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

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1 Introduction

Integration of multiple energies

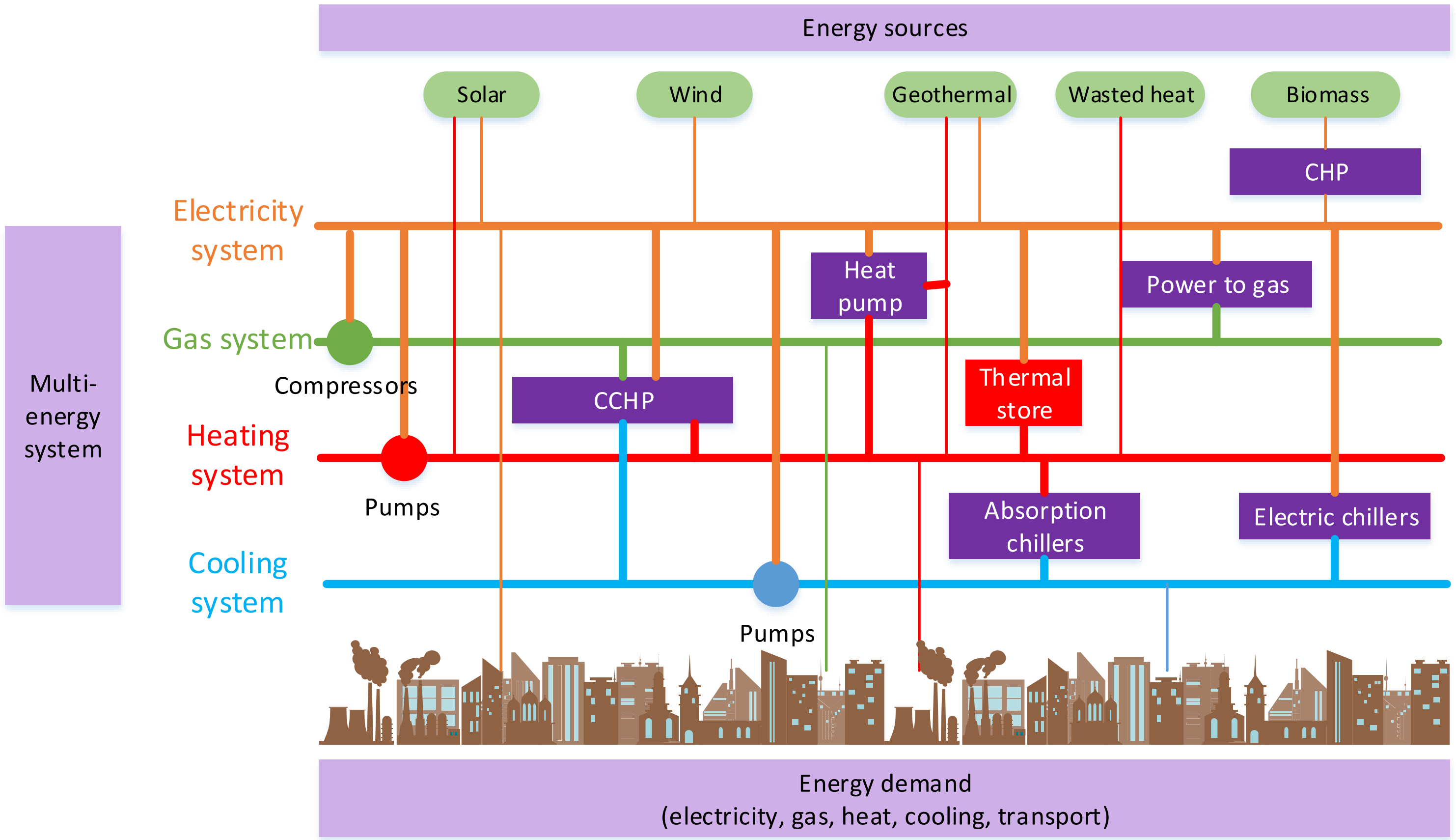
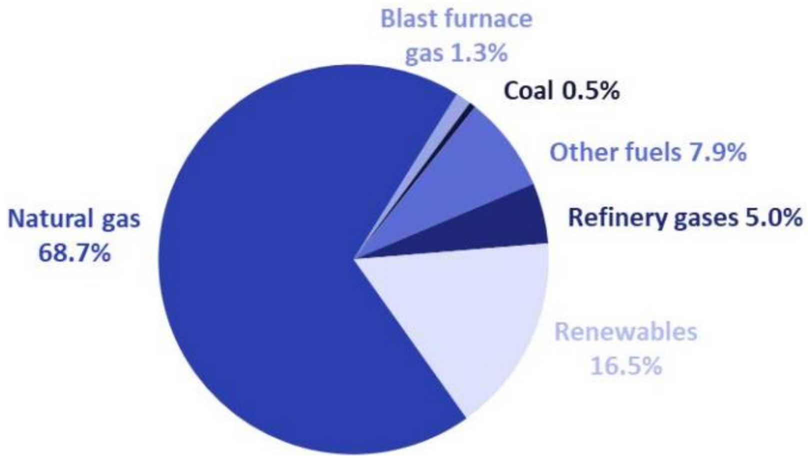


