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OPTIMAL SCHEDULING OF MULTI-ENERGY HUB SYSTEMS WITH INCOMPLETE INFORMATION

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ABSTRACT

It is difficult to ensure the completeness of information obtained in the market competition, so the study of optimal scheduling of multi-energy hub systems with incomplete information plays an important role in the stability and economic operation of the system. However, the energy hubs in the multi-energy hub systems restricted each other, and the optimal modeling with integrated demand response was affected by user behavior and market information asymmetry. Therefore, in view of the competition among energy hubs under the dynamic electricity price mechanism, incomplete information game was adopted to solve the optimization scheduling problem of multi-energy hubs under the condition of incomplete information. According to the difference of the behavior characteristics of users participating in the comprehensive demand response, the interruptible load type participating in the demand response was modeled as discrete random variables by introducing the user load interruption willingness factor. Furthermore, a multi-energy hub systems optimal scheduling model with incomplete information demand response selection was established and its Bayesian Nash equilibrium was given. Then the examples were given to verify the validity of the model and the method. The results show that the comprehensive demand response and incomplete information have an important impact on the dispatching decision of multi energy hub system. When making decision, it is necessary to consider all kinds of situations that may be formed due to incomplete information.

Keywords: The multi-energy hub system; Incomplete information game; Economic dispatch; Integrated demand response; Bayesian Nash equilibrium

NONMENCLATURE

Abbreviations	
EH	Energy hub
CHP	Combined heat and power
AC	Absorption chiller
GB	Gas boiler
EES	Electrical energy storage
IDR	Integrated Demand Response
Symbols	
C	Cost, $
P	Power, MW
L	Load, MW

1. INTRODUCTION

The use of multi-energy system is a pioneer method for optimizing energy systems, which is widely regarded as an effective way to improve the efficiency of the entire energy system and provide more flexibility to accommodate renewable energy [1]. An energy hub (EH) is an infrastructure unit in multi energy systems, which different types of energy carries as inputs are converted to the other types of energy and may be stored [2]. At present, the matter of energy hub and its optimal scheduling is a famous, but challenging research subject. Domestic and foreign scholars have carried out detailed research on the modeling of energy hub [3] and its application in multi energy coordination optimization [1]. At present, the modeling of energy hub has considered various possible elements in the multi-energy system, such as various energy conversion equipment including combined heat and power (CHP), Gas boiler (GB) new energy access and integrated demand response (IDR) [4].

However, in the process of energy hub modeling, it is necessary to further analyze the uncertainty of its internal conversion, input and output. For example, the randomness of user behavior and the uncertainty of renewable energy will affect the operation of the system [5,6].

Generally, the integrated energy system is composed of several energy hubs. In order to study the multi energy system more precisely, researchers have been focusing on the interaction and mutual restriction between multiple energy hubs, and the optimal scheduling problem of multi-energy hub systems [7,8]. However, few studies have considered the impact of the completeness of information on optimal scheduling, especially in terms of demand response. Static game with incomplete information is expected to become a powerful tool to solve this problem.

Therefore, considering the uncertainty of wind power generation and the participation of multi energy comprehensive demand response, this paper extends the basic model of energy hub in multi energy hub systems. According to the characteristics of user behavior, the user load interruption willingness factor is introduced to represent the comprehensive demand response type, and a more suitable energy hub model is established. Aiming at the problem of incomplete demand response information, an optimal scheduling model of multi energy hub system based on static game of incomplete information is established.

2. THE OPTIMAL SCHEDULING MODEL OF THE MULTI-ENERGY HUB SYSTEM

The economic optimal operation model of multi energy hub system is divided into two parts: objective function and constraint conditions.

2.1 Constraint conditions

In the multi energy hub system, each energy hub can obtain continuous energy supply through large power grid and gas pipeline, and meet the energy demand of users through internal dispatching. Figure 2 shows the schematic diagram of the energy hub in the multi-energy hub system studied in this paper.

