the power, respectively; and C_{CFUk} and $C_{\mathrm{DCFU}k}$ denote the operational and pollution treatment expenses for unit k per unit of the power, respectively.

3.2 Planning income of the transmission grid operator

Its revenue mainly consists of electricity sales revenue $\mathrm{B}_{\mathrm{SGI}}$ from energy suppliers, and its costs include the network loss cost C_{NLL}, transmission line investment cost C_{IL}, and electricity purchase cost

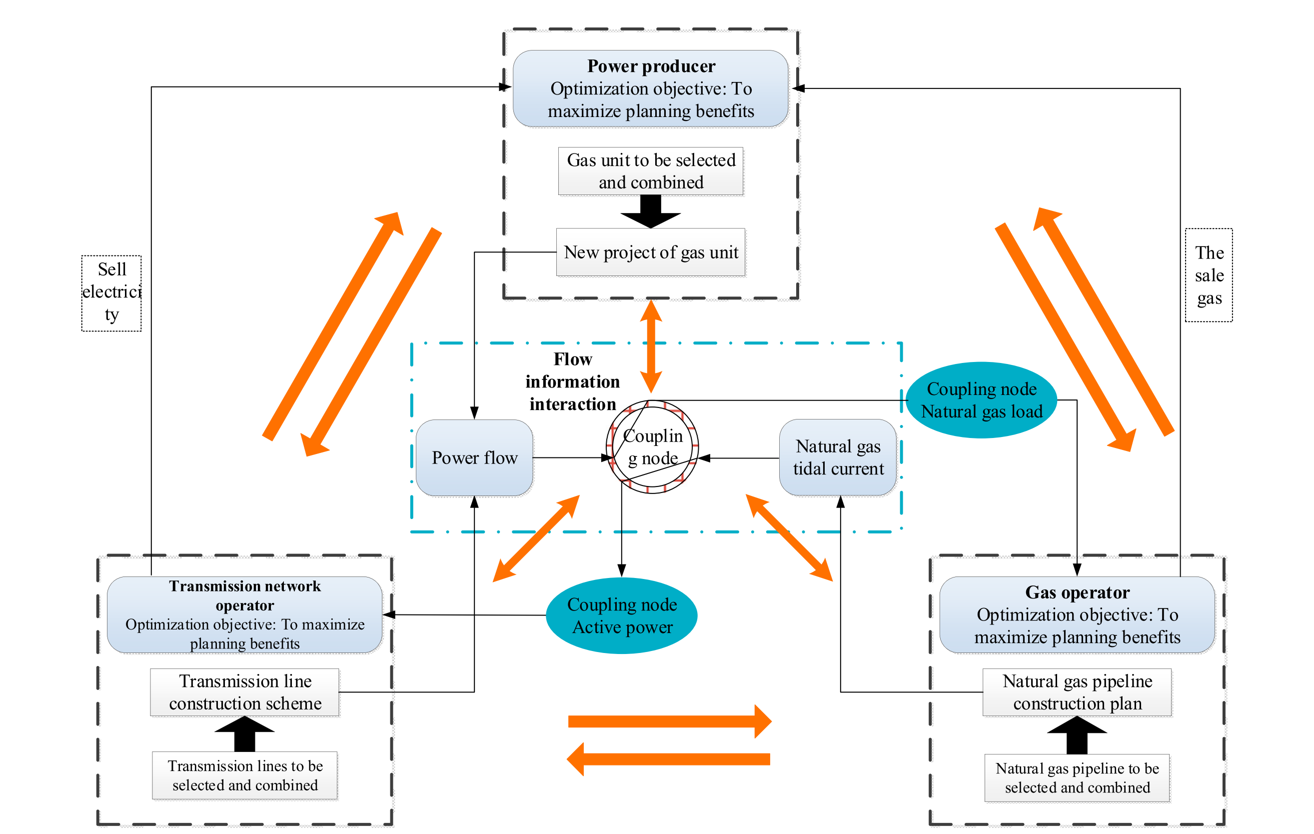

FIGURE 1
Three-game framework.

