Submission Template for IET Research Journal Papers

A Bi-Level Equivalent Model of Scheduling an Energy Hub to Provide Operating Reserve for Power systems

Shuiquan Ye [1], Wenjun Ruan[2], Sheng Wang [3*], Chong Zhang[1], Yi Ding [3]

[1] Hangzhou State Power Energy and Environment Research Institute Co., LTD., Hangzhou, China
[2] Marketing Department, State Grid Jiangsu Electric Power Co., LTD., Nanjing, China
[3] College of Electrical Engineering, Zhejiang University, Hangzhou, China
*wangsheng_zju@zju.edu.cn

Abstract:
The integration of multiple energy carriers, such as electricity, heat, and gas, allows users to schedule their energy consumptions coordinately. The development of information and communication technologies also makes it possible to reduce the electricity consumption instantly, and provide operating reserves to assist the reliable operation of the whole power system. This paper proposes a bi-level equivalent model for users to evaluate the capability and cost of providing operating reserves, in terms of scheduling their multiple energy consumptions under the framework of Energy Hub (EH). First, a typical distribution scale EH is modelled, consisting of various devices, such as the combined heat and power plant (CHP), electric heat pump, etc. A unified energy conversion matrix is formed to characterise the exact EH structure in this paper. Based on this, a bi-level equivalent model for economically providing operating reserves is formulated. The first level strategy concerns using energy substitution, such as ramping up CHP instead of the electric boiler to reduce electricity consumption. In the second level strategy, the feasible options extend to optimal load curtailment, the cost of which is formulated using customer damage functions. Finally, a test case is utilized to validate the proposed equivalent model.

1. Introduction

With the rising concerns for sustainable and low-carbon development around the world, the coordinate operation of different energies, such as electricity, gas, and heat, has become one of the most appealing ways to promote the efficient energy utilization [1]. In the meantime, owing to the electricity and gas distribution networks, the information and communication technologies, and the development of energy conversion technologies such as combined heat and power plant (CHP), the integrated operation of multiple energies also becomes feasible. In north Europe such as Denmark, the electricity generation from local CHP has raised by 13% from 2015 to 2016, where the natural gas takes 25.84% of the fuel consumption [2]. The concept of Energy Hub (EH) was therefore proposed [3].

The idea of EH not only integrates multiple energies, but also, enable the required energies by users to be provided through diverse alternative paths [4]. The EH is thus capable to schedule its energy consumptions to provide operating reserves (OR) for the power system. OR is a vital concept in power systems that assists the power system to maintain the balance between energy supply and demand during the operation horizon, in case of unexpected generator failures or load volatilities. OR can be provided through traditional demand response, which is realised by schedule electricity consumptions. The previous studies have addressed the equivalent OR modelling of electric vehicles [5-7], air conditions (AC) [8-10], or unified flexible resources [11], etc. The capacity, ramp rate, and other characteristics of OR provided by ACs are quantitatively analysed in [8], and a sequential-dispatch strategy is proposed in [12] to reduce the lead-lag rebound effect.

No matter how delicate the approaches are in these researches, the OR is provided at the sacrifice of users' comfort. However, it can be overcome if we address the scheduling of energy consumptions from the EH's point of view. It is also natural because the electricity loads, such as ACs, is also associated with the heating/cooling requirements of users. For example, regarding the space heating provided by the electric heat pump (EHP), when an OR is required, it can be replaced with ramping up the heat production from CHP. By this means, the need for electricity is transferred into the need for gas (or other fuel consumed by the CHP), which is defined as energy substitution in this paper.

Apart from the energy substitution, the available options for an EH to be scheduled to provide OR also include the traditional load curtailment, which is not cost-efficient though. Some of the issues in the scheduling of EHs have been studied. The modelling of demand response in an EH was introduced in [13-15]. A comprehensive model was proposed for self-scheduling an energy hub to supply cooling, heating and electrical demands of a building in [16], and its adequacy was evaluated in [17]. However, they focus on the reliable or economical operation of themselves under the demand response framework, while the ability to assist the whole energy system operation is not studied.

On the other hand, the provision for EH to provide OR is promising. The multi-energy micro-grid, which can also be regarded as an EH, is used to provide reserve and reliability services in [18]. However, it focuses on the economic analysis and business case demonstration, while the technical details are not elaborated.

On the above premises, this paper proposes a bi-level equivalent model for users to evaluate the OR capability of EH, in terms of scheduling their multiple energy consumptions. First, a typical distribution scale EH is modelled with various devices, such as CHP, absorption chiller (AB), EHP, gas boiler (GB), and electricity boiler (EB). A unified energy conversion matrix is formed to characterise the exact EH structure in this paper. Based on this, a bi-level equivalent model for economically providing OR is formulated. In the first level, the energy substitution only is implemented, while in the second level context, the feasible options extend to optimal load curtailment, the cost of which is formulated using customer damage functions (CDF). Finally, the numerical case studies are performed to verify the proposed equivalent model.