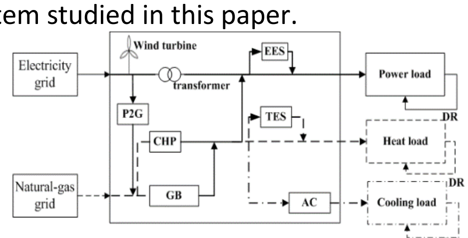

Fig 1 the energy hub in the multi-energy hub system

It includes CHP, AC, IDR, the transformer and uncertain wind power access. To ensure the economic and stable operation of the system, the power balance constraints of each energy hub are as follows:

$$\begin{cases} P_{grid,t}^{i}+P_{w,t}^{i}=P_{in,t}^{i} \\ \eta_{ee}P_{in,t}^{i}+P_{ees,dis,t}^{i}+\eta_{ge}P_{CHP,in,t}^{i}-P_{ees,ch,t}^{i}=L_{\mathrm{e,ori}}^{\mathrm{i}}(t)-L_{\mathrm{e,cur}}^{i}(t) \end{cases} \tag{1}$$

$$P_{gas,t}^{i}=P_{CHP,in,t}^{i}+P^{i}{}_{gb,t} \tag{2}$$

$$\begin{cases} \eta_{gh}P_{CHP,in,t}^{i}+\eta_{ghF}P^{i}{}_{gb,t}=L_{\mathrm{h,ori}}^{\mathrm{i}}(t)-L_{\mathrm{h,cur}}^{i}(t)+P^{i}{}_{AC,t} \\ \eta_{hc}P^{i}{}_{AC,t}=L_{\mathrm{c,ori}}^{\mathrm{i}}(t)-L_{\mathrm{c,cur}}^{i}(t) \end{cases} \tag{3}$$

In Equations (1)-(3), $P_{grid,t}^{i}$ and $P_{gas,t}^{i}$ are the electrical power purchased and the natural gas power purchased by energy hub i , respectively; $P_{w,t}^{i}$ is the predicted wind power output at time t; $P_{in,t}^{i}$ is the input power of the transformer at time t; $P_{ees,ch,t}^{i}$ and $P_{ees,dis,t}^{i}$ are the charging and discharging electricity powers of the EES; $P_{CHP,in,t}^{i}$ and $P_{gb,t}^{i}$ are the natural gas demands of the CHP unit and the GB unit; $P_{AC,t}^{i}$ is the heat power absorbed by the AC at time t; η_{ee} , η_{ge} , η_{gh} , η_{ghF} and η_{hc} are the conversion efficiency of the transformer, CHP, GB and AC respectively; $L_{\mathrm{e,ori}}^{\mathrm{i}}(t)$, $L_{\mathrm{h,ori}}^{\mathrm{i}}(t)$ and $L_{\mathrm{c,ori}}^{\mathrm{i}}(t)$ are the original electric, heat and cooling loads before participating in the comprehensive demand response, respectively. $L_{\mathrm{e,cur}}^{i}(t)$, $L_{\mathrm{h,cur}}^{i}(t)$ and $L_{\mathrm{c,cur}}^{i}(t)$ are the electric, heat and cold interruption loads at time t, respectively. IDR is only carried out in period $\mathrm{T_{cur}}$,and the interruption loads are no more than 5% of the fixed load of the period.

the models for EES was concluded as:

$$P_{ees,t}=P_{ees,t-1}+(\eta_{ees,ch}P_{ees,ch,t}^{i}-P_{ees,dis,t}^{i}/\eta_{ees,dis})\Delta t \tag{4}$$

Where, $P_{ees,t}$ are the energy stored in EES. $\eta_{ees,ch}$ and $\eta_{ees,dis}$ are the charging and discharging efficiency of EES. Δt is the running time,1h.

The minimum and maximum operation limit of each device of each energy hub are as follows:

$$P_{P2G,\min}\le P_{P2G,t}^{i}\le P_{P2G,\max} \tag{5}$$

$$G_{CHP,\min}\le G_{CHP,in,t}^{i}\le G_{CHP,\max} \tag{6}$$

$$G_{gb,\min}\le G^{i}{}_{gb,t}\le G_{gb,\max} \tag{7}$$

$$\begin{cases} P_{ees,ch}^{\min}\le P_{ees,ch,t}^{i}\le P_{ees,ch}^{\max} \\ P_{ees,dis}^{\min}\le P_{ees,dis,t}^{i}\le P_{ees,dis}^{\max} \\ P_{ees,dis}^{\min}\le P_{ees,dis,t}^{i}\le P_{ees,dis}^{\max} \end{cases} \tag{8}$$

Chance constrained programming can be used to solve the problem of uncertain wind power generation in the system. Meanwhile the system provides rotating reserve capacity to solve the problem that wind power prediction output is not equal to actual output.

