Optimal Operation of Micro Integrated Energy Systems Considering Electrical and Heat Load Classification and Scheduling

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***Abstract*—In this paper, we propose an optimal operation framework for energy hub based micro Integrated Energy Systems (micro-IES) considering multi-carrier load classification and scheduling. The electrical load is classified as shiftable load and important load, as well as the heat load is made up of curtailment load and rigid load. The objective function aims to minimum the total operation cost related to electricity, natural gas and heat, while shiftable electrical load and curtailable heat load scheduling model are added into the constraints of optimization formulation. A detailed case study with the consideration of three different scenarios validates the performance of presented optimal operation model. The application of shiftable electrical load and curtailable heat load leads to lower multi-carrier energy consumption cost and lower peak power and heat load demand for micro-IES.**

Keywords—integrated energy systems; energy hub; natural gas; heat; load classifaication and scheduling

I. Introduction

Energy is the basis for human survival and development, and it is the lifeblood of the national economy. Nowadays, people are faced with the double threat of energy crisis and environmental pollution [1]. Integrated Energy Systems (IES) has aroused widespread concern on account of high efficient energy utilization and the complementarity of multi energy such as electric power, heat and natural gas [2]. It is the key technology to realize multi energy mutual aid and energy cascade utilization, and considered as the main form of energy utilization for the future human society.

Unlike the application of IES in power grid in which electric power and natural gas are the main energy carrier due to limited distance for heating supply, micro Integrated Energy Systems (micro-IES) can take full advantage of electric power, heat and natural gas in a small area. Li Y et al [3] proposed a low-carbon stochastic optimal operation model for micro integrated electricity, gas and heat supply system including power to natural gas systems. In [4], Shabanpour-Haghighi et al presented the application of a steady-state power flow approach handling operation evaluation of electrical, natural gas, and district heating networks.

It is expected that optimal operation of micro-IES including electricity, natural gas and heat carriers can play a significant role in decreasing the total cost of operation. N. Ghorbani[5] presented exchange market algorithm to solve the CHP economic dispatching model for diverse combined heat and power systems. Y. Ruan et al [6] utilized linear programing(LP) method disposing the optimal operation problem of combined heat and power systems for buildings. In [7], J. Kim et al managed the optimal operation of combined heat and power based plants adopting mixed-integer nonlinear programming model to minimize the total cost of CHP plants.

However, the aforementioned studies did not take account of load classification and scheduling. It is expected that load classification and scheduling can have tremendous potential to reduce the total cost of operation while satisfy the end-user's comfort. Rastegar [8] et al considered the controllable and uncontrollable electrical appliance in home energy management (HEM) optimal operation model to further decrease the total cost pertaining to electricity and natural gas form upstream networks. In [9], Zhang Q et al presented an optimal operation model for smart home regarding the electric vehicle(EV) as battery storage which can exchange energy with home in bidirectional way. Nevertheless, these papers taking account of load classification and scheduling just considered the electrical loads, and was restricted in HEM. To the best of our knowledge, little research was concentrated on both the electrical and heat loads classification and scheduling for micro-IES.

Meanwhile, the literatures mentioned above [3]-[7] did not utilize the attractive modeling method, energy hub (EH). Energy hub contains conversion, distribution and storage segments, and humans' energy demands are abstracted into three categories: electric heat and cold. The static transfer and transformation relations of different energy carriers are given in energy hub. Geidl [10] et al proposed an optimal power flow model based on energy hub pertaining to electricity, natural gas and district heating systems. In [11], Shao C et al applied mix-integer linear programing (MILP) method based energy hub for multi energy carriers and refrained from dispatch factor using state variable model.