2. Energy hub model in the normal operating condition

Among the diverse configurations of EH, the structure of a typical distribution level EH studied in this paper is presented in Fig.1. The EH is fed by distributional gas and electricity network, to provide electricity, heating and cooling loads. Each device in the EH is abstracted as a node. The interconnections among devices in the EH is shown in Table 1. It should be noted that the EHP is able to operate in either heating or cooling mode.

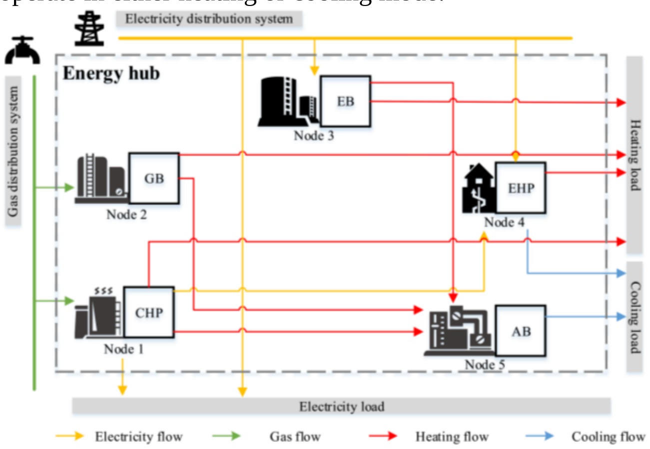

Fig. 1. *Structure of the proposed energy hub*

Table 1 Interconnections of components in the studied energy hub

	CHP	GB	EB	EHP
Input	Gas	Gas	Electricity	Electricity
Output	Electricity, heat	Heat	Heat	Heat or cooling
	AB	EES	TES	
Input	Heat	Electricity	Heat	
Output	Cooling	Electricity	Heat	

The normal operating conditions of components in the EH are determined in the day-ahead, based on the most economical way to satisfy the forecasted loads. The specific operating constraints that determine the energy conversion relationships for devices are:

$$GI_1 = a(EO_1)^2 + bEO_1 + c(HO_1)^2 + d(HO_1) + eEO_1 HO_1 + f \tag{1}$$

$$HO_2 = \eta_2 GI_2 \tag{2}$$

$$HO_3 = \eta_3 EI_3 \tag{3}$$

$$\begin{cases} HO_4 = \gamma COP_4^h EI_4 \\ CO_4 = (1-\gamma) COP_4^c EI_4 \end{cases} \tag{4}$$

$$CO_5 = HI_5 COP_5 \eta_5 \tag{5}$$

Where EI_i, GI_i, EO_i, HO_i, and CO_i denote the electricity and gas inputs, and electricity, heating and cooling outputs of the device at node i, respectively. a,b,c,d,e,f are the coefficients of CHP fuel function [19]. η_i is the energy conversion efficiency of device at node i. γ is the operation mode indicator of EHP, where $\gamma = 1$ represents the heating mode, and $\gamma = 0$ represents the cooling mode. COP_i represents the coefficient of performance for the component in node i, and COP_i^h, COP_i^c represent the coefficients of performance in heating and cooling mode of EHP, respectively.

For a given devices or the gas/electricity injection from the distribution systems, the energy distribution among the downstream devices is described by a set of distribution factors $\Omega = [\omega_{g,i}, \omega_{e,i}, \omega_{ee}, \omega_{i,j}, \omega_{i,e}, \omega_{i,h}, \omega_{i,c}], \forall i$, where $\omega_{g,i}$ and $\omega_{e,i}$ represent the distribution factors from gas and electricity distribution system to node i, $\omega_{e,e}$ represents the distribution factor from electricity distribution system to the electricity load, $\omega_{i,j}$ represents the distribution factor from node i to node j, and $\omega_{i,e}$, $\omega_{i,h}$ and $\omega_{i,c}$ represent the distribution factors from node i to electricity, thermal and cooling loads, respectively. For example, $GI_1 = \omega_{g,1} GI$. The distribution factors should meet the following constraints

$$\sum_{i=1}^{5} \omega_{e,i} + \omega_{e,e} = 1, \sum_{i=1}^{5} \omega_{g,i} = 1, \sum_{j=1}^{5} \omega_{i,j} + \omega_{i,h} + \omega_{i,c} = 1 \tag{6}$$

$$0 \le \Omega \le 1 \tag{7}$$

Therefore, the relationship between the electricity and gas inputs, EI and GI, and the electricity, heating and cooling outputs EO, HO and CO can be abstracted into an energy conversion function H. It is worth noting that the inherent non-linearity of CHP has been reserved and yet the energy conversion of EH cannot be expressed in a matrix form.

$$[EO \quad HO \quad CO]^T = H\left([EI \quad GI]^T\right) \tag{8}$$

The detailed elements in function H can be derived from (1) - (5).

