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Real-time Optimal Dispatching of Electricity-Gas Joint Coordination Considering Integrated Energy Interconnection

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ABSTRACT

In the Energy Internet, users no longer have a single demand response for electricity, but an integrated demand response for multiple types of energy. In integrated demand response, users participate in demand response directly by switching energy sources without having to change their energy usage time habits. A mathematical model of the electricity-heat-gas energy circuit, based on the correlation between different energy sources, considering the combined demand response economy and comfort of the household user. Real-time dispatch optimization modeling with the objective of real-time peak shaving within a day and tariff regulation as a means to provide a decision basis for real-time peak shaving and smoothing of the electricity load curve. An example is given to verify the effectiveness of the model and the feasibility of the solution method, at the peak of electricity consumption around 8 p.m., through real-time dispatching, the peak electricity load decreases by about 2 kWh, and the gas consumption increases slightly. And the economic basis of integrated demand response scheme decision-making is analyzed.

1. INTRODUCTION

In recent years, with the development of society and economy, people's demand for energy is more and more large, and the requirement for living standard is also higher and higher. Along with the development and improvement of new energy and energy internet [1] technology, there are also many difficulties and contradictions to be solved. On the energy supply side, due to the randomness of wind and solar energy, the absorption of new energy needs to be improved. In the application of integrated energy units, some constraints face challenges. In energy storage, Large-scale storage of electrical energy is difficult. Heat and natural gas, although easy to store, also face the difficulty of energy conversion. In this context, the demand for energy for people is diverse, and there is a spatial and temporal complementarity of the various types of energy in the various aspects of source, load and storage in time and space. Therefore, in recent years, the country has actively promoted the integrated energy system, expecting to solve the environment, new energy consumption, the balance of source-load and many other problems. The related research on the application of integrated energy is also actively carried out. In response to the above research questions, this paper is conducted in the context of the energy internet.

The integrated energy system is the physical basis for the practical application of energy interconnection, focusing on the complementary coupling of various energy types [1]. In the operation of integrated energy system, one of the research problems is the optimal dispatching of multiple types of energy existing and running at the same time [2], [3]. For example, study the power flow calculation and energy flow calculation of the integrated energy system [4], [5]. Another problem that has been widely studied is the supply-side coupling of multi-type energy and the conversion of multi-energy transmission channels. The cogeneration unit on the supply side is considered in reference [6]. The promotion of wind power consumption on the supply side is considered in reference [7]. The thermal and storage characteristics of the pipeline in the intermediate transmission process are considered in reference [8]. In summary, integrated energy involves the coupling and complementarity of many types of energy, resulting in whether it is energy flow calculation or joint optimization of multiple energy sources; whether it is considered from the region or from the power station, it is more complex and diverse for each component. Research in integrated energy demand [9], [10] has a more complex diversity as it involves users. In order to solve the problem of demand response under combined operation of integrated energy sources, this paper starts with the study of demand response of integrated energy sources.

The demand response of integrated energy is the

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demand side part of the integrated energy system. At present, there are different studies on the response of integrated energy demand for different engineering objects. In some literatures, the integrated energy demand response is considered in the intelligent community and the industrial park, the independent heat source in the park is considered respectively, and the coupling of heat and power and the flexibility of the equipment in the park are considered for optimization analysis [11-14]. It is also studied from the economic point of view of the energy market. The integrated demand response model is studied from the bidding strategy of energy joint market in reference [15], [16]. The joint demand response of energy hub and photothermal power station is optimized and analyzed in reference [17], [18]. In addition, the combination of energy storage system and photovoltaic wind power has also been studied in some literature [19], [20] and other energy sources combined with photovoltaic wind power [21], [22].