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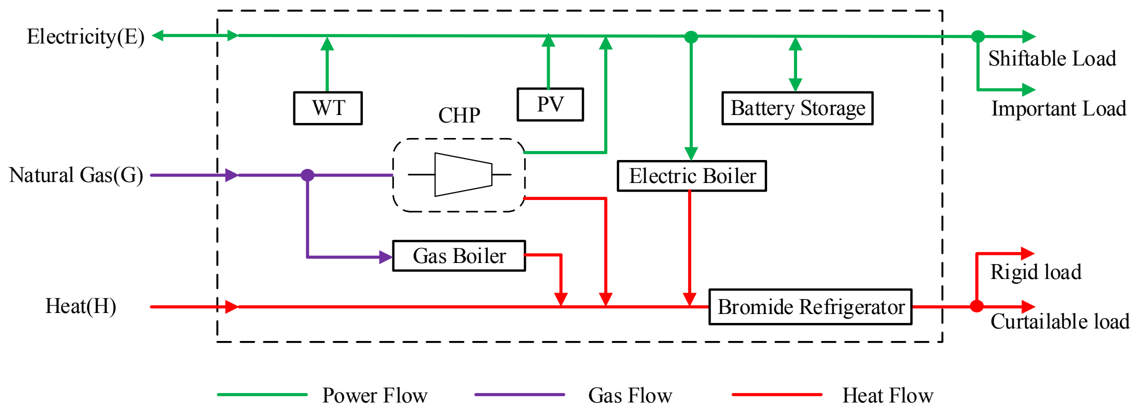

Fig. 1 Micro-IES Schematic Diagram Based Energy Hub

In this paper, we aim to present an optimal dispatching model for micro-IES based on energy hub (EH) considering loads Classification and Scheduling to further reduce the total cost of operation. The main contributions of this paper are as follows. On the one hand, we utilize energy hub (EH) to present the framework of micro-IES, and the input of EH consists of not only electricity and natural gas but also heat from district heating systems for community. On the other hand, we particularly exploit the load classification and scheduling. The electrical loads are classified as shiftable loads and important loads, and the heat loads are classified as curtailment loads and rigid loads. Then the component model of electrical shiftable load model and heat curtailment model is added into optimal dispatching formulation of mic-IES.

The other part of this paper is structured as follows. The problem formulation of energy hub based micro-IES considering load classification and scheduling is given in Section II. Section III provides numerical results for micro-IES optimal operation. And the conclusion of this paper is summarized in Section V.

II. PROBLEM FORMULATION

A. *Overview of Energy Hub based Micro-IES*

The integral picture of proposed micro-IES is illustrated in Fig. 1[3]. The EH involves three energy carriers, i.e., electricity, natural gas and heat, and the micro-IES is made up of micro-grid, micro-gas system and micro-heat system. Certainly, there is also energy interface which is the transformation medium of different energy carriers among three micro systems. The energy interface consists of micro combined heat and power unit, electric boiler and gas boiler. The CHP utilizes natural gas to simultaneously product heat and electricity. Electricity and heat, gas and heat are related respectively by electric boiler and gas boiler.

In micro-grid system, electrical load which is classified as shiftable load and important load can be supplied by power distribution network, distributed generators, i.e., wind turbine and photovoltaic panel, micro CHP unit and battery storage. The time interval of shiftable load can be flexible, and it can be flexibly arranged within a certain time range. Cool storage air conditioners, water heaters, electric vehicles all belong to this type of electrical load. Important load is some basic electrical equipment, such as lighting, communication power. The feature of this kind of electrical load is that power supply must be guaranteed in real time. Battery storage can charge when the output of renewable generation is in a high level or the electricity price is low, and it can discharge to guarantee the power balance when the load is heavy. Meanwhile, as shown in Fig. 1, electricity exchange between main grid and micro-IES is bidirectional, the EH can sell the extra electricity to grid when the renewable power generation is high and the load is small.

As for micro-gas section of IES, the input of natural gas is split into two gas flows, one flow to CHP unit, and the other to gas boiler. In micro-heat section of IES, the heat load is supplied by district heating network, gas boiler, CHP unit and electric boiler through bromide refrigerator. Due to the existence of bromide refrigerator, the micro-heat system can not only supply heat load in winter but also supply cooling load in summer. To reduce the total cost of operation for micro-IES and improve energy efficiency, we classify the heat load as curtailment load and rigid load. Curtailment load is very popular in practice, such as space heating load and ventilation heat load. It can change the power demand in every time interval of scheduling while the total energy expenditure is not less than a certain value to guarantee the customer's comfort. Meanwhile, heat load for special industrial process belongs to rigid load that has to be satisfied with a constant value anytime.