3. Bi-level equivalent model of scheduling the EH to provide ORs

During the real-time operation, the power system may suffer from a contingency state for various reasons, such as random failures of generators, the volatilities of wind powers or the errors of load forecasts. To settle the unbalance of the system and maintain the reliable operation, a bi-level equivalent model of scheduling the EH is proposed to provide ORs.

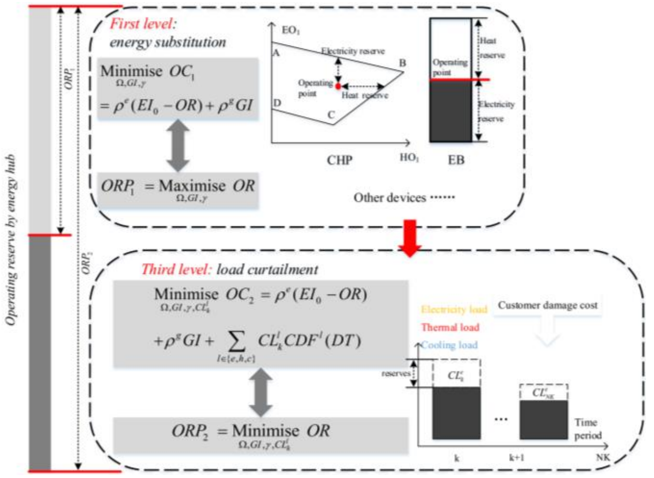

Fig. 2. *Bi-level equivalent model of scheduling EH to provide ORs*

3.1. First level: energy substitution

Within the energy substitution context, the key point is to schedule the energy hub, such as replacing part of the heat production from EB by ramping up the operating point of CHP, and the user's energy demand will not be changed. That is, the service requirement from energies will not be interrupted, and no inconvenience will be suffered. This distinguishes from traditional ORs, such as those from adjusting the setting temperatures of ACs, which will directly affect the comfort level of users.

In the proposed EH model, the operating conditions are determined by the input energies GI and EI, the set of distribution factors Ω, and the operating mode of EHP γ, once the loads EO, HO, and CO are given and remain unchanged during the scheduling according to the OR required by the system. The scheduling of EH will be conducted to satisfy the OR requirement while minimising the operating cost OC_1. The optimal schedule of EH within the first level is formulated as:

Problem 1:

$$\underset{\Omega,GI,\gamma}{\text{Minimise}}\ OC_1 = \rho^e(EI_0 - OR) + \rho^g GI \tag{9}$$

Subject to:(6), (7), (10) – (16)

$$\begin{bmatrix} EO & HO & CO \end{bmatrix}^T = H\left(\begin{bmatrix} EI-OR & GI \end{bmatrix}^T\right) \tag{10}$$

$$HO_1 \geq 0 \tag{11}$$

$$EO_1 - E_A - \frac{E_A - E_B}{H_A - H_B} HO_1 \leq 0 \tag{12}$$

$$EO_1 - E_B - \frac{E_B - E_C}{H_B - H_C}(HO_1 - H_B) \geq 0 \tag{13}$$

$$EO_1 - E_D - \frac{E_C - E_D}{H_C - H_D} HO_1 \geq 0 \tag{14}$$

$$\begin{aligned} &\begin{bmatrix} \underline{HO_2} & \underline{HO_3} & \underline{CO_5} \end{bmatrix} \leq \begin{bmatrix} HO_2 & HO_3 & CO_5 \end{bmatrix} \\ &\leq \begin{bmatrix} \overline{HO_2} & \overline{HO_3} & \overline{CO_5} \end{bmatrix} \end{aligned} \tag{15}$$

$$\begin{bmatrix} \gamma\underline{HO_4} & (1-\gamma)\underline{CO_4} \end{bmatrix} \leq \begin{bmatrix} HO_4 & CO_4 \end{bmatrix} \leq \begin{bmatrix} \gamma\overline{HO_4} & (1-\gamma)\overline{CO_4} \end{bmatrix} \tag{16}$$

Where (11) - (14) represent the convex feasible operating region of the CHP [20]. (H_A, E_A), (H_B, E_B), (H_C, E_C), (H_D, E_D) are the four extreme points forming the feasible operating region of the CHP. $\overline{HO_i}$, $\overline{CO_i}$ is the capacities of heating and cooling for the device at node i, respectively

The potential capacity of providing OR (ORP) is time-independent, which means the scheduling of EH in this moment will not affect the ORP in the future. The ramping of the devices in this small scale EH can be completed almost instantly (in the time scale of a few seconds or minutes), therefore the ramp rate is not discussed in this paper. The ORP at the first level ORP_1 is limited by the capacities of devices in the EH. It can be calculated by solving