In the study of integrated energy demand response, is rarely combined with smoothing power load curve, peak cutting and valley filling. In the previous traditional research on power demand response, the most common research is to cut the peak and fill the valley of power load through the response of power demand side from the electric energy, which is a single energy. That is, by means of time-sharing electricity tariffs [23], [24], a temporal leveling of the electricity load occurs so that the temporal curve of the electricity load tends to level off [25]-[27]. This approach influences the energy consumption habits of users. Because there is no coordinated operation of many types of energy in the traditional energy market, there is no research on smoothing power load through energy conversion. In this paper, the consideration of the integrated energy demand response is that users can no longer use a single increase or decrease in the use of electricity to cooperate with the response, but can integrated response by changing energy types. In this way, we can not only achieve the purpose of cutting the peak and filling the valley of power load, but also have little impact on the convenience and comfort of users. Household users are not only the end-users of the energy load, but also a very large group of users in the energy sector, which is related to social peace and people's peace and contentment. Therefore, in this paper, from the study of the energy consumption characteristics of the household user cluster, considering the most basic needs of the household users, the mathematical model of the energy cost is established[28-30], and the general comfort model reflecting the household users is established. carry on the household integrated energy demand response optimization analysis, so as to achieve the purpose of power peak cutting. Through the research, the response relationship between temporary peak cutting and electricity price in the integrated energy coupling environment of household users is analyzed, which provides technical support for the follow-up power real-time peak cutting decision.

2. HOUSEHOLD INTEGRATED ENERGY DEMAND RESPONSE IN INTEGRATED ENERGY SYSTEM

Integrated energy demand response, although starting from the research on the demand side, the purpose of the research is still mostly for the economic cost and new energy consumption. The research of this paper is that the goal of household users is to reduce the integrated energy cost and keep the comfort, and the power supply company aims at the real-time peak reduction of power load. Firstly, considering the actual characteristics of energy use of most ordinary household users, the mathematical description of various energy forms of the integrated energy system shown in Figure 1 is constructed into the mathematical model of energy supply and use of household users. At present, no matter what type of integrated energy system is transmitted to the household load side, there are three types of energy: electric energy, thermal energy and natural gas. They all have mature household access pipes. P^{in}, G^{in}, H^{in} are the entrance of energy circuit. They represent electricity, natural gas and heat in turn. When it is expressed as the energy utility of household users, it is ultimately the utility of electric energy and thermal energy. P^{out}, H^{out} are the terminal energy forms. It means that there are two kinds of energy for household use: electric energy and thermal energy. According to energy conversion and conservation, energy conversion for households can be expressed as:

$$\begin{bmatrix} \gamma_{pp}\eta_{pp} & \gamma_{gp}\alpha_{gp}\eta_{gp} & \gamma_{hp}\alpha_{hp}\eta_{hp} \\ (1-\gamma_{pp})\alpha_{ph}\eta_{ph} & (1-\gamma_{gp})\alpha_{gh}\eta_{gp} & (1-\gamma_{hp})\eta_{hh} \end{bmatrix} \begin{bmatrix} P^{in} \\ G^{in} \\ H^{in} \end{bmatrix} = \begin{bmatrix} P^{out} \\ H^{out} \end{bmatrix} \quad (1)$$

In the Equation 1: γ is the conversion ratio coefficient of energy quantity, values are 0～1. γ_{pp} , γ_{gp} and γ_{hp} represent the proportion of electricity to electricity, heat to electricity and gas to electricity quantities respectively. For example, $1-\gamma_{pp}$ indicates that part of the input electric energy is converted into heat energy for use; α is the energy conversion efficiency coefficient, α_{ph}, α_{gp} and α_{hp} represent the energy conversion efficiency of electricity to heat, heat to electricity and gas to electricity respectively . For example how many joules of thermal energy can be converted into 1kW• h of electrical energy. η is the energy conversion loss coefficient, η_{pp} , η_{gp} and η_{hp} represent the conversion loss coefficients for electricity to electricity, heat to electricity and gas to electricity respectively. For example, the conversion efficiency of electrical energy to heat energy is generally only 80 percent.