Therefore, based on chance constrained programming, the expressions of reserve capacity constraints are listed as follows:

$$P_r\left\{r_t^u \geq W_t - W_{av,t}\right\} \geq \alpha_1 \tag{9}$$

$$P_r\left\{r_t^d \geq W_{av,t} - W_t\right\} \geq \alpha_2 \tag{10}$$

In Equations (9) and (10), α_1 , α_2 represent the confidence intervals for positive and negative spinning reserve to meet the requirements; $W_{av,t}$ represents the actual output of the wind turbine, W_t represents the predicted output of the wind turbine in t period; r_t^u and r_t^d are the positive spinning reserve capacity and the negative spinning reserve capacity provided by the system at period t, respectively.

According to the cumulative distribution function and inverse function of wind power output, the probabilistic constraint problem of spinning reserve capacity is transformed into a deterministic constraint.

$$W_t - r_t^u \leq \frac{cP_{w\max}}{v_{rate} - v_{in}}\left|\ln\left(\alpha_1 + \exp\left(-\frac{v_{out}^k}{c^k}\right)\right)\right|^{\frac{1}{k}} - \frac{v_{in}P_{w\max}}{v_{rate} - v_{in}} \tag{11}$$

$$r_t^d + W_t \geq \frac{cP_{w\max}}{v_{rate} - v_{in}}\left|\ln\left((1-\alpha_2) + \exp\left(-\frac{v_{out}^k}{c^k}\right)\right)\right|^{\frac{1}{k}} - \frac{v_{in}P_{w\max}}{v_{rate} - v_{in}} \tag{12}$$

In Equations (11)-(12), k and c represent the shape factor and scale factor of wind power generation, respectively. $P_{w\max}$ represents the rated power of the wind turbine; v_{in} , v_{out} and v_{rate} are the cut in speed, cut-off speed and rated speed of wind turbine respectively.

At the same time, the constraints of positive and negative spinning reserve capacity r_t^u and r_t^d are as follows:

$$\begin{cases} 0 \leq r_t^u \leq r_{up} + r_{bup} \\ 0 \leq r_t^d \leq r_{dw} + r_{bdw} \end{cases} \tag{13}$$

Where, r_{up} and r_{dw} represent the positive and negative spinning reserve capacity provided by the grid, respectively; r_{bup} and r_{bdw} represent the positive and negative rotating reserve capacity of the electric energy storage device respectively.

2.2 *Objective function*

Each energy hub adopts the dynamic electricity price mechanism. The electricity purchase cost of energy hub i is as follows:

$$\lambda(t) = a(P_{grid,t})^c + b \tag{14}$$

$$C_e^i(t) = \lambda(t)P_{grid,t}^i\Delta t \tag{15}$$

In Equations (14)-(15)， $P_{grid,t} = \sum_{i=1}^{N} P_{grid,t}^i$ is the total load power of the grid, *N* is the number of energy hubs in the multi-energy hub system. $\lambda(t)$ is the electricity price of system at period t; a , b and c are the price parameter.

The natural gas purchase cost of energy hub i is as follows:

$$C_g^i(t) = \lambda_g \cdot P_{gas,t}^i \tag{16}$$

Where, λ_g is the price of natural gas. The compensation cost of IDR of energy hub i is as follows:

$$C^i_{\mathrm{IDR}}(t) = (1\text{-}\sigma_i)\left[c_{\mathrm{e}}^{cur}L_{\mathrm{e,cur}}^i(t) + c_{\mathrm{h}}^{\mathrm{cur}}L_{\mathrm{h,cur}}^i(t) + c_{\mathrm{c}}^{\mathrm{cur}}L_{\mathrm{c,cur}}^i(t)\right]\Delta t \tag{17}$$

Where, σ_i is the load interruption willingness factor of user, c_{e}^{cur} , $c_{\mathrm{h}}^{\mathrm{cur}}$ and $c_{\mathrm{c}}^{\mathrm{cur}}$ are the cost coefficients of interruptible electrical power load, interruptible thermal load and interruptible cooling load, respectively. The cost of spinning reserve is as follows:

$$C_r^i(t) = k_d r_t^d + k_u r_t^u \tag{18}$$

k_d and k_u are the cost coefficient of negative spinning reserve and positive rotation reserve respectively.