Fig. 1 Structure of multi-energy system (From a presenter from Cardiff University in 1st IEEE EI2)

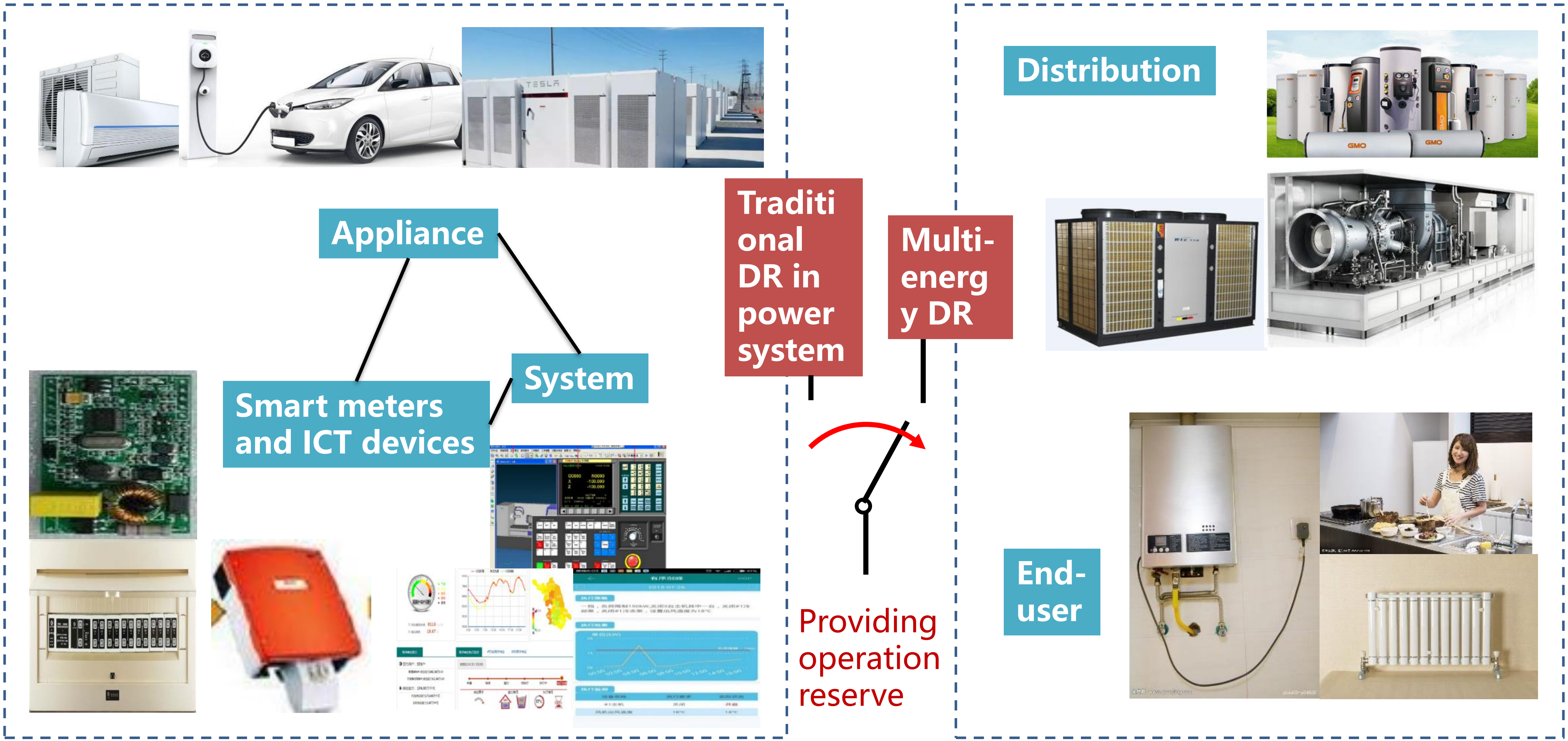


- **68.7%** of the fuel used in CHP schemes in 2017 was natural gas in UK [1].

Multiple energy sources, transmission and distribution systems and energy demands are organized for production, delivery and consumption, especially **electricity**, **gas** and **heat** in demand side.

[1] GOV.UK:Department for Business EIS. Digest of UK Energy Statistics (DUKES): combined heat and power 2018 July. <https://www.gov.uk/government/statistics/combined-heat-and-power-chapter-7-digest-of-united-kingdom-energy-statistics-dukes>.

1 Introduction



Challenges of this topic

How much can the operating reserve be provided

How will the operational cost change

- ✓ The previous studies 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.

- ✓ The previous studies focuses on the economic analysis and business case demonstration, while the **technical details** are not elaborated.

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Description about the Energy Hub model