B_{EGI} from power producers. See Formulas 30–32 for the above income and cost calculation, and see Formula 33 for its income function.

$$B_{SGI} = \sum_{t=1}^{T} E_{Lt}{}^{*} s_L, \tag{30}$$

$$C_{NLL} = \sum_{t} \sum_{l} N_{LClt}(\varpi_l), \tag{31}$$

$$C_{IL} = \frac{r}{1-(1+r)^{-T_{LLS}}} \left(\sum_{i=1}^{S_{WL}} y_j \tau_j \right), \tag{32}$$

$$F_{EL} = B_{SGI} - C_{NLL} - C_{IL} - B_{EGI}, \tag{33}$$

where E_{Lt} is the load quantity of the t time period; s_L represents the selling price of the power transmission grid provider; TLLS represents the lifespan of the transmission line; S_{WL} is a set to be chosen for the power transmission line; y_j and τ_j represent the investment 0/1 variable and the investment cost of the transmission line j, respectively; l is the line number; N_{LClt} represents the loss of line l in the t period; and ϖ_l is the cost of network loss per unit line.

3.3 Natural gas operator planning revenue

The revenue of natural gas operators is mainly gas sales revenue B_{GPI}. Its cost covers the capital expenditure C_{IGP} of the gas transmission pipeline and the operation cost C_{OGS} of the natural gas source. See Formulas 34–36 for the above income and cost calculation, and see Formula 37 for its income function F_{GP}.

$$6B_{GPI} = \sum_{t=1}^{T} E_{Gt}{}^{*} s_G, \tag{34}$$

$$C_{IGP} = \frac{r}{1-(1+r)^{-T_{GPL}}} \left(\sum_{i=1}^{S_{NGP}} \ell_i \psi_i \right), \tag{35}$$

$$C_{OGS} = \sum_{t} \sum_{N} h_{Nt} (C_{UOGS}) P_{Gt}, \tag{36}$$

$$F_{GP} = B_{GPI} - C_{IGP} - C_{OGS}, \tag{37}$$

where E_{Gt} is the annual load; SNGP, TGPL, ℓ_i, and ψ_i are, respectively, the set to be selected, service life, 0/1 variable of investment, and investment cost of the gas transmission pipeline; N, C_{UOGS}, and P_{Gt} are the number, operation cost, and unit production of the natural gas source, respectively.

3.4 Network constraints

3.4.1 Electrical constraints

$$\sum_{i\in\Omega_2} \boldsymbol{EG}_{pm} P_{gzt} + \sum_{l\in\Omega_1} \boldsymbol{LN}_{pl} f_{Elt} = \sum_{k\in\Omega_3} \boldsymbol{KN}_{pk} E_{Ldkt} \quad \forall t, \forall p \in \Omega_4 \tag{38}$$