Therefore, the total cost C^i of energy hub i is expressed as:

$$C^i = \sum_{t=1}^{T}(C_e^i(t) + C_g^i(t) + C_{IDR}^i(t) + C_r^i(t)) \tag{19}$$

Where, *T* is the total number of daily scheduling periods,24h.

From the formulas (14)-(19), it can be seen that the power purchase cost of energy hubs is related to the total power consumption of the system. Therefore, while pursuing their own minimum payment, each energy hub is affected and restricted by other hubs. And, due to the asymmetry of market information, energy hub can't know the willingness of load interruption of other energy hub users, which leads to incomplete IDR information in the system. Therefore, this paper uses incomplete information game optimization method to study the scheduling problem of multi energy hub system.

3. OPTIMAL SCHEDULING OF MULTI-ENERGY HUB SYSTEM BASED ON INCOMPLETE INFORMATION GAME

In the game, each energy hub has the knowledge of its type of IDR but could lack such information on other EHs. Hence, the competition among EHs is modeled here as an incomplete information game. It is necessary for a EH to model its opponents' unknown information into different types when the knowledge about its opponents is incomplete. A EH would model the partial information on its opponents as different types by providing the corresponding joint probability distribution of the game. where θ_i^t represents the type of EH i , θ_{-i}^t represents the type combination of all EHs except EH i . And Θ_{-i} is the set of all the type combinations θ_{-i}^t. Thus, establishing the multi-energy hub optimal scheduling model based on incomplete information game as follows:

(1) Participants are n energy hubs in the system: $N=\{n_1,\cdots,n_i,\cdots,n_N\}$

(2) Based on the joint probability distribution $\rho(\theta_i^t,\theta_{-i}^t)$, each energy hub infers the actual type probability of other energy hubs as $\rho(\theta_i^t\mid\theta_{-i}^t)$, that is, if the type of energy hub i is θ_i^t, the conditional probability that the type set of other energy hubs is θ_{-i}^t. It satisfies Bayes law:

$$\rho(\theta_i^t\mid\theta_{-i}^t)=\rho(\theta_i^t,\theta_{-i}^t)/\rho(\theta_i^t) \tag{20}$$

(3) Energy hub i develops a power purchase strategy $s_i^t\in S_i$ for type θ_i^t, S_i is the collection of each type of power purchase strategy of energy hub i. Then the game player's strategy combination Ω_i can be expressed as follows: $\Omega_i=\left(S_i,S_{-i}(\theta_{-i})\right)$, Among them, $S_{-i}(\theta_{-i})$ represents a collection of policies developed by the remaining participants for each of their possible types.

(4) According to the above analysis, When type of energy hub i is θ_i^t, the payoff function of energy hub i participating in the game is the minimum expected cost:

$$R^i(s_i^t,S_{-i}(\theta_{-i}),\theta_i)=\min\sum_{\theta_{-i}\in\Theta_{-i}}\rho(\theta_{-i}\mid\theta_i)C^i \tag{21}$$

For the static game with incomplete information, the iterative search method can be used to obtain the Bayesian equilibrium solution. The solving steps are as follows:

Step 1: Input load demand, precision ζ and parameter values, and define joint probability distribution $\rho(\theta_i^t,\theta_{-i}^t)$.

Step 2: Give the initial strategy values $s_1^t(k),\cdots,s_i^t(k),\cdots,s_n^t(k)$ for each possible type of each energy hub randomly in the feasible region.