The northern regions in China are all centrally heated and are not considered in this paper. In the south, there is very little central heating, so there is no direct heat input. The energy road entrance is neatly divided into two groups, the power grid and the natural gas pipeline. The household energy load is still the electric load and the heat load. At present, there is no gas-to-electricity or heat-to-electricity device in households, so Equation 1 is expressed as Equation 2:

$$\begin{bmatrix} \gamma_{pp} & 0 \\ (1-\gamma_{pp})\alpha_{ph} & \alpha_{gh} \end{bmatrix} \begin{bmatrix} P^{in} \\ G^{in} \end{bmatrix} = \begin{bmatrix} P^{out} \\ H^{out} \end{bmatrix} \qquad (2)$$

The above mathematical model is shown in Figure 1. In the frame is the coupling relation of electricity - heat - gas. The conversion relationship of the hardware unit is expressed in terms of the conversion ratio, efficiency and losses of the energy conversion.

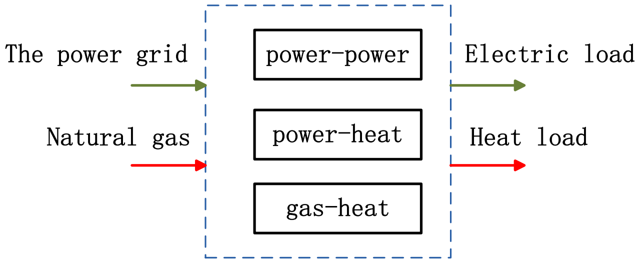

Fig. 1. Integrated household energy supply and demand chart.

3. MATHEMATICAL MODELING OF HOUSEHOLD INTEGRATED ENERGY DEMAND RESPONSE

In this paper, in the response of household integrated energy demand, the power supply department achieves the goal of electric peak reduction by issuing the instruction of time price temporarily. In this study, under the condition that the total energy cost and comfort level of the family users remain unchanged, the response can be achieved by adjusting the energy use type during the period.

Considering that household users are in the integrated energy response, the total cost of household energy expenditure cannot be increased or even reduced, otherwise household users will not respond to the instructions of relevant energy departments.

The total operating cost is:

$$F = F_1 + F_2 \qquad (3)$$

F_1: Cost of electricity; F_2:Gas cost.

Before the energy sector's response programme, the household energy cost was expressed as:

$$F_q = F_{q1} + F_{q2} = WJ + VK = \sum_{t=1}^{24} P_{t\_q} tJ + \sum_{t=1}^{24} Q_{t\_q} tK \qquad (4)$$

F_q :household energy costs before demand response implementation; F_{q1}:power cost before demand response implementation; F_{q2} :Natural gas cost before implementing demand response; W :electricity consumption, per kilowatt hour; J:electricity price, unit yuan per kilowatt hour; V :the volume of natural gas, in cubic meters; K :natural gas price, CNY/M^3; P :power consumption, unit KW; Q :Hourly gas consumption; t:time, 24 hours in a day.

After the response programme from the energy sector, household energy costs are expressed as Equation 5, where the tariff j_t includes the tariff for peak-shaving periods:

$$F_h = F_{h1} + F_{h2} = \sum_{t=1}^{24} P_{t\_h} tj_t + \sum_{t=1}^{24} Q_{t\_h} tk \qquad (5)$$

The premise for home users to be able to respond to demand is that the energy cost should not exceed the energy cost before the response, otherwise the responsiveness of home users is very low. Therefore, the objective function is changed to the constraint condition as Equation 6:

$$F_q \geq F_h \qquad (6)$$

Family comfort is the subjective feeling of family life, which is influenced by the external environment and subjective consciousness of oneself. The International Standards Organization (ISO) proposed the ISO 7730 thermal comfort model [12].

$$I = aT + bY + c \qquad (7)$$

In Equation 7, T is temperature, Y is humidity, a, b and c are all parameters. To apply the above model, it is necessary to investigate people of different ages, so as to fit the three parameters a, b and c, and get a suitable model. That is to say, although the above model is universal, it can only be applied after adjusting the parameters for different objects. In order to solve this problem, a general comfort model is proposed, which uses thermal energy consumption to replace ambient temperature and humidity. That is, the thermal energy consumption is constant, and the comfort level is considered to have no significant change. This can be adapted to different ages, since the model is based on a before-and-after comparison of the amount of heat consumed by people of the same age. Therefore, the mathematical description of the second constraint condition is as follows:

$$\sum_{1}^{24} P_{t\_q\_r} t\mu_1 + \sum_{1}^{24} Q_{t\_q} t\mu_2 \leq \sum_{t=1}^{24} P_{t\_h\_r} t\mu_1 + \sum_{1}^{24} Q_{t\_h} t\mu_2 \qquad (8)$$

Home heat comes from two sources, one from the conversion of electricity and the other from the combustion of natural gas. $P_{t\_q\_r}$: the portion of electrical power that is converted to heat before a demand response; μ_1:the conversion of electrical energy to thermal energy is efficient; μ_2 :gas to thermal efficiency; $P_{t\_h\_r}$:the portion of electrical power that is converted to thermal energy after a demand response.