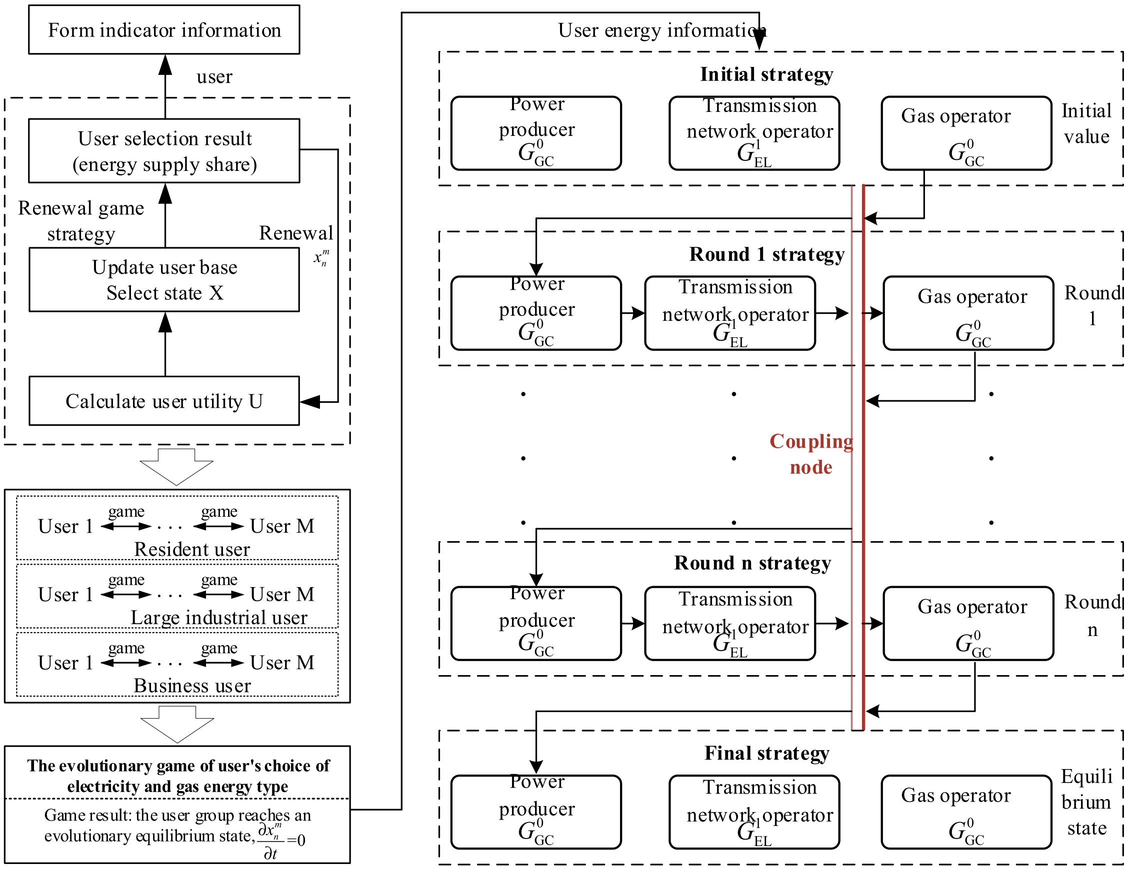

FIGURE 2
Game behavior diagram.

$$\mathrm{L}_{\min,\rho} \le \mathrm{f}_{\rho,qw} \le \mathrm{L}_{\max,\rho}\ \forall \rho \in \Omega_4, \tag{39}$$

$$\begin{cases} P_a = U_a \sum_{a \in b} U_b \left(G_{ab}\cos\theta_{ab} + B_{ab}\sin\theta_{ab}\right), \\ Q_a = U_a \sum_{a \in b} U_b \left(G_{ab}\sin\theta_{ab} - B_{ab}\cos\theta_{ab}\right), \end{cases} \tag{40}$$

$$\mathrm{U}_{k,\ \min} \le U_{k,t} \le \mathrm{U}_{k,\max}, \tag{41}$$

$$\begin{gathered} P_{\mathrm{cfu},d}^{\min} \le P_{\mathrm{cfu},d} \le P_{\mathrm{cfu},d}^{\max} \\ \forall d \in S_{\mathrm{CFU}}. \end{gathered} \tag{42}$$

In the Formulas 38–42, EG, LN, and KN are associated matrixes of generators, transmission lines, loads and power network nodes, respectively. z is the generator number; P_{gzt}, $f_{\mathrm{E}lt}$, and $E_{\mathrm{Ld}kt}$ are the output of z, the power flow of line l, and the load of node k in the t period, respectively; $\Omega_k\ k \in (1,4)$ represents the corresponding collection for the aforementioned system; $\mathrm{L}_{\max,\rho}$ and $\mathrm{L}_{\min,\rho}$ denote the upper and lower bounds of line capacity; $\mathrm{f}_{\rho,qw}$ is the power flow of line qw; P_a and Q_a are active and reactive power at node q, respectively; U_a, U_b, and θ_{ab} are the voltage amplitude and voltage phase angle difference of nodes a and b, respectively; G_{ab} and B_{ab} are the conductance and admittance of branch ab; $\mathrm{U}_{k,\max}$ and $\mathrm{U}_{k,\min}$ are the upper and lower limits of the voltage amplitude of node k; $P_{\mathrm{cfu},d}^{\max}$ and $P_{\mathrm{cfu},d}^{\min}$ are the upper and lower limits of the output of the unit d, respectively; and S_{CFU} denotes the set of CU.

3.4.2 Constraints on coupled nodes

$$f_{\mathrm{Ei}_c} + \Theta f_{\mathrm{pc}} = f_{\mathrm{Loc}} + E_{\mathrm{Ldc}}\ \forall c \in S_{\mathrm{GU}}, \tag{43}$$

$$\begin{gathered} \mathrm{W}_{\mathrm{GU}}^{\min} \le \mathrm{W}_{\mathrm{GU}} \le \mathrm{W}_{\mathrm{GU}}^{\max} \\ \forall d \in S_{\mathrm{GU}}, \end{gathered} \tag{44}$$

In Formulas 43, 44, c is the coupling node; $f_{\mathrm{E}lt}$ and f_{Lco} are the power flow flowing into and out of c, respectively; f_{pc} is the air flow into c; Θ is the conversion coefficient of GU; $E_{\mathrm{Ld}c}$ is the load of c; S_{GU} is the GU set; and $\mathrm{W}_{\mathrm{GU}}^{\max}$ and $\mathrm{W}_{\mathrm{GU}}^{\min}$ represent the maximum and minimum limits of unit d output, respectively.