B. *Mathematical Formulation of Optimal Operation Model for Micro-IES*

In this subsection, we present an optimal operation problem for micro-IES considering two types of load classification and scheduling. The scheduling time horizon is one day (24 hours), and the time interval is one hour.

1) The Objective Function: The objective function of proposed optimization model is to aim at minimizing the total cost of operation, which consists of the tariff of electricity, heat and natural gas. The formulation is as follows:

$$\min C = \sum_{t=1}^{t_N} (C_{grid}(t) + \lambda_g G_{net}(t) + \lambda_h H_{net}(t)) \tag{1}$$

In Eq. (1), t_N represents the total number of time intervals in the scheduling time horizon; λ_g , λ_h are the price of natural gas and heat per unit; $G_{net}(t)$, $H_{net}(t)$ are the consumed natural gas and heat at time interval t from upstream networks. In addition, $C_{grid}(t)$ represents the electricity cost in micro-IES from main grid, and Eq. (2) gives it's formulation.

$$C_{grid}(t) = \lambda_e^{Buy}(t)P_{grid}^{Buy}(t) - \lambda_e^{Sale}(t)P_{grid}^{Sale}(t) \tag{2}$$

where, $\lambda_e^{Buy}(t)$, $\lambda_e^{Sale}(t)$ are electricity purchase and sale price respectively at time interval t; $P_{grid}^{Buy}(t)$, $P_{grid}^{Sale}(t)$ represent the bidirectional transaction power with the power distribution network. Without loss of generality, the objective of this optimization model aims at minimizing the total operation cost for the whole micro-IES which includes the fuel cost of CHP unit, and the fixed operation and maintenance costs of CHP and battery storage are extremely smaller than the whole system operation cost. To concentrate on the load classification and scheduling model, the operation costs of CHP unit and battery storage system are omitted.

2) The Optimization Constraints: The constraints related to power balance of different energy carriers, transaction powerlimit, component such as wind turbine, Micro-CHP and bromide refrigerator, shiftable electrical load and curtailable heat load are given in the following.

a) Power balance of three energy carriers: In Fig. 1, the power balance equations of electricity, natural gas and heat are given as follows:

$$P_E^{In}(t) = P_{grid}^{Buy}(t) - P_{grid}^{Sale}(t) + P^{WT}(t) + P^{PV}(t) + P^{CHP}(t) \tag{3a}$$

$$P_E^L(t) = P_{ch}^{BS} - P_{dis}^{BS} + P_{imp}^L(t) + P_{sh}^L(t) \tag{3b}$$

$$P^{EB}(t) = \beta(t)P_E^{In}(t) \tag{3c}$$

$$P_E^L(t) = (1-\beta(t))P_E^{In}(t) \tag{3d}$$

$$G^{CHP}(t) = v(t)G_{net}(t) \tag{4a}$$

$$G^{GB}(t) = (1-v(t))G_{net}(t) \tag{4b}$$

$$H_{net}(t) + H^{GB}(t) + H^{CHP}(t) + H^{EB}(t) = H_{br}^L(t) \tag{5a}$$

$$Q_{br}^L(t) = H_{br}^L(t)k_{br} \tag{5b}$$

$$Q_{br}^L(t) = Q_{cur}^L(t) + Q_{rig}^L(t) \tag{5c}$$

In the above formulation, constraints (3) represent power flow equation of micro-grid system in micro-IES. $P_E^{In}(t)$ is the total power generation including renewable energy and received electricity from main grid and micro-CHP, and $P_E^L(t)$ is the summation of battery power and load power. $P^{EB}(t)$ represents the power of electric boiler with dispatch factor $\beta(t)$. $P^{WT}(t)$, $P^{PV}(t)$ are the dispatch power of wind turbine and photovoltaic panel at time interval t. $P^{CHP}(t)$ is the power output of micro-CHP at hour t. P_{ch}^{BS}, P_{dis}^{BS} represent the charge and discharge power of battery storage. Furthermore, $P_{imp}^L(t)$, $P_{sh}^L(t)$ are on behalf of important electrical load and shiftable electrical load respectively.