Problem 2:

$$ORP_1 = \underset{\Omega,GI,\gamma,OR}{\text{Maximise}}\ OR \tag{17}$$

Subject to: (6),(7), (10) – (16)

3.2. Second level: load curtailment

If the EH is intended to furtherly provide OR beyond ORP_1, the load curtailment would be required in the second level strategy. During the load curtailment, the on-going activities of users will be interrupted, and thus cause a certain level of inconvenience. This kind of inconvenience could incur possible economic losses. The interruption cost depends on the customer sector, such as industrial, commercial, or residential customers, and the interruption duration. It can be quantified the CDFs. However, there lack CDF formulations on other energies, such as gas and heat. Considering electricity can cover most of the services, the CDF for electricity can provide a baseline to reconstruct the CDFs for other energies [21].

$$CDF^l(DT) = CDF^e(DT)\eta^l / \eta^e, l \in \{e,h,c\} \tag{18}$$

Where CDF^l represent the CDF for energy l. DT is the duration time of the interruption. η^l and η^e are the average efficiencies for energy l and electricity to satisfy the users' needs, respectively.

The load curtailment is not commonly utilized as a measure to provide OR for its relatively high cost. However, it is still a feasible option if the shortage of electricity supply is enormous. Therefore, the optimal schedule of EH in the second level can be formulated as

Problem 3:

$$\begin{aligned} &\underset{\Omega,GI,\gamma,CL_k^l}{\text{Minimise}}\ OC_3 = \rho^e(EI_0 - OR) + \rho^g GI \\ &+ \sum_{l\in\{e,h,c\}} CL_k^l CDF^l(DT) \end{aligned} \tag{19}$$

Subject to: (6), (7), (11) – (16), (20), (21)

$$\begin{aligned} &\begin{bmatrix} EO - CL_k^e & HO - CL_k^h & CO - CL_k^c \end{bmatrix}^T \\ &= H\left(\begin{bmatrix} EI - OR & GI \end{bmatrix}^T\right) \end{aligned} \tag{20}$$

$$CL_k^e \leq \beta^e EO, CL_k^h \leq \beta^h HO, CL_k^c \leq \beta^c CO \tag{21}$$

Where the CL_k^e, CL_k^h, CL_k^c denote the curtailed electricity, heating and cooling loads, and β^e, β^h, β^c denote the proportion of curtailable electricity, heating and cooling load, respectively.

Similarly, we can obtain the ORP_2 by solving

Problem 4:

$$ORP_2 = \underset{\Omega, GI, \gamma, CL_k^l}{\text{Maximise}}\ OR \tag{22}$$

Subject to (6), (7), (11) – (16), (20), (21).

4. Procedures for evaluating the capacities and costs of ORs

Based on the equivalent model proposed in Section 3, the OR capacities and costs of EH with different levels of strategies can be evaluated. Its procedure is presented in Fig. 3. The problem 1 – problem 4 are all mixed integer programming problem (MIP), thus they are solved using Branch&Bound method in this paper. In each branch, the sub-problems with continuous decision variables are solved using interior point method (IPM). The steps for analysing the OR capacities and costs can be summarised as follows:

(a) Initialise the corresponding data and parameters, including the capacities and operating parameters of the devices in the EH, the electricity, heating and cooling load profiles, and the electricity and gas prices.

(b) Formulate the energy conversion function H according to the (1) - (5).

(c) Evaluate the ORPs from two levels ORP_1 and ORP_2, by solving *Problem 2*, and *Problem 4*, respectively.

(d) Continuously increase the OR by ΔOR. If $0 < OR \le ORP_1$, solve *Problem 1* and obtain the cost of providing OR with the first level strategy.

(e) If $ORP_1 < OR \le ORP_2$, calculate the CDFs for different energies according to (18). Then, solve *Problem 3* to calculate the cost of providing OR with the second level strategy.

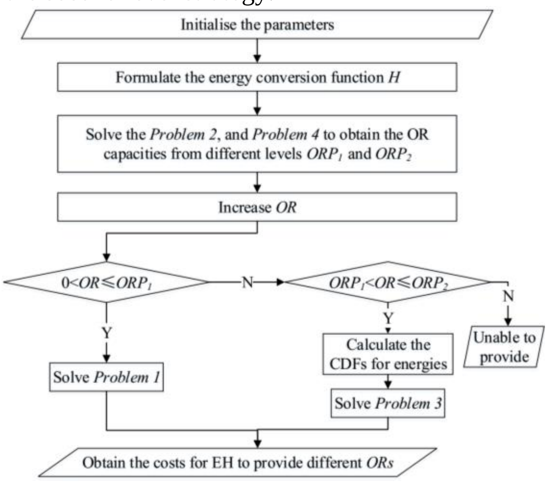

Fig. 3. *flowchart of analysing the OR capacities and costs*

5. Case studies

A test EH is presented in this section to validate the proposed bi-level equivalent model of EH to provide OR. The structure of the test EH is the same as in Fig.1, and the capacities of the devices, as well as the detailed parameters, are presented in Table. 2 and Table. 3, respectively. The hypothetical electricity, thermal and cooling loads for the test EH in a selected winter day are presented in Fig. 4 [16]. The electricity price is set based on the time of use (TOU) mechanism according to [16], and the gas price is 48 mu/kWh (mu stands for monetary units). The CDF for commercial users is used in this paper, which can be acquired from [22].