3.4.3 Natural gas constraint

$$\pi_e^{\min} \le \pi_e \le \pi_e^{\max}\ e \in S_5, \tag{45}$$

$$\begin{gathered} \mathrm{sl}_f PQ_{\min,f} \le PQ_{f,t} \le \mathrm{sl}_f PQ_{\max,f} \\ \forall t, \forall f \in S_f, \end{gathered} \tag{46}$$

$$\begin{aligned} &\sum_{c \in S_C} \boldsymbol{VE}_{wc} f_{ct} + \sum_{f \in S_{GP}} \boldsymbol{PA}_{wf} f_{\mathrm{P}ft} + \sum_{N \in S_{WT}} \boldsymbol{RV}_{wN} W_{Nt} \\ &= \sum_{h \in S_{BL}} \boldsymbol{GL}_{Bh} E_{\mathrm{Gd}et}\ \forall w \in S_5, \forall t, \end{aligned} \tag{47}$$

$$\begin{cases} \pi_{q2t} \le \Gamma_h \pi_{q1t}, \\ 0 \le f_{ht} \le C_o^{\ \max}, \\ o \in S_O, \end{cases} \tag{48}$$

TABLE 1 Parameter values of $\phi_{0,n}^{m}$ and $\gamma_{c,n}^{m}$ in index A_1.

User type	$\phi_{0,n}^{m}$/yuan		User type	$\gamma_{c,n}^{m}$/yuan	
	Power supply	Gas supply		Power supply	Gas supply
Residents	1,900	1,600	Residents	2,300	2,000
Big industry	2,000	1,400	Big industry	2,600	1,700
Business	1,800	1,900	Business	2,350	2,700

TABLE 2 Parameter value of χ_n in index A_3.

Type of energy supply	Mean time to disability
Power supply	0.50
Gas supply	1.05

In Formulas 45–48, $\pi_e^{\max}$ and $\pi_e^{\min}$ denote the maximum and minimum limits of the air pressure amplitude at node e, respectively; S_5, S_f, S_O, and S_{BL} are the collection of network nodes, pipelines, compressors, and all load nodes of natural gas, respectively; $PQ_{\max,f}$, $PQ_{\min,f}$, and sl_f are the upper and lower limits and safety fluctuation coefficient of the pipeline transmission flow, respectively; VE, PA, RV, and GL are the correlation matrices for the compressor, pipeline, natural gas source, natural gas load, and natural gas network nodes, respectively. $E_{\mathrm{Gd}et}$ and $f_{\mathrm{P}ft}$ are, respectively, the gas load at node e and the natural gas flow in pipeline f in the t-period; Γ_h and $C_o{}^{\max}$ are the boosting ratio of the compressor h and the upper limit of transmission capacity, respectively; π_{q2t}, π_{q1t}, and f_{ht} are, respectively, the air pressure and air flow at the air outlet and air inlet flowing through h in the t-period.

4 Electricity–gas multi-agent planning considering energy consumption behavior of users

4.1 Planning ideas

In this section, the planning decisions of the generator, the transmission grid provider, and the natural gas operator (all of whom are familiar with all the strategic information about the other party) are the new construction schemes of GU, transmission line, and pipeline, respectively. The three-party game framework is shown in Figure 1. All three parties decide with the aim of optimizing their individual gains. Taking the first round game as an example, the generator first optimizes the new GU construction scheme based on the gas network information at the coupling nodes and makes a decision. The transmission network provider obtains the above information and then updates the line decision scheme. After solving the power flow, the coupling node receives the information from the grid side, transmits it to the natural gas operator, completes the optimization of the pipeline scheme, and then makes a decision. Then, the user calculates the utility of the selected energy type n according to Eq. 16. Then, the utility model is evaluated to determine the three key elements of the evolutionary game, and based on this, the game strategy is updated. The power supplier updates the power supply share according to the selection status of the current user group and releases it to the three types of users. The two sides achieve the final evolutionary equilibrium state in the process of the evolutionary game. The Nash equilibrium solution (that is, the user's energy consumption data) is passed to the operators of natural gas, transmission lines, and pipelines, and the three are combined with the user's energy consumption data to carry out the game among the three, as shown in Figure 2.