Step 3: Taking energy hub i as the optimization object, The strategy under all types of other N-1 energy hubs is regarded as fixed value, we can solve the payment function formula (21) of energy hub i in the feasible region. Then the optimal strategy s_i^t for actual type of energy hub i is obtained, Let, $s_i^{t*}(k+1)=s_i^t$.

Step 4: Similar to step 3, the remaining energy hubs are taken as optimization objectives in turn.

Step 5: Calculate $\sum|s^*(k+1)-s^*(k)|$. If it is greater than the accuracy ζ, repeat steps 3 and 4. If it is less than, the optimal strategy of each type of energy hub under Bayesian equilibrium is obtained.

The solution flow chart is shown in Figure 2:

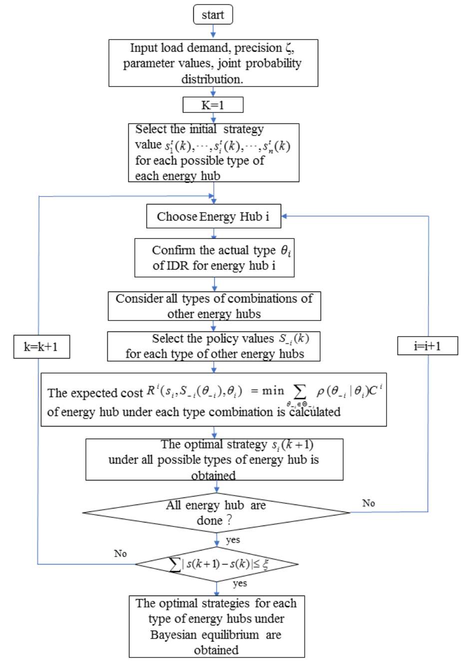

Fig2 Flow chart of incomplete information game solution

4. CASE STUDIES

The multi-energy hub system is composed of three hubs with the same structure as figure 1. The hub changes the distribution strategy of power and natural gas with the goal of minimizing its own energy cost, and is constrained by the power balance and the other two energy hub scheduling needs.

In this paper, the IDR participation period T_{cur} is t_6-t_{22}. The cost coefficient of each interruptible load is $c_e^{cur}=100$, $c_h^{cur}=71$, $c_c^{cur}=71$,\$/(MWh). Considering the difference of load interruption willingness factor σ_i of users, the IDR of each energy hub can be divided into two types. The σ_i is 0.3, which indicates that the IDR of energy hub is type 1. The σ_i is 0.65, which indicates that the IDR of energy hub is type 2. Suppose the joint probability distribution is shown in Table 1.

Table 1 Joint probability distribution of IDR types

		Combination of IDR types in EH 2 and 3			
	EH 1 IDR type	（1,1）	（1,2）	（2,1）	（2,2）
$\rho(\theta_i^t,\theta_{-i}^t)$	1	0.125	0.125	0.125	0.125
	2	0.125	0.125	0.125	0.125

The relevant parameters of each equipment of each energy hub are set to be the same, which are shown in Table 2.

Table 2 Related parameters of equipment in multi-energy hub systems

Equipment	Parameter	Value
Transformer	Transformer efficiency	0.98

EES	Initial state	120MWh
	Maximum state	600MWh
	Minimum state	120MWh
	Charging and discharging efficiency	0.9
	Upper limit of energy storage charging and discharging	120MWh
	Lower limit of energy storage charging and discharging	0
CHP	Capacity	250 MW
	Electrical efficiency	0.35
	thermal efficiency	0.45
GB	Capacity	600MW
	Efficiency	0.9
AC	Capacity	500MW
	Efficiency	0.95

The parameters of electricity price of multi energy hub system described in this paper are a=0.2、b=20、c=0, the price of natural gas is 0.31\$/m^3, the calorific value of natural gas is 9.7×10^{-3}(MWh)/m^3, The cost coefficients of positive and negative spinning reserve capacity are both 65\$/(MWh). The related parameters of uncertain distribution of wind power are shown in Table 3. The confidence level of positive and negative spinning reserve capacity is 0.95.