Constraints (4) describe the power balance of natural gas, where $G_{net}(t)$ represents the received natural gas power at time period t. $G^{CHP}(t)$, $G^{GB}(t)$ are two gas power flows of $G_{net}(t)$ with dispatch factor $v(t)$ and 1-$v(t)$ separately. The reason why dispatch factor $\beta(t)$ and $v(t)$ are involved in our optimization model is to make the model formulation comply with the standard form of energy hub [10]. From the above constraints (5), we can see the heat power balance in micro-IES, and $H_{br}^L(t)$, $Q_{br}^L(t)$ are the input and output of bromide refrigerator (BR) which has the heating efficiency k_{br}. $H_{net}(t)$, $H^{CHP}(t)$ indicate the consumed heat power from district heating supply and the heat power output of micro-CHP. What's more, $H^{GB}(t)$, $H^{EB}(t)$ are the heat power supply of gas boiler and electric boiler respectively at hour t. It is corresponding to micro-grid system, $Q_{rig}^L(t)$, $Q_{cur}^L(t)$ describe the model of rigid heat power and curtailable heat load.

b) Transaction power limit between micro-IES and upstream networks: The constraints of received and sold power of electricity, received heat power and consumed natural gas power are as follows.

$$0 \le P_{grid}^{Buy}(t) \le P_{grid}^{Buy,max} \tag{6a}$$

$$0 \le P_{grid}^{Sale}(t) \le P_{grid}^{Sale,max} \tag{6b}$$

$$H_{net}^{min} \le H_{net}(t) \le H_{net}^{max} \tag{7}$$

$$G_{net}^{min} \le G_{net}(t) \le G_{net}^{max} \tag{8}$$

where, $P_{grid}^{Buy,max}$, $P_{grid}^{Sale,max}$ are the maximum value of bidirectional transaction power; H_{net}^{min}, H_{net}^{max} describe the minimum and maximum received heat power form district heating network; G_{net}^{min}, G_{net}^{max} indicate lower and upper bounds of consumed natural gas for micro-IES.

c) Component contraints in micro-IES: In addition to the constraints of power balance and transaction power flow in micro-IES, there are component constraints, i.e., wind turbine, photovoltaic panel, battery storage, micro-CHP, electric boiler, gas boiler, and bromide refrigerator.

$$P_{min}^{WT} \le P^{WT}(t) \le P_{max}^{WT} \tag{9}$$

$$P_{min}^{PV} \le P^{PV}(t) \le P_{max}^{PV} \tag{10}$$

$$0 \le P_{ch}^{BS}(t) \le P_{ch,max}^{BS} \tag{11a}$$

$$0 \le P_{dis}^{BS}(t) \le P_{dis,max}^{BS} \tag{11b}$$

$$SOC^{BS}(t) = SOC^{BS}(t-1) + P_{ch}^{BS}(t)\eta_{ch}^{BS} - P_{dis}^{BS}(t)/\eta_{dis}^{BS} \tag{11c}$$