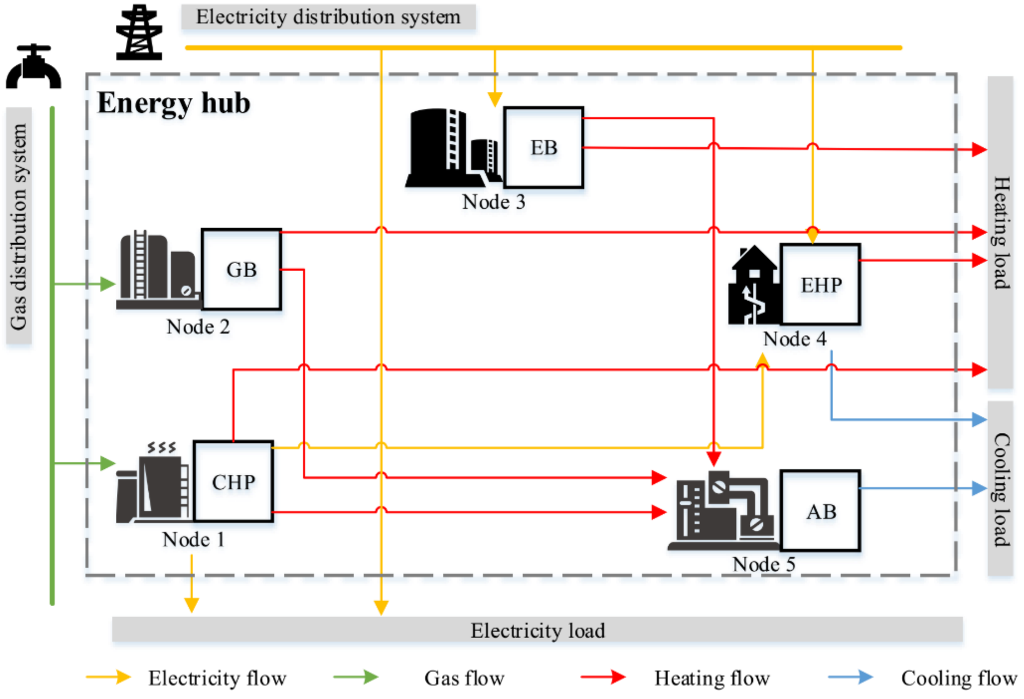

Fig. 2. Structure of the proposed energy hub

Table 1 Interconnections of components in the studied energy hub

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

- Energy distribution

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

$$0\le\Omega\le 1$$

- Energy conversion

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

$$\left.\begin{aligned}
&h_{11}(EI)=\omega_{ee}EI\\
&h_{12}(GI)=\omega_{1,e}F^{-1}(\omega_{g,1}GI)\\
&h_{21}(EI)=(\omega_{e,3}\eta_3\omega_{3,h}+\gamma\omega_{e,4}COP_4^h)EI\\
&h_{22}(GI)=\omega_{g,2}\eta_2\omega_{2,h}GI+\kappa F^{-1}(\omega_{g,1}GI)\omega_{1,h}\\
&\qquad\qquad+\gamma\omega_{1,4}\kappa F^{-1}(\omega_{g,1}GI)COP_4^h\\
&h_{31}(EI)=(COP_5\,\omega_{e,3}\eta_3\omega_{3,5}+(1-\gamma)COP_4^c\omega_{e,4})EI\\
&h_{32}(GI)=COP_5\,\omega_{g,2}\eta_2\omega_{2,5}GI\\
&\qquad\qquad+(COP_5\,\omega_{1,5}+(1-\gamma)\omega_{1,4}COP_4^c)\kappa F^{-1}(\omega_{g,1}GI)
\end{aligned}\right\}\ \text{Elements of } H$$