Table 2 Capacities of the devices in the test EH (kW) [23, 24]

H_A	E_A	H_B	E_B	H_C	E_C	H_D
0	250	110	210	90	50	0
E_D	$\overline{HO_2}$	$\underline{HO_2}$	$\overline{HO_3}$	$\underline{HO_3}$	$\overline{HO_4}$	$\underline{HO_4}$
100	250	20	250	20	450	20
$\overline{CO_4}$	$\underline{CO_4}$	$\overline{CO_5}$	$\underline{CO_5}$			
450	20	300	0			

Table 3 Detailed parameters of the devices in the test EH (dimensionless) [16]

a	b	c	d	e	f	η_2
0.00216	0.90625	0.00188	0.26250	0.00188	16.56	0.95
η_3	COP_4^h	COP_4^c	COP_5	β^e , β^h , β^c		
0.85	3	3	0.65	0.1		

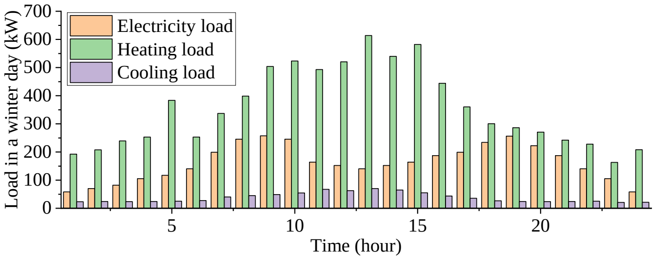

Fig. 4. *Daily load profile in a selected winter day*

In order to set the baseline for implementing the scheduling of EH, the normal operating conditions of the devices in the EH is calculated, where OR is not required. The results are illustrated in Fig.5 and Fig. 6. As Fig. 5 indicates, the purchasing of gas is quite steady during the operation, while the electricity consumption is constantly adjusted to follow the load volatilities. Consequently, the operating cost changes with the quantity of electricity consumption.

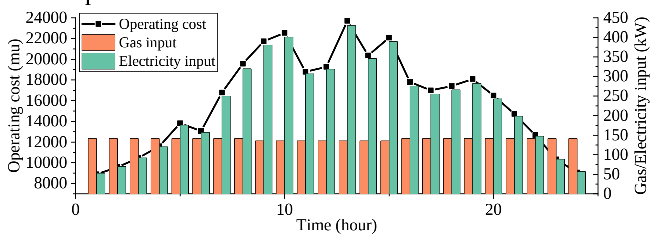

Fig.5. *the electricity and gas inputs, and the operating cost of EH*

Fig. 6 further depicts the distribution of input energies and demonstrates the operating conditions of the representative devices in the EH. The GB remains its minimum operating capacity of 20 kW, and the cooling output of EHP equals zero during the whole simulation. It can be observed that the heating load is mainly satisfied by EHP due to its high cost-efficiency, until the peak hours during 8:00 – 16:00, where the EHP reaches its maximum capacity. During that period, the CHP ramp up its heat production by reducing its electricity production to supplement the shortage of heating load, as well as the EB. During other heating load valleys, the CHP is at its minimum operating region, and its electricity and heat productions are 80.07 and 35.88 kW, respectively. As for the electricity load, it is mainly supplied by the electricity distribution system directly. The heat productions of CHP, GB, and EB are in part injected into AB to provide for the cooling load.