G* is the optimal strategy of itself under the optimal strategy of other agents. The formula is as follows:

$$\begin{cases} G_{GC}^{*} = \mathrm{argmax} F_{GC}\left(G_{GC}^{*}, G_{EL}^{*}, G_{GP}^{*}\right) \\ G_{EL}^{*} = \mathrm{argmax} F_{EL}\left(G_{GC}^{*}, G_{EL}^{*}, G_{GP}^{*}\right) \\ G_{GP}^{*} = \mathrm{argmax} F_{GP}\left(G_{GC}^{*}, G_{EL}^{*}, G_{GP}^{*}\right). \end{cases} \tag{49}$$

4.2 Solution of the model

The Nash equilibrium is solved using an iterative search method, and the specific solving steps are as follows:

(1) User energy consumption information is updated, and load data, initial network topology parameters, electricity price, gas price, GU and coal unit parameters are initiated to be selected, in addition to GU cost, transmission line and natural gas pipeline cost, and other related system parameters.
(2) A set is generated to be selected of GU, the power transmission line, and gas transmission pipeline, comprising the strategy set of the game players.
(3) A group of planning strategy schemes of three main bodies is randomly selected as an initial value.
(4) The initial value of iteration is set as $\varphi = 2$
(5) Dynamic game among the three subjects of power generation companies, transmission grid operators, and natural gas operators.
(6) Whether the Nash equilibrium state is reached is checked. If not, return to the step (5); if so, the equilibrium solution of the model is output.

5 Example simulation and analysis

5.1 Explanation of examples

In this study, the dynamic decision-making process among residential, industrial, and commercial users, as well as the selection

TABLE 3 Grid topology structure.

Power grid		Natural gas network	
Existing GU	3 sets	Natural gas source	2
GU to be selected	5 sets	Gas load (without the coupling node)	5
Existing CU	9 sets	Piping	12
Transmission line to be selected	8	Pipeline branch to be selected	6
		Compressors (all gas powered)	4

Note: Each branch of the pipeline can be expanded by 2 at most. The transmission line shall be expanded by 1 line at most.

TABLE 4 Parameter value.

Parameter	Price
C_{IL}	682,025 yuan/km
C_{IGP}	RMB 102,795/km
s_E	RMB 0.5/kWh
s_L	0.55 yuan/kWh
S_G	3 yuan/m^3

TABLE 5 Combination weight of each type of user index.

Combination weight	$r^m_{1T,1}$	$r^m_{1T,2}$	$r^m_{1T,3}$	$r^m_{1T,4}$
Residents	0.369	0.132	0.260	0.239
Big industry	0.088	0.347	0.217	0.348
Business	0.228	0.046	0.260	0.466

of electricity and gas energy types, is examined. On this basis, based on the integrated energy network of 15-bus natural gas network and IEEE24-bus power system, the planning and decision-making ideas of the three main bodies are analyzed. The economic life cycle in index A1 is 10 years; the discount rate is 7%; and its parameters $\phi^m_{0,n}$, $\gamma^m_{c,n}$, and χ_n in A3 are shown in Tables 1, 2, respectively; see Table 3 for the unit and line composition of the two types of grid planning. C_{IL}, C_{IGP}, C_{OGS}, and other parameters are shown in Table 4 (other parameters are shown in the attached table).

5.2 Case result

To mitigate the influence of substantial fluctuations in energy load on the assessment outcomes of end-user utility, α is set to 0.6 in this study, with the flexibility to be adjusted based on the specific context of the energy type chosen by users. Calculated in combination with the above index values and each index parameter, the final combined weight value $\omega^m_{T,h}$ is shown in Table 5, and the user utility results are shown in Table 6.

On the basis of determining the user's energy consumption behavior, this paper sets up two examples for IES planning and compares the calculation results. The two examples are as follows:

TABLE 6 Users' utility function values.

User type	Power supply	Gas supply
Residents	0.653	0.508
Big industry	1.607	1.172
Business	2.032	0.535

(1) Example 1: Electricity–gas joint planning without game. The joint planning is realized directly by optimizing the total revenue.
(2) Example 2: Electricity–gas joint programming considering the complete information dynamic game. Based on the premise of individual rationality, the three main bodies realize the Nash equilibrium with the optimal income of all parties based on the dynamic game.
(3) Example 3: Electricity–gas joint planning based on the complete information dynamic game considering users' comprehensive energy consumption behavior.

In Example 1 and Example 2, the demand for electricity load is the same, while the new construction and operation of GU have an impact on the gas load. In Example 3, the electricity load and gas load are allocated according to the proportion of the above user utility function values. The planning results of the power grid and natural gas network in the three examples are shown in Figures 3, 4 above.

It can be seen from the above figure that there are differences in the planning schemes of the two examples. For the GU planning scheme, the units of Example 1 are set at nodes 3, 13, 23, and 24, and the units of example 2 are set at nodes 3, 23, and 24. For the transmission network planning scheme, all branches to be selected in Example 1 have new lines, while only 8–7 branches in Example 2 have no new lines.