First level to provide operating reserves

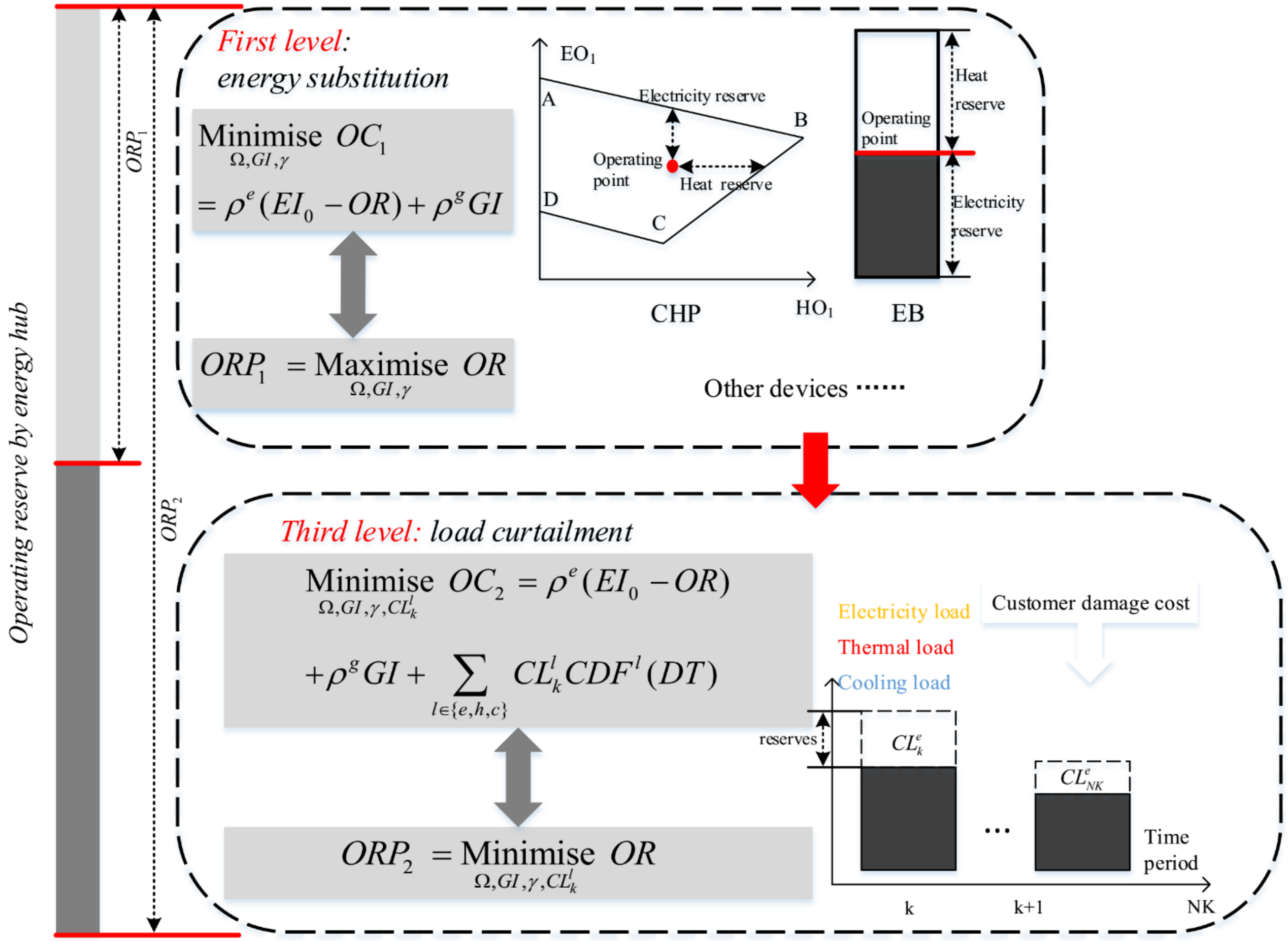

Fig.3 Bi-level equivalent model of scheduling EH to provide ORs

First level strategy: **energy substitution**

- Objective function of providing a given OR

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

- Objective function of calculating OR penitential

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

- Subject to

$$[EO \quad HO \quad CO]^T = H\left([EI - OR \quad GI]^T\right)$$

$$HO_1 \geq 0$$

CHP operating constraints:

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

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

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

$$\left[\underline{HO_2} \quad \underline{HO_3} \quad \underline{CO_5}\right] \leq \left[HO_2 \quad HO_3 \quad CO_5\right] \leq \left[\overline{HO_2} \quad \overline{HO_3} \quad \overline{CO_5}\right]$$

$$\left[\gamma \underline{HO_4} \quad (1-\gamma)\underline{CO_4}\right] \leq \left[HO_4 \quad CO_4\right] \leq \left[\gamma \overline{HO_4} \quad (1-\gamma)\overline{CO_4}\right]$$