$$SOC_{min}^{BS} \le SOC^{BS}(t) \le SOC_{max}^{BS} \tag{11d}$$

$$SOC^{BS}(t_1) = SOC^{BS}(t_N) \tag{11e}$$

$$G_{min}^{CHP} \le G^{CHP}(t) \le G_{max}^{CHP} \tag{12a}$$

$$P^{CHP}(t) = G^{CHP}(t)\eta_{ge} \tag{12b}$$

$$H^{CHP}(t) = G^{CHP}(t)\eta_{gh} \tag{12c}$$

$$H^{EB}(t) = P^{EB}(t)\eta_{eb} \tag{13a}$$

$$H_{min}^{EB} \le H^{EB}(t) \le H_{max}^{EB} \tag{13b}$$

$$H^{GB}(t) = G^{GB}(t)\eta_{gb} \tag{14a}$$

$$H_{min}^{GB} \le H^{GB}(t) \le H_{max}^{GB} \tag{14b}$$

$$Q_{br}^{L,min} \le Q_{br}^{L}(t) \le Q_{br}^{L,max} \tag{15}$$

In the above equations and inequations, constraints (9) and (10) describe the range of schedulable wind power and photovoltaic power output. Formulation (11) represent the operation constraints of battery storage, where (11a)-(11b) indicate the limitation of charge and discharge power at time interval t, and η_{ch}^{BS}, η_{dis}^{BS} are the efficiency of charge and discharge power ; (11a)-(11b) give the eqution constraint and lower and upper bounds of state of charge(SOC); (11e) express that initial state[12] and end state of SOC should be equal for battery storage. What's more, constraints (12) describe the consumed gas limitation of micro-CHP and the relation formulas between electric and heat power output and micro-CHP gas input, and η_{ge}, η_{gh} are the electric and heat production efficiency of micro-CHP. Next, constraints (13) and (14) represent the lower and upper bounds of heat output and heat production formulation for electric boiler and gas boiler. Finally, constraint (15) describes the output limitation of bromide refrigerator which can supply both heating and cooing for end-users[5].

d) Shiftable electrical load and curtailable heat load constraints : The electrical and heat load's classification and model are the key segment for our proposed energy hub based micro-IES framework, so the shiftable electrical load and curtailable heat load constraints are added into the optimization formulation as follows.

$$P_{sh}^{L}(t) = \sum_{\tau=t-T_{sh}+1}^{t} B_{sh}^{L}(\tau)P_{sh}^{L} \tag{16a}$$

$$\sum_{\tau=t_1}^{t_N-T_{sh}+1} B_{sh}^{L}(\tau) = 1 \tag{16b}$$

$$Q_{cur}^{L,min} \le Q_{cur}^{L}(t) \le Q_{cur}^{L,max} \tag{17a}$$

$$\sum_{t\in AI} Q_{cur}^{L}(t) \ge Q_{cur}^{L,cft} \tag{17b}$$

where, equtions (16) represent the shiftable electrical load constraints. (16a) gives the power formula of shiftable load at time interval t, in which $B_{sh}^{L}(t)$ is the starting up binary variable of shiftable load at hour t and P_{sh}^{L}, T_{sh} are the power and duration time of shiftable electrical load respectively. Eq. (16a) describes the constriants of starting up binary variable $B_{sh}^{L}(t)$, and t_1, t_N are the initial and end time interval. Inequtions (17) represent the curtailment heat load constraints. (17a) gives the lower and upper bounds of curtailment heat load at hour t. (17b) represents that the summation of curtailment heat load power during AI time intervals should not be less than a predefined heat energy value $Q_{cur}^{L,cft}$ to guarantee the end-users' comfort. AI stands for the time horizon of curtailment heat load, and AI is 24 hours in this paper for modeling simplification.

III. NUMERICAL RESULTS

A. The Proposed Micro-IES Parameter Setting

- **Scenario #1**- The optimal dispatching model is applied in energy hub based micro-IES without considering electrical load and heat load classification and scheduling.
- **Scenario #2-** The electrical load classification and scheduling is added to Case 1.
- **Scenario #3**- The heat load classification and scheduling is added to Case 2.

As shown in Fig. 1, it is assumed that the micro-IES in case study has a wind turbine, a set of photovoltaic panels, an electric boiler, a battery storage and electrical load in micro-grid segment of micro-IES; a micro-CHP, a gas boiler in micro-gas segment; a bromide refrigerator and heat load in micro-heat segment. Fig. 2 presents the forecasted load power of electricity and heat, as well as the predicted generation power of wind turbine and photovoltaic panels.