The natural gas pipeline has storage characteristics, natural gas has the characteristics of immediately storage without use, and natural gas does not respond as quickly as electricity. Therefore, natural gas price is not suitable as a temporary incentive means. Thermal energy has strong thermal inertia, so the decision goal for household energy demand response in electricity load as far as possible close to the temporary electricity peak clipping goal, namely the demand response after temporary cut peak electricity usage is close to target the ideal electricity usage, achieve complete response, can make the energy Internet [1] in the network to achieve a better balance between supply and demand. The mathematical expression of the objective function is as follows:

$$\min \left| \sum_{t=1}^{t_0} P_{t\_h} t - (1-\beta) \sum_{t=1}^{t_0} P_{t\_q} t) \right| \quad (3)$$

β: peak clipping target, calculated as a percentage; $0 \sim t_0$ is the temporary peak clipping period.

4. MATHEMATICAL MODEL SOLUTION

According to the established objective function and constraint conditions, linear programming simplex method is used to optimize the solution. The decision variable is the peak-shaving power price, that is, what peak-shaving price should be used to achieve the optimal peak-shaving goal. In the process of solving the above mathematical model, the iterative local optimal solution does not conform to the practical logic, and the electricity price is negative, or the gas consumption of natural gas is negative. However, in this method, the electricity subsidy policy of the power supply company is not considered, only the electricity price is considered as the incentive. And in the average household, there is no biogas digester. Therefore, the boundary conditions are added to make the local optimal solution within the appropriate interval.

$$b.c. \begin{Bmatrix} Q_{t\_h} \geq 0 \\ j_t \geq J \\ 0 \leq P_{t\_h\_r} \leq P_{t\_q\_r} \\ 0 \leq P_{t\_q\_r} \leq P_{t\_q} \end{Bmatrix} \quad (10)$$

We can get the price adjustment range:

$$\rho = \frac{j_t}{J} - 1 \quad (11)$$

Thus, the response value of price range and peak shaving range is obtained, that is, the price range to be adjusted when the peak shaving target is different in percentage.

$$\varepsilon = \frac{\rho}{\beta} \quad (12)$$

Analysis response under different peak clipping the target value, obtain the behavior of the users in response to different extent, later also can according to domestic users integrated energy load historical data, for different season time based on the analysis of demand response behavior, research in peak clipping the goal and the stereoscopic trend curve of time, home users to better research group in the response behavior of integrated demand response characteristics.

5. ILLUSTRATION OF CALCULATION EXAMPES

According to the mathematical model of household integrated energy demand response described above, YALMIP under the Matlab simulation platform was used to establish the model and solve it. Daily household integrated energy load curve is taken as the initial simulation data, as shown in Figure 2 below.