Second level to provide operating reserves

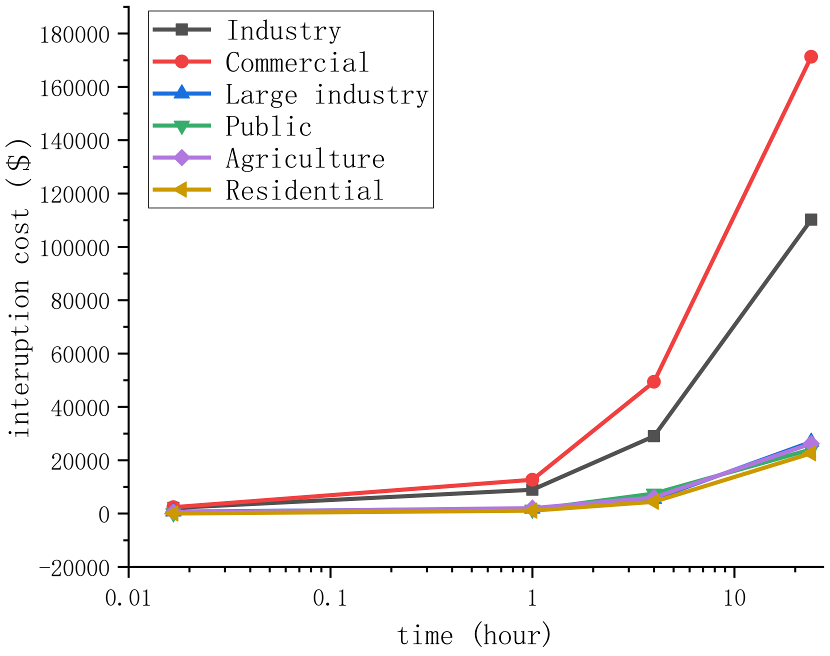

Fig.4 electricity CDF for different customer sectors

- ✓ utilities' planning and operating activities
- ✓ Cost benefit assessment operating policies and strategies devising or modifying load shedding or load restoration sequences
- ✓ emergency strategies
- ✓ operating policies

- Gas curtailment cost

$$CDF^g(t) = \sum_{m\in M^e} CC^{e,m}(t)\eta_g / \eta_e$$

- Heat curtailment cost

$$CDF^h(t) = \sum_{m\in M^h} CC^{e,m}(t)\eta_h / \eta_e$$

Optimal schedule of EH within the second level

- Objective function of providing a given OR

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

- Objective function of calculating OR penitential

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

- Subject to

$$CL_k^e \le \beta^e EO, CL_k^h \le \beta^h HO, CL_k^c \le \beta^c CO$$

$$\left[EO - CL_k^e \quad HO - CL_k^h \quad CO - CL_k^c\right]^T = H\left(\left[EI - OR \quad GI\right]^T\right)$$