Table3 Related parameters of uncertain wind power

Parameter name	Value
shape factor *k*	2.4
Scale factor *c*	8.4
Rated speed of wind	12.5m/s
Cut-in speed of wind	4m/s
Cut-out of wind	20m/s
Rated power of wind turbine	15MW

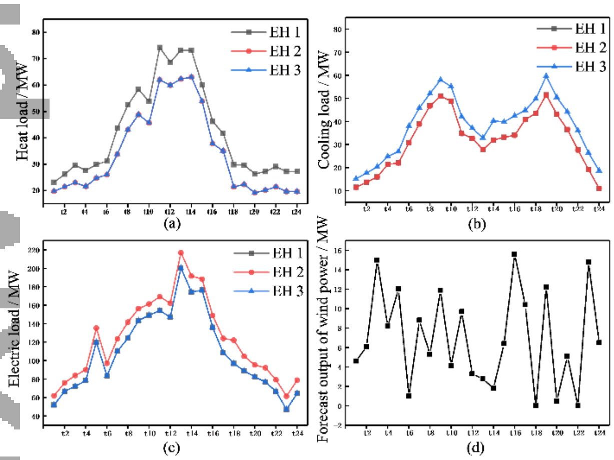

Fig3 variation curve of load and wind power: (a) heat load; (b) cooling load; (c) Electric load; (d) Forecast output of wind power

The electric load, heat load, cooling load and wind power prediction values of each energy hub within 24 hours [30] are shown in Figure 3.

According to the above data, based on incomplete information game and mixed integer nonlinear model solver, the optimal scheduling problem of multi energy hub considering incomplete information of IDR is solved. Table 4 show the Economic optimization results of incomplete information game in multi-energy hub systems.

Table 4 Expected cost under each type of energy hub

	type	Expected cost
Energy hub 1	1	218479.425
	2	215315.715
Energy hub 2	1	231234.217
	2	227978.581
Energy hub 3	1	217839.893
	2	214664.033

Assuming that the actual type combination of the multi energy hub system is (1,1,1), the optimal scheduling result of the multi energy hub system considering the incomplete information demand response type is shown in Figure 4-7. Among them, the actual cost of energy hub 1 is 218876.684 \$, the actual cost of energy hub 2 is 231738.894 \$, and the actual cost of energy hub 3 is 218260.251 \$.

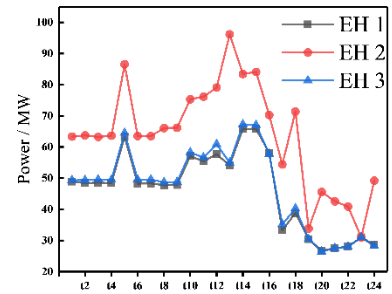

Fig 4 Input electricity of each energy hub

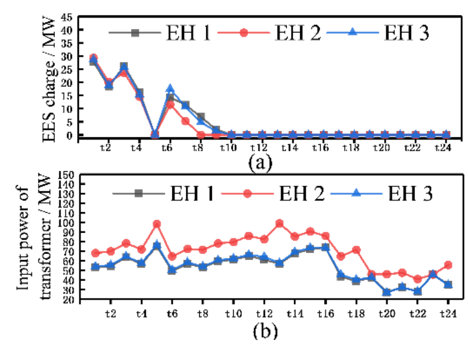

Fig 5 The distribution of Input electricity: (a) EES equipment inputs electricity every hour; (b) Power input of transformer per hour

It can be seen from the figure 4, 5 that the power injection volume of energy hub 2 is the largest, that of energy hub 3 is the second, and that of energy hub 1 is the smallest. Because the electrical load of energy hub 2 is greater than that of the other two energy hubs. And although the electrical loads of energy hubs 1 and 3 are the same, the thermal load of hub 1 is greater than that of hub 3. As a result, energy hub 1 transfers more natural gas to CHP for heating. Therefore, The CHP device of energy hub 1 generates more electricity than energy hub 3, so the power injection of energy hub 1 is less than that of energy hub 3. Each energy hub stores energy at the low load to reduce the peak valley difference of power demand.