5.3 Comparative analysis of the result

To validate the efficiency of the multi-agent planning approach considering users' holistic energy consumption behavior, three examples are set for comparison to analyze the benefits of each agent. The results of Example 1, Example 2, and Example 3 are shown in the following table.

Observing Table 7 reveals that, in contrast to Example 1, the gas purchase cost, GU investment cost, operation cost, and pollution treatment cost in Example 2 are reduced by 2.445×10^7, 1.244×10^7, 2.367×10^7, and 1.958×10^7 yuan, respectively.

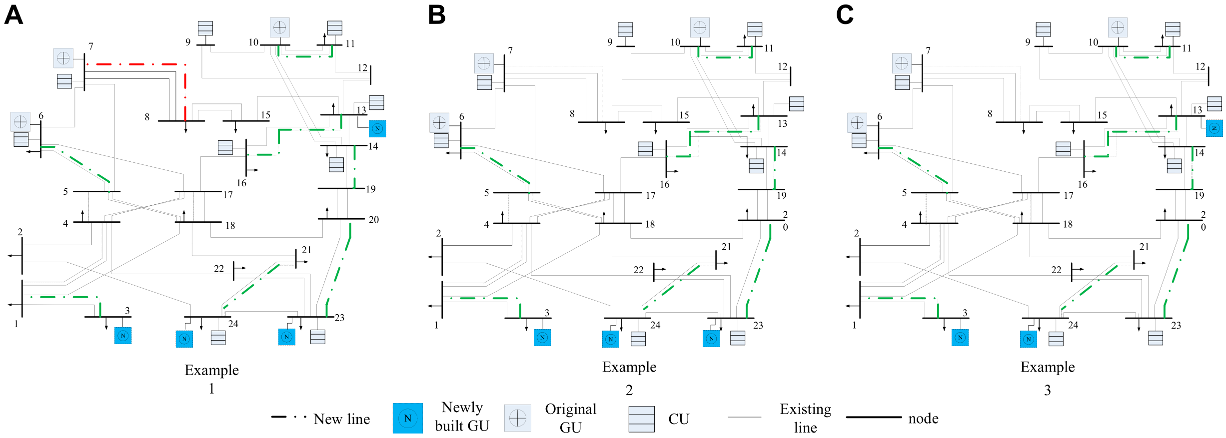

FIGURE 3
Power network simulation planning diagram **(A–C)**.