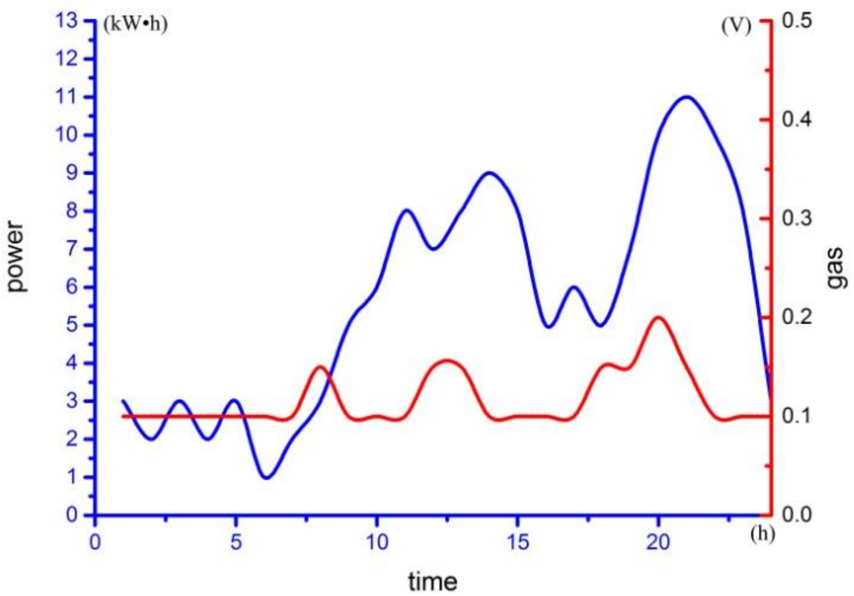

Fig. 2. Daily consumption of household electricity and gas.

Data can be extracted according to the diagram, and basic data of household time-share electricity and time-share gas consumption before demand response can be set, as well as the ratio of electric energy to thermal energy. According to the general household electricity price is set at \$0.08/kWh, gas price is set at \$0.42/m^3. It can be seen from the figure that the maximum peak of electric energy and natural gas use occurs around 8 p.m.. For natural gas, the natural gas pipeline has storage characteristics, and the response is slightly slow, and there is no need for real-time supply and demand balance and immediate peak cutting requirements. On the other hand, electric energy needs real-time balance of supply and demand, and the storage capacity of electric energy is small, so it needs users' demand response to achieve the real-time peak reduction of electric energy. The maximum peak-clipping demand of electric energy is in this period, so this period is taken as the scene for calculation and analysis.

In the program, the basic data matrix of electricity price and gas price is established according to 24 hours. The electricity-gas joint function relationship is established according to the constraint conditions and objective function described above. In turn, the power peak reduction target of the target period is set to 10% Murray 40%, and the corresponding electricity value is calculated respectively. In other words, in order to achieve the peak reduction target, electricity prices need to be adjusted before users will respond.

5.1 Response Performance Analysis

The real-time peak cutting dispatching price of the power supply company must be adjusted to a certain value before the household users will respond, so as to meet the peak cutting demand of the power supply department. And the larger the power peak reduction target, the greater the electricity price adjustment, so that more users will participate in the response, so as to achieve the power peak reduction target. As shown in Figure 4, the solid blue line is the power load before the response, the dotted blue line is the power load after the response, the solid red line is the gas consumption before the response, and the dotted red line is the gas consumption after the response. During the time period around 8 p.m., the power load is at its peak and the pressure on the grid capacity is high. If the dispatch instructions for the peak period of power load reduction of 10%, through the aforementioned mathematical model and objective optimisation methodology, the price of electricity needs to be calculated from the base price of \$0.08/kWh, up 5.5% to \$0.09/kWh, some users will respond to real-time dispatch instructions to reduce the use of electricity in that time, so as to achieve the goal of 10% peak power shaving. At this time, the gas consumption of household users increases, converting part of the channels that would have been heated from electricity to heat by gas, and the gas consumption increases in that time period, from 0.2m^3 to 0.22m^3, to meet the requirements of household comfort. The simulation results verify the validity of the mathematical model established in the previous section for real-time peak shaving dispatch of electricity through integrated demand response. Peak shaving is transformed from the traditional single electric energy time response, which changes the time use habits of electric energy to achieve the desired goal, to achieving the goal of integrated demand response through the conversion of the use of multiple energy types.

The peak-clipping around 8 p.m. was successively designated as 20%, 30% and 40%. The 40% peak-clipping was close to the average load of the whole day, and further reduction might have peak-valley inversion. To achieve the above peak shaving requirement dispatch instruction target, the real-time tariff strategy should be adjusted to \$0.09/kWh, \$0.10/kWh, and \$0.11/kWh, respectively, in order to have more household users responding to the real-time dispatch programme, thus achieving the real-time peak shaving scheduling requirement of the power supply sector. At this time, the price of electricity increases by 11.4%, 18.7% and 28.5%, respectively. Equations are used to calculate load price response values, as shown in Table 1.