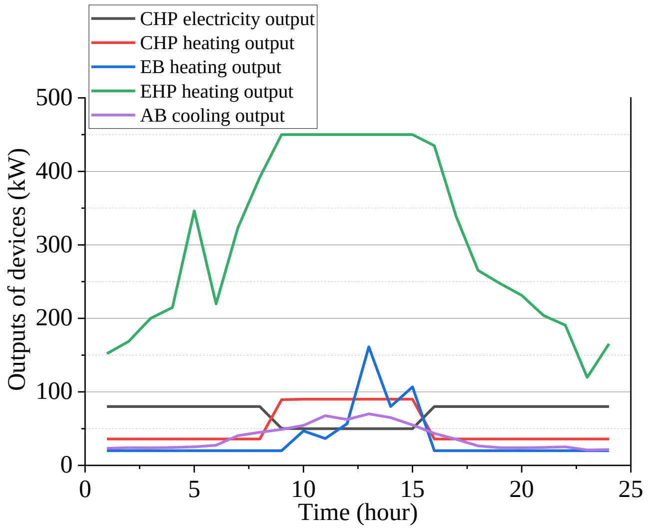

Fig. 6. *Operating conditions of the representative devices in the EH*

Based on the normal operating conditions, the evaluation results of ORP_1 and ORP_2 for all the simulation time are presented in Fig. 7. The gas input of the EH is manually limited to 1.5 times its normal gas consumption to avoid severe impacts on the gas system. As it indicates, the average ORP_1 is 53.42 kW. During most of the off-peak time of the heating load, the ORP_1 is around 50 kW. Influenced by the first level strategy, the mean gas consumption for the EH raises by 49.60%, and the maximum growth rate during the operation is 50.00%, which is the constraints for the gas consumption manually set. By introducing the second level strategy, the average ORP_2 is 88.92 kW, increased by 66.45%. Its profile appears the same peak and valley patterns with the ORP_1 . Its maximum value of 174.70 kW appears at 13:00. The gas consumption profile does not differ much from that in providing ORP_1 .

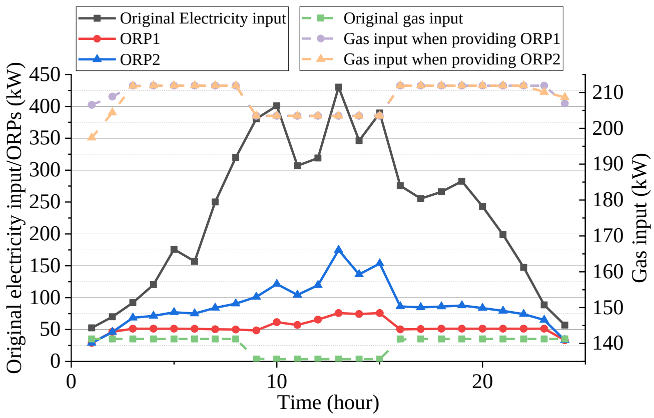

Fig. 7. *Bi-level ORPs and their effects on the gas input*

Fig. 8 compares the operating costs of OR=0, ORP_1 and ORP_2 . The mean operating costs for these three scenarios are 1.61×10^4 , 1.73×10^4 and 2.45×10^5 mu, respectively. It is obvious that the operating cost involved with only first level strategy does not increase much from that in the normal operating condition. However, the further increase of OR from ORP_1 to ORP_2 results in the dramatic increase of the operating cost.

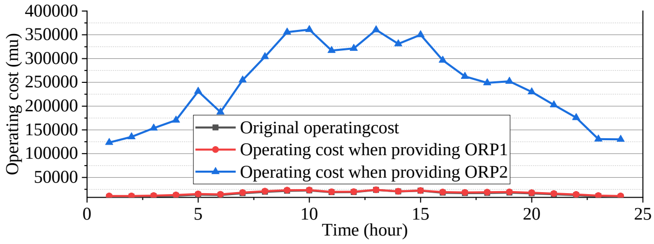

Fig. 8. *Operating costs with different ORPs*

To explicitly explore the impacts of OR requirement on the operations of the devices in the EH, the operating conditions considering specific OR requirements in a typical time point, t=12h for example, are compared in Table 4. The electricity, heating and cooling loads are 152.1, 520.6, and 62.5 kW, and the ORP_1 and ORP_2 are 65.63 and 119.46 kW at that time point, respectively. The ORs being compared are 0, 40kW and 100kW, respectively.

Table 4 Operation condition of EH with different ORs

OR (kW)	0.00	40.00	100.00
GI (kW)	135.64	171.43	203.46
EO_1 (kW)	50.00	50.00	91.55
HO_1 (kW)	90.00	90.00	95.19
HO_2 (kW)	20.00	54.00	26.05
HO_3 (kW)	56.75	22.75	20.00
HO_4 (kW)	450.00	450.00	450.00
CO_5 (kW)	62.50	62.50	56.25
Operating cost ($)	19265	19383	189996

When OR_1 = 40 kW, $0 < OR_1 \le ORP_1$, only the first level strategy is involved. The operating conditions of CHP, EHP and AB are not changed. The electricity reduction is realised by substituting the heating production by EB with the GB. By this means, the gas consumption increases, along with the operating cost. When OR_2 = 100 kW, $ORP_1 < OR_2 \le ORP_2$, the second level strategy is furtherly involved. In this stage, the gas consumption furtherly increases to its maximum value. The CHP electricity production increases dramatically, although it is not regarded to be cost-efficient when the electricity input is sufficient. The heating productions for GB and EB also drop. It can be observed that with the reduction of electricity input for all most all the devices, some of the electricity, heating, and cooling loads are not able to be maintained. They have been curtailed for 15.21, 15.90, and 6.25 kW, respectively, which accounts for the dramatic increase in the operating cost.