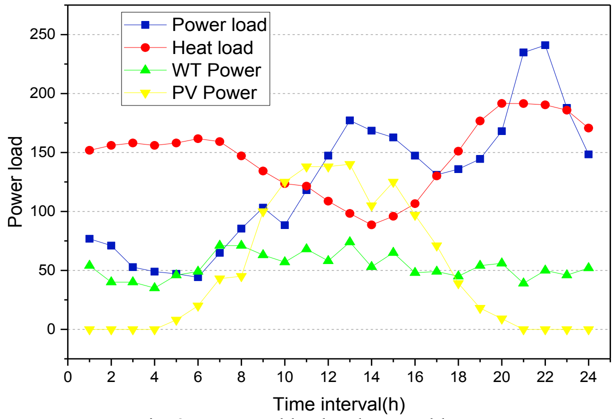

Fig. 2 Forecasted load and renewable power

In micro-grid segment of micro-IES, the TOU price [13] is applied, which is utilized commonly in literature. The peak time intervals are 12-16 h and 20-24 h, set at 1.015 RMB/kWh. The normal time intervals are 8-11 h and 17-19 h, set at 0.756 RMB/kWh. While, the valley time period is 1-7 h, and the price is set at 0.432 RMB/kWh. On the contrast, the price of selling electricity to main grid is a constant value for every time intervals, set at 0.3 RMB/kWh. The upper bounds of bidirectional transaction power are 120 kW and 50 kW respectively corresponding to consumed power and selling power of micro-IES. The rated power and heat efficiency are assumed as 40 kW and 0.95. As for battery storage (BS), the capacity and the upper bound of SOC are both set at 300 kWh, while the lower bound of SOC is 90 kWh. The maximum charge and discharge power for BS at a time interval are 60 kW, as well as the efficiency related to charge and discharge mode are both set at 0.95. What's more, the initial energy state is assumed as 100 kWh. The last but not the least, there are 5 shiftable load in proposed micro-IES, and the detail parameters are illustrated in Table I.

Table I PARAMETERS OF SHIFTABLE ELECTRICAL LOAD

No.	P_{sh}^{L} (kW)	T_{sh} (h)
1	10	2
2	12.5	2
3	20	3
4	12.5	2
5	17.5	3

In micro-gas segment of micro-IES, the gas price has the value at 1.21RMB/kWh, and the upper transaction natural gas power level between micro-IES and upstream gas network is assumed as 200 kW. For micro-CHP, the rated gas power input is 200 kW, and the minimum technical output is set at 20 kW to guarantee the safe and stable operation. The electricity and heat efficiency η_{ge} , η_{gh} are given 0.3 and 0.4 respectively. It is similar to electric boiler, the rated gas power and heat efficiency are assumed as 30 kW and 0.9. In micro-heat segment of micro-IES, the received heat price from heating district is 0.35, and the maximum limitation of consumed heat for micro-IES is set at 120 kW. The rated heat power and heat efficiency of bromide refrigerator are set at 300 kW and 0.9. In addition to bromide refrigerator, the parameters of two types of curtailable heat load are described in Table II and Table III. The predefined comfort heat energy value $Q_{cur}^{L,cft}$ of curtailable heat load type #1 and type #1 are given at 300 kWh and 190.4 kWh respectively.

It should be noted that the unit of natural gas and heat is applied with kW for power and kWh for energy to simplify the complex formulation. Moreover, the optimal operation model for micro-IES is solved using MATLAB R2014a with CPLEX software, and the running time is less than 1s on a windows desktop computer with Intel processor i7-4770, 3.10 GHz processor and 16 GB RAM.

Table II PARAMETERS OF CURTAILABLE HEAT LOAD FOR type #1

Time Intervals	$Q_{cur}^{L,max}$ (kW)	$Q_{cur}^{L,min}$ (kW)
1-5 and 24 h	10	0
6-23 h	20	10

Table III PARAMETERS OF CURTAILABLE HEAT LOAD FOR type #2

Time Intervals	$Q_{cur}^{L,max}$ (kW)	$Q_{cur}^{L,min}$ (kW)
1-5 and 18-20 h	12	8
6-7 and 21-24 h	16	12
8-17 h	8	4

B. *The Proposed Micro-IES Simulation Numerical Results*

We study the three scenarios which are mentioned above to validate the performance of proposed model considering load classification and scheduling. The scheduling results of shiftable electrical load are illustrated in Fig. 3, meanwhile, we can see the contrast with the one without load scheduling. Due to the presence of shiftable load, the peak load at time interval 21-23 h is shifted to the time period 9-13 h when the generation of renewable energy, i.e., wind turbine and photovoltaic panels is very large, so the total operation cost can be reduced. As shown in the picture, it should be noted that the time period of power consumption of shiftable load is continuous, so the dispatching result is relatively centralized.