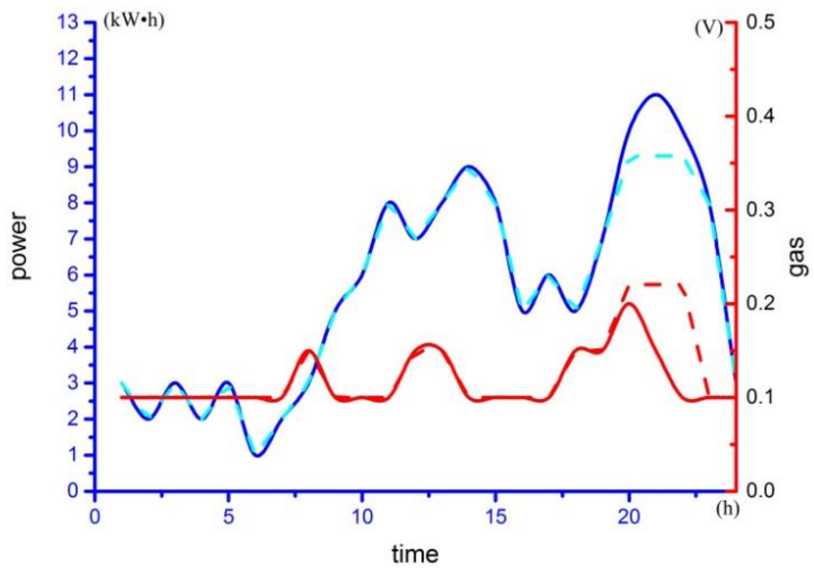

Fig. 3. Integrated use of energy after household integrated energy demand response.

Table 1. Peak reduction price ratio table.

Peak clipping target	Electricity prices ($)	Electricity price adjustment range	Response values
0	0.08	0	0
10%	0.09	5.5%	0.55
20%	0.09	11.4%	0.57
30%	0.10	18.7%	0.62
40%	0.11	28.5%	0.71

It can be seen that the higher the demand for peak clipping is, the higher the price is required to rise, and the response value is not unchanged, but increases in direct proportion. It proves that if we want to change the daily electricity and gas habits of household residents, we need to change much, and pay more and more. Peak shaving targets and tariffs will not be so high as to cause a shift from peak to trough, to the detriment of smoothing the electricity load curve.

5.2 Response to Economic Analysis

Discusses the economic revenues and expenditures of the electric sector, natural gas companies, and household customers prior to real-time dispatch, and for different dispatch peak shaving targets. The economic revenues and expenditures for a single day without real-time dispatch, with a 10% real-time dispatch peak shaving target, with a 20% real-time dispatch peak shaving target, with a 30% real-time dispatch peak shaving target and with a 40% real-time dispatch peak shaving target, respectively, are shown in Table 2.

The economic income and expenditure curve is shown in Figure 4. The higher the peaking target of the power company, the more profits it will yield. In order to meet the response value of the household users, the household energy expenditure will be reduced. In other words, the profits from the power company are divided between the gas company and the home user.

Table 2. The economics of the parties involved in the demand response.

Peak clipping target	0	10%	20%	30%	40%
The power sector ($)	11.33	11.2	11.05	10.89	10.72
Natural gas company ($)	1.17	1.26	1.38	1.51	1.64
Home users ($)	12.5	12.46	12.42	12.39	12.37