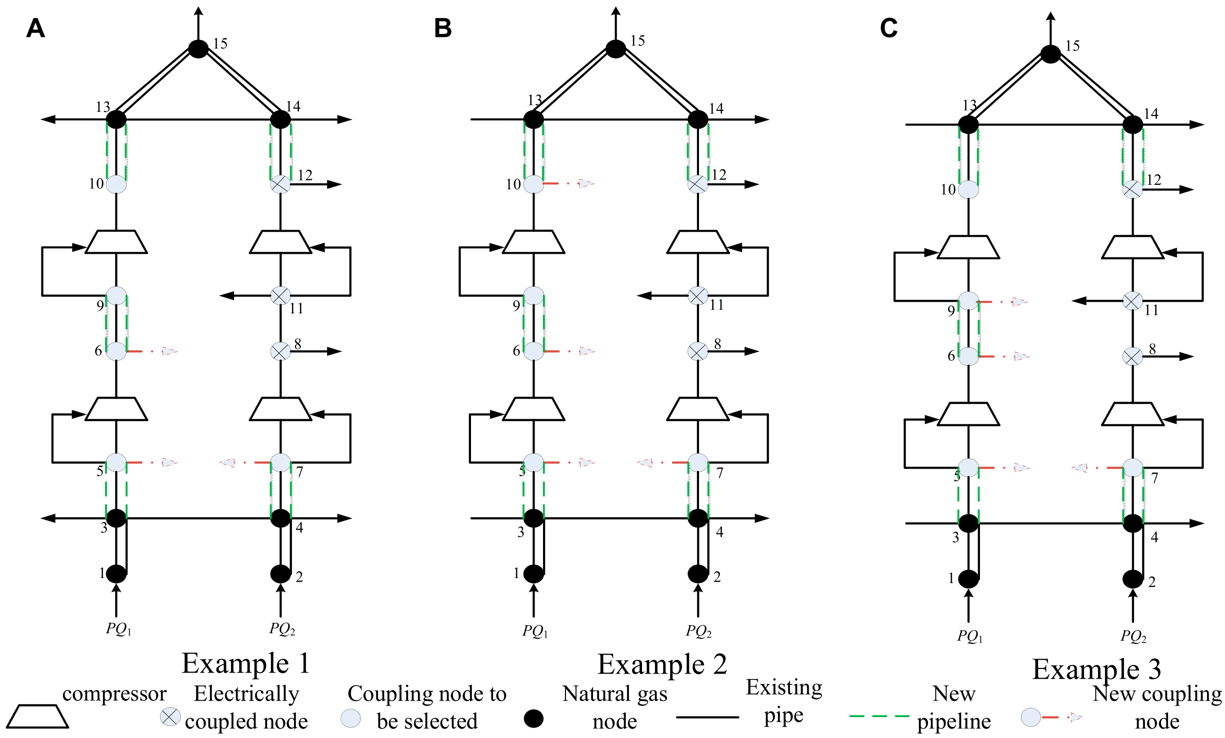

FIGURE 4
Natural gas network simulation planning diagram **(A–C)**.

The operation cost and pollution treatment cost of CU increased by 1.855×10^8 and 9.48×10^7 yuan, respectively. This is because, in scenario 2, utilizing the multi-agent game, the generation company optimizes the new GU set, that is, the investment of one GU is reduced, and the investment cost is reduced by 1.244×10^7 yuan. In addition, in case 2, the transmission grid provider reduces one line on the GU side in the planning, resulting in the power generation load of some power generators being dispersed from the GU to CU side, which leads to the continuous increase in the CU output, the increase in its operation cost, and the increase in pollution treatment cost. At the same time, the cost of GU operation and pollution treatment is reduced because the GU supply is diverted. Compared with Example 2, the gas purchase cost, GU operation cost, and pollution treatment cost in Example 3 increased by 9.230×10^7, 0.821×10^7, and 0.780×10^7 yuan, respectively. The operation cost and pollution treatment cost of

TABLE 7 Costs and benefits of power producers.

	An example	1	2	3
Income	Total income	5.030×10^9	5.030×10^9	5.283×10^9
Cost	GU investment	9.998×10^7	8.754×10^7	8.754×10^7
	Gas purchase	7.102×10^8	4.657×10^8	5.580×10^8
	GU operation	5.472×10^7	3.105×10^7	3.926×10^7
	CU operation	3.970×10^8	5.825×10^8	6.252×10^8
	GU pollution treatment	5.683×10^7	3.725×10^7	4.505×10^7
	CU contamination treatment	1.600×10^8	2.548×10^8	2.858×10^8

TABLE 8 Costs and benefits of transmission grid operators.

	An example	1	2	3
Income	Total income	6.456×10^9	6.456×10^9	6.745×10^9
Cost	Network loss	2.572×10^8	2.471×10^8	2.512×10^8
	Investment	1.980×10^7	1.928×10^7	1.928×10^7
	Purchase of electricity	5.030×10^9	5.030×10^9	5.301×10^9

TABLE 9 Costs and benefits of a natural gas company.

	An example	1	2	3
Income	Total income	2.697×10^9	2.625×10^9	2.165×10^9
Cost	Run	1.518×10^9	1.488×10^9	1.103×10^9
	Investment	9.474×10^7	9.474×10^7	9.474×10^7

CU increased by 0.427×10^7 and 3.100×10^7 yuan, respectively. The reasons are as follows: according to the analysis results of the comprehensive energy consumption behavior of users, the utility function of the electricity load is greater than that of the gas load, and users will prefer to use electricity load when making energy consumption decisions. Therefore, the income of power generators will increase, and the corresponding cost will increase.

Table 8 reveals that, in contrast to Example 1, the network loss cost and line investment cost of Example 2 are reduced by 1.01×10^7 and 5.2×10^5 yuan, respectively. The reason is that in Example 2, based on the multi-agent game, the transmission network provider optimizes the set of new lines, and there is no line expansion in branches 23–20, resulting in some lines not required to be put into use, and the overall transmission distance of the line is reduced. It can be seen that the cost of these two items in Example 2 is relatively low. Compared with Example 2, the network loss cost of Example 3 will increase due to the large electrical load.