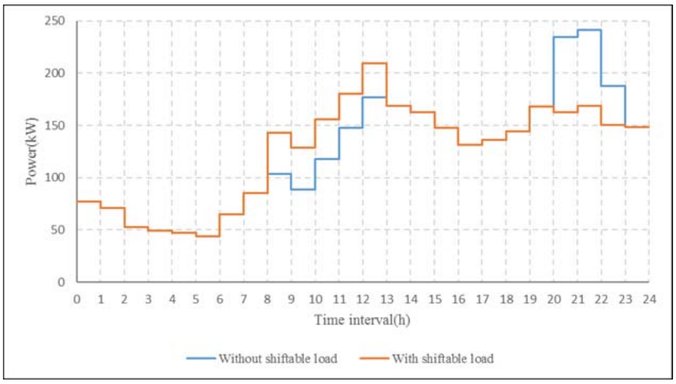

Fig. 3 The comparison of scenarios without and with shiftable electrical load

The performance of curtailment heat load scheduling is detailed in Fig. 3, it can decrease the energy consumed cost tremendously while satisfy the end-user's comfort. From the comparison of scenarios, we can realize that the heat load has been at a high level especially at peak load time period when there is no curtailable load. For scenario with curtailable load, the heat load is close to the one in scenario without curtailable load at valley load time period to guarantee the total energy consumption for users' comfort, while it is reduced to a lower level at peak load time interval in pursuit of economy.

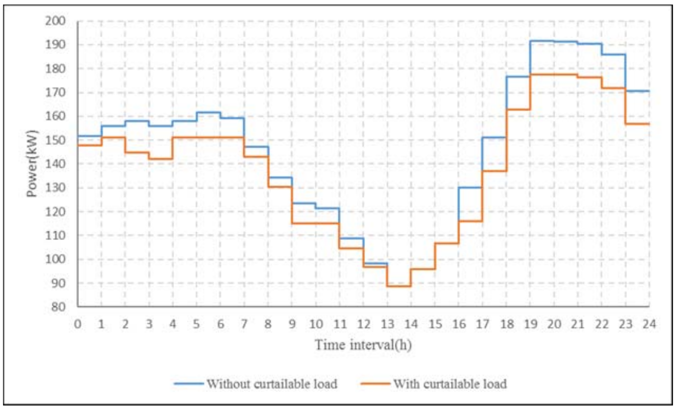

Fig. 4 The comparison of scenarios without and with curtailable heat load

Table IV give the operation cost of micro-IES for three scenarios including the total cost, electricity consumed cost, gas received cost and district heating supply cost. The total operation cost of three different carriers is decreased gradually from scenario #1 without load scheduling to scenario #3 with both electrical and heat load classification and scheduling. It is noted that the heat consumed cost in scenario #2 is higher than the cost in scenario #1, this is because the shiftable electrical load affects the heat output of the electric boiler when renewable energy generation is large. In scenario #2 the renewable energy is utilized to satisfy shiftable electrical demand, and the heat output of electric boiler becomes lower correspondingly. Because of the high price of natural gas, the reduction of gas consumption plays an important role in reducing the operation cost of the whole system. From second and fourth column of Table IV, we can find that the total operation cost decreases 15.35% and the natural gas cost decreases 35.15% because of the application of electrical and heat load classification and scheduling.

Table IV OPERATION COST (RMB) COMPARISON

Scenarios	Cost_Total	Cost_Grid	Cost_Gas	Cost_Heat
#1	2977.45	885.04	1161.56	930.85
#2	2804.82	798.41	1028.77	977.64
#3	2520.38	791.62	753.29	975.47

IV. CONCLUSION

This paper presents an optimal operation model for energy hub based micro-IES which consists of electricity, heat and natural gas energy carriers considering electrical and heat load classification and scheduling. The load demand classification and scheduling are developed in a multi-carrier energy environment. The electrical load is classified as shiftable load and important load, as well as the heat load is classified as curtailable load and heat load.