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Evaluation procedures

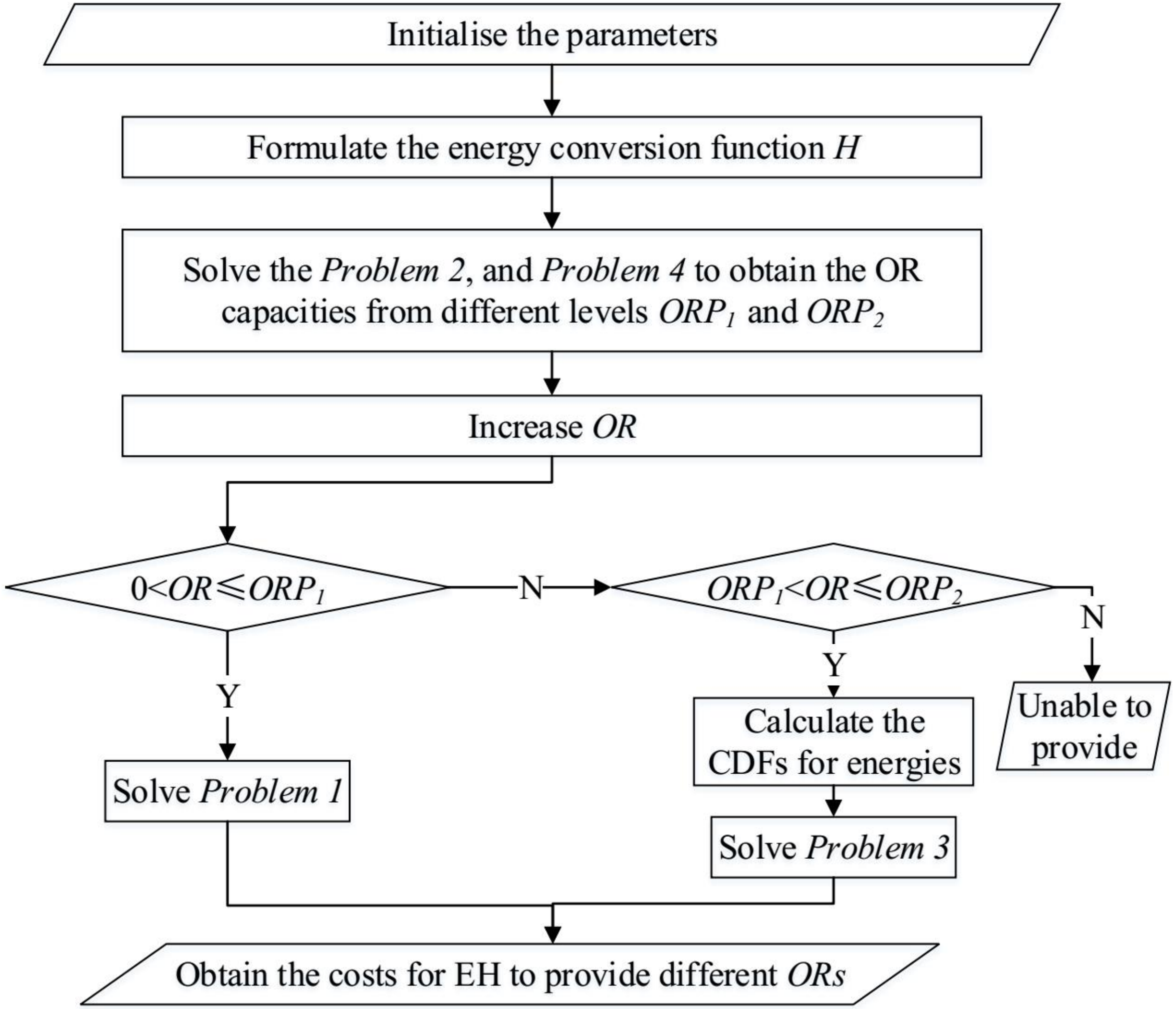

Fig. 5. flowchart of analysing the OR capacities and costs

- The *problem 1* – *problem 4* are all **mixed integer programming problem (MIP)**
- 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)**.