In order to quantitatively associate the OR capacities with the operating costs, the corresponding sensitivity analysis is conducted in Fig. 9. As it indicates, there is a clear boundary for operating cost as the OR increases. Before ORP_1 , the cost increases due to the gas and electricity purchasing cost. Between the ORP_1 and ORP_2 , the cost increases rapidly due to the interruption costs for load curtailments. If we take a closer look at the segment before ORP_1 , the cost increases in an almost piecewise linear way. In the first piece, the specific strategy for the EH is to replace the heating device EB with GB. After EB reaches its minimum operating capacity 20 kW, the EH tends to lift the operating point of CHP, causing the marginal price for providing OR to further increase.

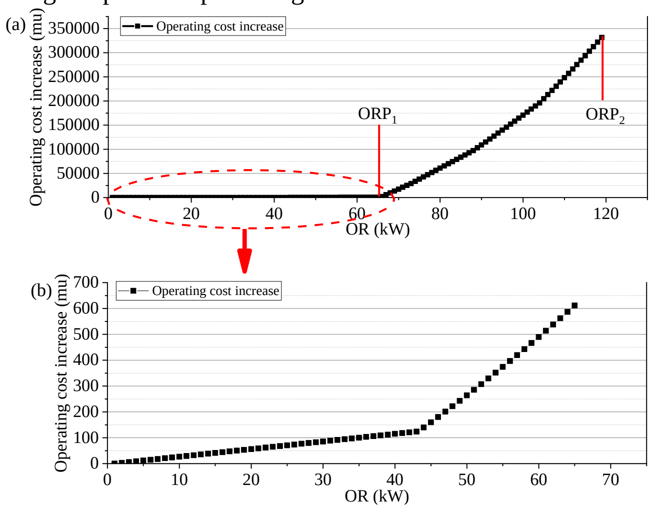

Fig. 9. *Operational cost with the increasing OR*

6. Conclusion

This paper proposes a bi-level equivalent model for users to evaluate the capability of providing OR, in terms of scheduling their multiple energy consumptions in the studied EH. The bi-level structure offers a more flexible way for EH to provide OR. The numerical case studies have demonstrated the effectiveness of the proposed equivalent model. The EH does present a great potential for providing OR. In the first level, the OR is realised mostly by replacing the heat production from EB with GB, which results in the mild increase of the operational cost. However, if the OR requirement is beyond the ORP of the first level strategy, the exceeded OR have to be provided by jointly ramping up the heat production of CHP, and curtail part of the loads. The latter action will result in a significant increase in operating cost. With the worldwide practice of integrating the demand side resources to participate in the operation of the whole energy system, the equivalent modelling in this paper can provide a new perspective of using the EH as an OR provider, and the quantitative analysis may also be useful in the OR pricing and market design.

7. Acknowledgments

This work was supported by State Grid Science and Technology Project (Research and Development on Key Technology of University Energy Flow Model Based Regional Multi-Energy System).

8. References

[1] Lei, Y.K., Hou, K., Wang, Y., Jia, H.J., Zhang, P., Mu, Y.F., Jin, X.L., and Sui, B.Y., 'A New Reliability Assessment Approach for Integrated Energy Systems: Using Hierarchical Decoupling Optimization Framework and Impact-Increment Based State Enumeration Method', *Applied Energy*, 2018, 210, pp. 1237-1250.

[2] 'Energinet, Environmental Report 2017: Environmental Report for Danish Electricity and Chp for 2016 Status Year ', https://en.energinet.dk/-/media/C4170984026F4BFD921F6E852446208A.pdf, accessed July 2018.

[3] Geidl, M., Koeppel, G., Favre-Perrod, P., and Klockl, B., 'Energy Hubs for the Future', *Power & Energy Magazine IEEE*, 2007, 5, (1), pp. 24-30.

[4] Wang, J., Zhong, H., Ma, Z., Xia, Q., and Kang, C., 'Review and Prospect of Integrated Demand Response in the Multi-Energy System', *Applied Energy*, 2017, 202, pp. 772-782.

[5] Sarker, M.R., Dvorkin, Y., and Ortega-Vazquez, M.A., 'Optimal Participation of an Electric Vehicle Aggregator in Day-Ahead Energy and Reserve Markets', *IEEE Transactions on Power Systems*, 2016, 31, (5), pp. 3506-3515.

[6] Shafie-khah, M., Moghaddam, M.P., Sheikh-El-Eslami, M.K., and Catalão, J.P.S., 'Optimised Performance of a Plug-in Electric Vehicle Aggregator in Energy and Reserve Markets', *Energy Conversion and Management*, 2015, 97, pp. 393-408.