An appropriate case study consisting of three different scenarios is utilized to validate the role of proposed optimal operation model. The numerical results demonstrate that shiftable electrical load and curtailable heat load can play an important role in reducing multi-carrier energy consumption cost and alleviating peak load demand for micro-IES. Due to the application of load classification and scheduling for electricity and heat carriers, the total operation cost of the whole micro-IES reduces 15.35%, as well as the natural gas consumption cost decreases 35.15%. For the operator of micro-IES, the application of load scheduling can lead to tremendous benefits, e.g., lower energy consumed cost and lower peak load demand while the comfort level is also guaranteed for customers.

It should be noted that this paper assumes customers and operator are stakeholders, so the objective function does not include load scheduling cost. In the future work, multi-stakeholders, uncertainty of different energy carriers and the environmental cost will be considered in the optimization formulation of micro-IES.

REFERENCES

[1] R. Baños, F. Manzano-Agugliaro, F. G. Montoya, C. Gil, A. Alcayde, and J. Gómez, "Optimization methods applied to renewable and sustainable energy: A review," Renewable & Sustainable Energy Reviews, vol. 15, pp. 1753-1766, 2011.

[2] X. Jin, Y. Mu, H. Jia, J. Wu, X. Xu, and X. Yu, "Optimal day-ahead scheduling of integrated urban energy systems," Applied Energy, vol. 180, pp. 1-13, 2016.

[3] Y. Li, Y. Zou, Y. Tan, Y. Cao, X. Liu, M. Shahidehpour, S. Tian, and F. Bu, "Optimal Stochastic Operation of Integrated Low-Carbon Electric Power, Natural Gas and Heat Delivery System," IEEE Transactions on Sustainable Energy, vol. PP, p. 1-1, 2017.

[4] A. Shabanpour-Haghighi and A. R. Seifi, "An Integrated Steady-State Operation Assessment of Electrical, Natural Gas, and District Heating Networks," IEEE Transactions on Power Systems, vol. 31, pp. 3636-3647, 2016.

[5] N. Ghorbani, "Combined heat and power economic dispatch using exchange market algorithm," International Journal of Electrical Power & Energy Systems, vol. 82, pp. 58-66, 2016.

[6] Y. Ruan, Q. Liu, Z. Li, and J. Wu, "Optimization and analysis of Building Combined Cooling, Heating and Power (BCHP) plants with chilled ice thermal storage system," Applied Energy, vol. 179, pp. 738-754, 2016.

[7] J. S. Kim and T. F. Edgar, "Optimal scheduling of combined heat and power plants using mixed-integer nonlinear programming," Energy, vol. 77, pp. 675-690, 2014.

[8] M. Rastegar, M. Fotuhi-Firuzabad, H. Zareipour, and M. Moeini-Aghtaie, "A Probabilistic Energy Management Scheme for Renewable-Based Residential Energy Hubs," IEEE Transactions on Smart Grid, vol. PP, pp. 1-11, 2017.

[9] Q. Zhang and S. H. Zhang, "Smart Home Energy Management with Electric Vehicles Considering Battery Degradation," Advanced Materials Research, vol. 860-863, pp. 1085-1091, 2014.

[10] M. Geidl and G. Andersson, "Optimal Power Flow of Multiple Energy Carriers," IEEE Transactions on Power Systems, vol. 22, pp. 145-155, 2007.

[11] C. Shao, X. Wang, M. Shahidehpour, X. Wang, and B. Wang, "An MILP-Based Optimal Power Flow in Multicarrier Energy Systems," IEEE Transactions on Sustainable Energy, vol. 8, pp. 239-248, 2017.

[12] A. Gabash and P. Li, "Active-Reactive Optimal Power Flow in Distribution Networks With Embedded Generation and Battery Storage," IEEE Transactions on Power Systems, vol. 27, pp. 2026-2035, 2012.

[13] Y. Cao, S. Tang, C. Li, P. Zhang, Y. Tan, Z. Zhang, and J. Li, "An Optimized EV Charging Model Considering TOU Price and SOC Curve," IEEE Transactions on Smart Grid, vol. 3, pp. 388-393, 2012.