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Test case description

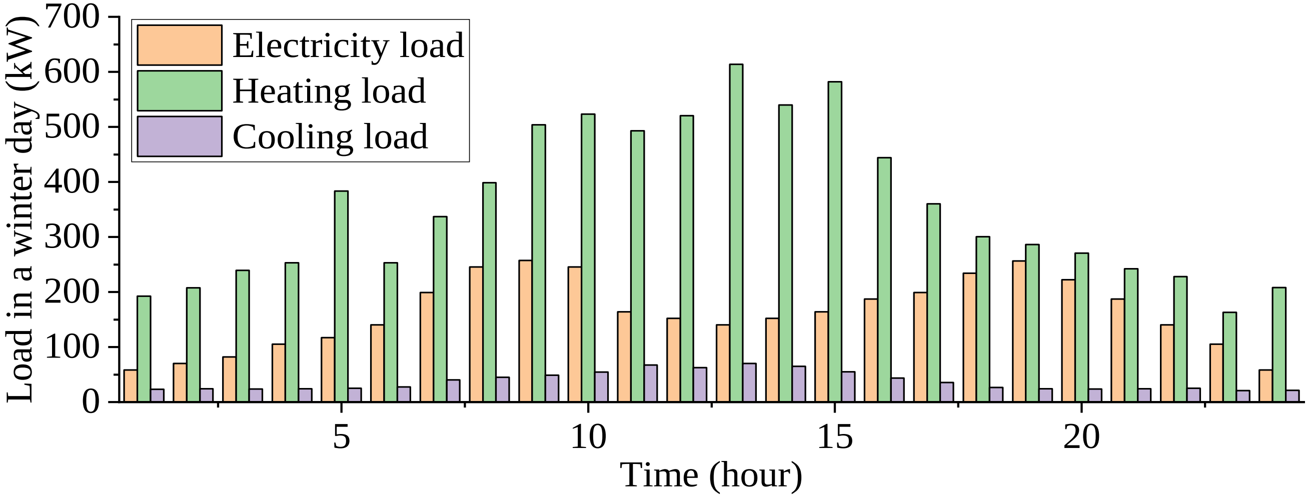

Fig. 6. Daily load profile in a selected winter day

- The electricity price is set based on the **time of use (TOU)** mechanism, and the gas price is **48 mu/kWh** (mu stands for monetary units)

Table 2 Capacities of the devices in the test EH (kW)

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)

a	b	c	d	e	f	η_2
0.002	0.906	0.001	0.262	0.001	16.5	0.9
16	25	88	50	88	6	5
η_3	COP_4^h	COP_4^c	COP_5	β^e, β^h, β^c		
0.85	3	3	0.65	0.1		