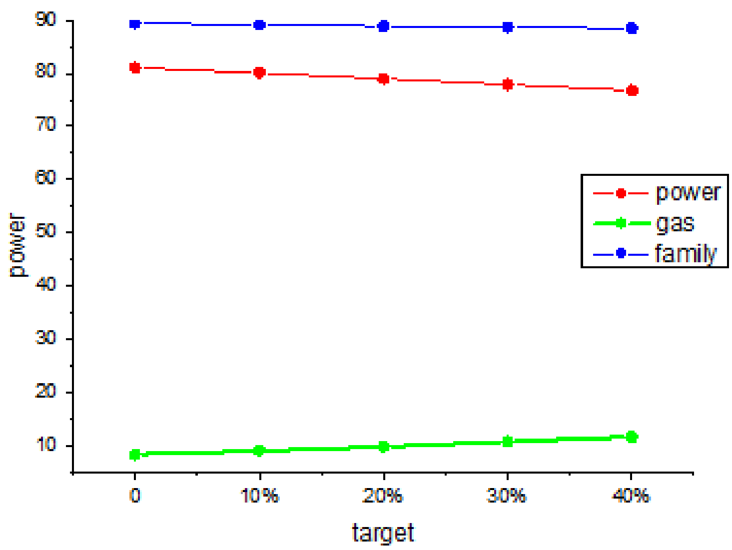

Fig. 4. Supply and demand side economic balance.

As shown in Table 2 and Figure 4, natural gas companies profits increase, while household users on the demand side benefit. Under the condition that their comfort level is guaranteed, the integrated energy consumption costs are reduced, but the profits of electric power companies decline and do not benefit. The smooth development of integrated demand response requires the benefit of all parties. If the supply side does not benefit, the response plan will not be put forward, nor will the peak clipping instruction be given. If the demand side does not benefit, the peak clipping plan will not respond to the supply side. The utility sector also benefits when considering the installation and operating costs of its spare capacity. For example, if a thermal unit is used as a standby, even if only the construction cost of the installed capacity is taken into account, it is roughly equivalent to $419.57 for 1kW of power for 10 years of operation. When the peak shaving target is 10%, the peak load drops from 11kW to 9.3kW, reducing the standby capacity by 1.7kW, and the integrated demand response group is set to be 1,000 households, which reduces the standby capacity by 1,700kW, totaling $0.71 million. In the integrated demand response programme, the power sector single day single household concessions for $0.13, then 10 years 1000 households total concessions $0.48 million. The actual benefit of implementing integrated demand response in the power sector is more than $0.14 million.

6. CONCLUSION

In order to give full consideration to the application of integrated energy demand response under the integrated energy system, the traditional means of time-sharing tariffs to achieve peak shaving targets through the time transfer of power loads is transformed into real-time intraday peak shaving targets through the change of the use of energy types, which is able to not change the user's time habits of energy consumption without affecting the user's living comfort. The main conclusions are as follows.

1) Considering the integrated energy-use characteristics of households, an integrated household energy demand response model is established. Based on the law of conversion and conservation of energy, the mathematical relationship between the type of entry and exit of integrated household energy use and the conversion coupling is fully and clearly reflected.
2) On the basis of the household integrated energy demand response model, the power supply company further establishes the mathematical model of household integrated energy use with the goal of minimising the difference between the actual value and the expected value in real-time power load shaving dispatch, and the user with the goal of minimising the cost of integrated energy use. The feasibility of the application of the household integrated demand response mathematical model in real-time peak shaving dispatching is verified through the analysis of examples. When the power supply company raises the price of electricity during the peak load shaving time, some users will respond to the real-time dispatching scheme of the power supply company by using less electricity and switching to natural gas in order to reduce the cost of energy consumption. The power supply company achieves the goal of real-time peak load shaving, the customer reduces the overall energy cost, and the natural gas company increases its revenue, thus benefiting all parties.
3) Because the usual model of home comfort is more complicated in the calculation of energy and temperature conversion, and need to determine the coefficients of a specific population research, in order to establish a more accurate comfort formula for different populations. In this paper, we fuzzy express the user's comfort invariance by keeping the total integrated energy use of household users constant, and use this as the model constraints.

Based on the work in this paper, the follow-up work will further conduct in-depth research and analysis on the joint optimization of integrated energy demand response in horizontal shift of time and vertical conversion of energy types. Realize the complementarity of the integrated energy demand response in time and space.

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DECLARATION OF COMPETING INTEREST

We declare that we have no conflict of interest.

AUTHOR CONTRIBUTIONS STATEMENT

Wei Xiong: Thinking idea, method design; Xianshan Li: Theoretical guidance; Shiwei Su: Data analysis.

DATA AVAILABILITY STATEMENT

The data presented in this study are available on request from the corresponding author.

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