Table 9 illustrates that concerning the natural gas network, compared with Example 1, the investment cost of Example 2 is unchanged, and the total revenue and operation cost are reduced by 7.2×10^7 and 3×10^7 yuan, respectively. The reason is that Example 2 is based on the multi-agent game because the investment of one GU is reduced, the resulting lower operating cost of GU directly weakens the demand for natural gas, and the supply of natural gas will also decrease, so the operating cost of the gas source also shows a slight fluctuation and downward trend. Conversely, the total revenue of natural gas operators is reduced by reducing the new construction of GU, resulting in higher operation and pollution treatment costs of power generators. For Example 2, the operation cost of natural gas is 1.457×10^9 and 9.055×10^8 yuan higher than that of GU and CU, respectively. The reason is that the gas price is higher than the coal price, and based on the analysis of the above factors such as the cost change on the generator side, the natural gas operation cost is the highest among the three parties. However, the natural gas operator has not changed its investment strategy, so the investment cost remains unchanged. Compared with Example 2, the gas load in Example 3 is relatively small. Although the amount of gas purchased by power generators increases, the amount of natural gas directly used by users as energy decreases, which ultimately leads to the decrease in the total revenue of natural gas companies. The corresponding operating costs are also reduced.

It can be seen from Table 10 that, compared with Example 1, in Example 2, the revenue of the power generator and the transmission grid provider increases by 2×10^7 and 1.1×10^7 yuan, respectively, and the revenue of the natural gas operator decreases by 4.2×10^7 yuan, resulting in the total revenue of the electricity–gas planning decreasing to 1.1×10^7 yuan. The reason is that from the perspective of overall rationality, the final planning scheme is directly obtained through the unified decision-making of the three main bodies. Although its overall economy is relatively high, it deviates from the current IES market reform mechanism and market vitality at the cost of weakening the profits of transmission grid operators and natural gas operators. On the contrary, the dynamic game process based on the real-time interaction of tripartite decision-making information takes into account the individual rational behavior and ensures the rationality of the decision-making scheme while taking into account the interests of the three main bodies in the market, thus enhancing the vitality of the energy market. Compared with Example 2, in Example 3, the revenue of power generators and transmission grid increases by 7.115×10^7 and 1.352×10^7 yuan, respectively, while the revenue of natural gas operators decreases by 7.474×10^7 yuan, which ultimately leads to an increase in 9.89×10^6 yuan in the total revenue of electricity–gas planning. The reason is that, on the basis of planning and decision-making from the perspective of individual rationality in Example 2, Example 3 considers the comprehensive energy consumption behavior of users and allocates more resources to the electricity load with a larger proportion of energy consumption, which leads to the increase in the revenue of power generators and transmission grid operators and the decrease in the revenue of natural gas operators. The approach in this study considers the concerns of every market participant while enhancing the overall revenue.

TABLE 10 Total revenue of the three parties.

	An example	1	2	3
Income	Total income	1.418×10^{10}	1.411×10^{10}	1.419×10^{10}
Cost	Total cost	8.399×10^{9}	8.338×10^{9}	8.410×10^{9}
Earnings	Total revenue	5.784×10^{9}	5.773×10^{9}	5.782×10^{9}
	Generator	3.551×10^{9}	3.571×10^{9}	3.672×10^{9}
	Power transmission network operator	1.149×10^{9}	1.160×10^{9}	1.174×10^{9}
	Natural gas operators	1.084×10^{9}	1.042×10^{9}	0.937×10^{9}

6 Conclusion

This paper introduces a multi-agent collaborative planning approach for an integrated electricity–gas energy system utilizing game theory in the context of integrated user energy consumption. First, the model depicting characteristics in users' energy consumption is constructed, and an analysis of users' overall energy usage patterns is conducted through the application of evolutionary game theory. On this basis, the game relationship between different investment agents is fully considered, and a dynamic game model of electricity–gas multi-agent planning considering comprehensive energy consumption behavior is proposed. Ultimately, the model is resolved through an iterative search technique. The simulation example yields the following conclusions:

(1) In contrast to conventional approaches, this study takes into account users' holistic energy usage patterns, enhancing the efficacy of the multi-agent planning scheme for electricity and gas.
(2) This paper plans from the overall point of view of the integrated energy system combining electricity and gas, and the planning scheme increases the total income of the electricity–gas integrated energy system on the whole.
(3) In the planning of this paper, the game behavior of each investor is fully considered, and the interests of all market participants are taken into account, which not only conforms to the market operation mechanism but also effectively guarantees the market vitality.

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

WL: writing–original draft. BZ: writing–review and editing. MO: writing–original draft. WZ: writing–review and editing. GH: writing–original draft and writing–review and editing. TM: writing–review and editing.

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Conflict of interest

Authors WL, MO, and GH 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.

Publisher's note

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