[7] Zhao, T., Li, Y., Pan, X., Wang, P., and Zhang, J., 'Real-Time Optimal Energy and Reserve Management of Electric Vehicle Fast Charging Station: Hierarchical Game Approach', *IEEE Transactions on Smart Grid*, 2018, 9, (5), pp. 5357-5370.

[8] Hui, H., Ding, Y., Liu, W., Lin, Y., and Song, Y., 'Operating Reserve Evaluation of Aggregated Air Conditioners', *Applied Energy*, 2017, 196, pp. 218-228.

[9] Cheng, D., Zhang, W., and Wang, K., 'Hierarchical Reserve Allocation with Air Conditioning Loads Considering Lock Time Using Benders Decomposition', *International Journal of Electrical Power & Energy Systems*, 2019, 110, pp. 293-308.

[10] Xie, D., Hui, H., Ding, Y., and Lin, Z., 'Operating Reserve Capacity Evaluation of Aggregated Heterogeneous Tcls with Price Signals', *Applied Energy*, 2018, 216, pp. 338-347.

[11] Jia, H., Ding, Y., Song, Y., Singh, C., and Li, M., 'Operating Reliability Evaluation of Power Systems Considering Flexible Reserve Provider in Demand Side', *IEEE Transactions on Smart Grid*, 2018, (Early Access), pp. 1-1.

[12] Cui, W., Ding, Y., Hui, H., Lin, Z., Du, P., Song, Y., and Shao, C., 'Evaluation and Sequential Dispatch of Operating Reserve Provided by Air Conditioners Considering Lead–Lag Rebound Effect', *IEEE Transactions on Power Systems*, 2018, 33(6), (6), pp. 6935-6950.

[13] Bahrami, S. and Sheikhi, A., 'From Demand Response in Smart Grid toward Integrated Demand Response in Smart Energy Hub', *IEEE Transactions on Smart Grid*, 2016, 7, (2), pp. 650-658.

[14] Salehimaleh, M., Akbarimajd, A., Valipour, K., and Dejamkhooy, A., 'Generalized Modeling and Optimal Management of Energy Hub Based Electricity, Heat and Cooling Demands', *Energy*, 2018, 159, pp. 669-685.

[15] Wang, S., Ding, Y., and Shao, C., 'Generalized Modeling of Self-Scheduling Demand Resource in Multi-Energy System', in, *2018 IEEE International Conference on Communications, Control, and Computing Technologies for Smart Grids (SmartGridComm)*, (2018)

[16] Moghaddam, I.G., Saniei, M., and Mashhour, E., 'A Comprehensive Model for Self-Scheduling an Energy Hub

to Supply Cooling, Heating and Electrical Demands of a Building', *Energy*, 2016, 94, pp. 157-170.
[17] Shariatkhah, M.-H., Haghifam, M.-R., Chicco, G., and Parsa-Moghaddam, M., 'Adequacy Modeling and Evaluation of Multi-Carrier Energy Systems to Supply Energy Services from Different Infrastructures', *Energy*, 2016, 109, pp. 1095-1106.
[18] Martínez Ceseña, E.A., Good, N., Syrri, A.L.A., and Mancarella, P., 'Techno-Economic and Business Case Assessment of Multi-Energy Microgrids with Co-Optimization of Energy, Reserve and Reliability Services', *Applied Energy*, 2018, 210, pp. 896-913.
[19] Subbaraj, P., Rengaraj, R., and Salivahanan, S., 'Enhancement of Combined Heat and Power Economic Dispatch Using Self Adaptive Real-Coded Genetic Algorithm', *Applied Energy*, 2009, 86, (6), pp. 915-921.
[20] Lahdelma, R. and Hakonen, H., 'An Efficient Linear Programming Algorithm for Combined Heat and Power Production', *European Journal of Operational Research*, 2003, 148, (1), pp. 141-151.
[21] Helseth, A. and Holen, A.T., 'Impact of Energy End Use and Customer Interruption Cost on Optimal Allocation of Switchgear in Constrained Distribution Networks', *IEEE Transactions on Power Delivery*, 2008, 23, (3), pp. 1419-1425.
[22] Wacker, G. and Billinton, R., 'Customer Cost of Electric Service Interruptions', *Proceedings of the IEEE*, 1989, 77, (6), pp. 919-930.
[23] Mancarella, P. and Chicco, G., 'Real-Time Demand Response from Energy Shifting in Distributed Multi-Generation', *IEEE Transactions on Smart Grid*, 2013, 4, (4), pp. 1928-1938.
[24] Ghaffarpour, R., Mozafari, B., Ranjbar, A.M., and Torabi, T., 'Resilience Oriented Water and Energy Hub Scheduling Considering Maintenance Constraint', *Energy*, 2018, 158, pp. 1092-1104.