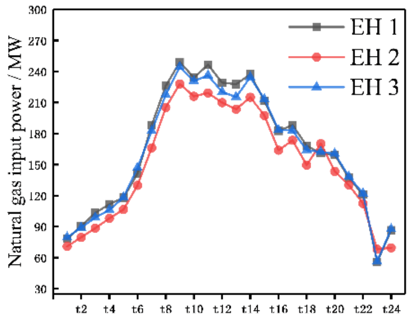

Fig 6 Input natural gas of each energy hub

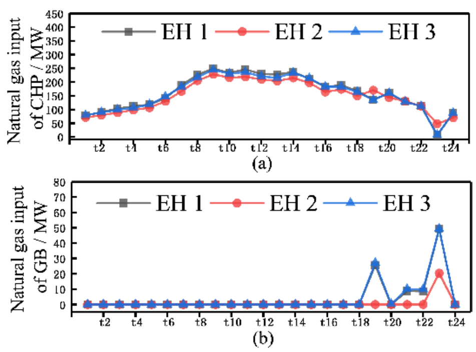

Fig 7 the distribution of natural gas; (a) CHP unit inputs natural gas per hour; (b) Natural gas input of GB

It can be seen from figure 6 that the natural gas injection rate is consistent with the heat load change trend, and the natural gas injection volume of energy hub 1 is the largest, that of energy hub 3 is the second, and that of energy hub 2 is the smallest. This is due to the largest heat load of energy hub 1, which requires more natural gas heat transfer to meet the heat load demand. Moreover, the cooling load demand of energy hub 3 is larger than that of energy hub 2, so natural gas is required to be converted into heat and then cooled to meet the cooling load demand. Therefore, the natural gas injection volume of energy hub 3 is large. It can be seen from Figure 7 that in order to make full use of the price advantage of natural gas, CHP units should be used as far as possible to meet the cold and hot demand. However, at night, when the heat load decreases, the cooling load increases and the output of GB unit increases, the economic optimization can be realized

5. CONCLUSIONS

Aiming at the optimal scheduling problem of multi energy hub system under incomplete information, an optimization model based on incomplete information game is established, which successfully solves the problems of serious coupling, interaction between hubs and incomplete information of IDR in multi-energy hub systems. After optimization, the power load demand in peak hours is greatly reduced, the peak valley difference of load demand is reduced, and the price advantage of natural gas is fully utilized. Meanwhile, the incomplete information of IDR also brings decision-making risk to each energy hub in the system. All kinds of possible situations formed by incomplete information are considered in the decision-making of each energy hub, which is conducive to maintaining the stable economic operation of the system.

REFERENCE

[1] Wang Y, Zhang N, Zhuo Z, et al. Mixed-integer linear programming-based optimal configuration planning for energy hub: Starting from scratch. Applied Energy, 2018: 1141-1150.

[2] Davatgaran V, Saniei M, Mortazavi S S, et al. Optimal bidding strategy for an energy hub in energy market. Energy, 2018: 482-493.

[3] Beigvand S D, Abdi H, La Scala M, et al. A general model for energy hub economic dispatch. Applied Energy, 2017: 1090-1111.

[4] Yuan Z, He S, Alizadeh A, Nojavan S, Jermsittiparsert K. Probabilistic scheduling of power-to-gas storage system in renewable energy hub integrated with demand response program. Elsevier Ltd,2020,29.

[5] Seyed M M, Morteza J, Soheil M, Scott K. Optimal operation of an energy hub considering the uncertainty associated with the power consumption of plug-in hybrid electric vehicles using information gap decision theory. International Journal of Electrical Power & Energy Systems, 2019,112,92-108.

[6] Thomas D, Deblecker O, Ioakimidis C S. Optimal operation of an energy management system for a grid-connected smart building considering photovoltaics' uncertainty and stochastic electric vehicles' driving schedule. Applied Energy, 2018, 210, 1188–1206.

[7] Yu H, Weiting Z, Kai Y, Weizhen H, Yiran H. An Optimal Scheduling Method for Multi-Energy Hub Systems Using Game Theory. Energies, 2019, 12, 2270.

[8] Sheikhi A, Rayati M, Bahrami S, et al. Integrated Demand Side Management Game in Smart Energy Hubs. IEEE Transactions on Smart Grid, 2015, 6(2): 675-683.