Case studies

The normal operating conditions

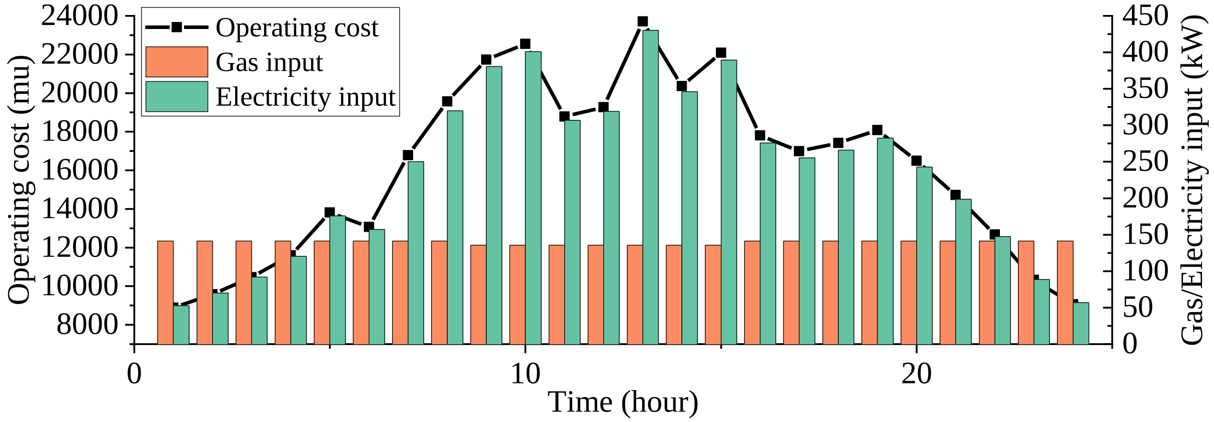

Fig.7. the electricity and gas inputs, and the operating cost of EH

- The GB remains its minimum operating capacity of 20 kW.
- the cooling output of EHP equals zero during the whole simulation.
- the heating load is mainly satisfied by **EHP** due to its **high cost-efficiency**
- During the peak hours during 8:00 – 16:00, the **CHP ramps up** its heat production by reducing its electricity production to supplement the shortage of heating load, as well as the EB.
- the electricity load 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.

- the purchasing of gas is quite steady during the operation, while the electricity consumption is constantly adjusted to follow the load volatilities.

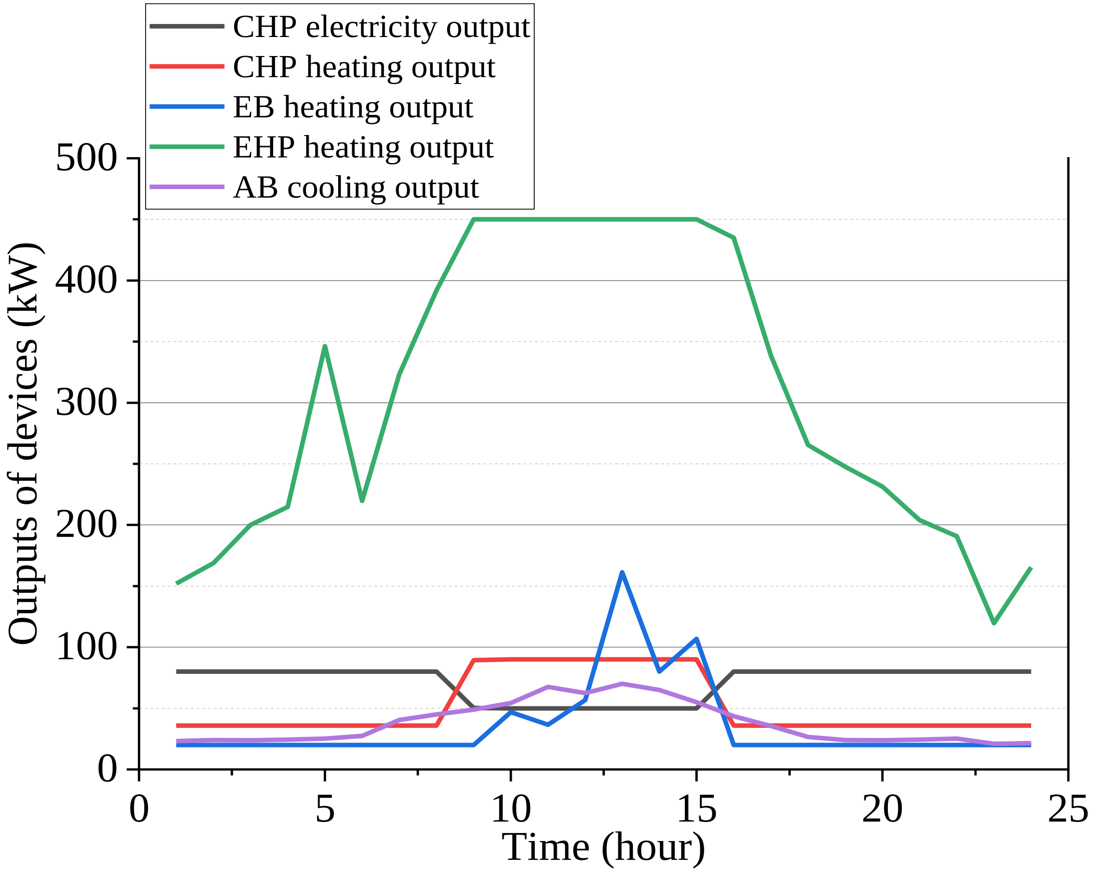

Fig. 8. Operating conditions of the representative devices in the EH

Case studies

Operation reserve capacities and costs

- 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

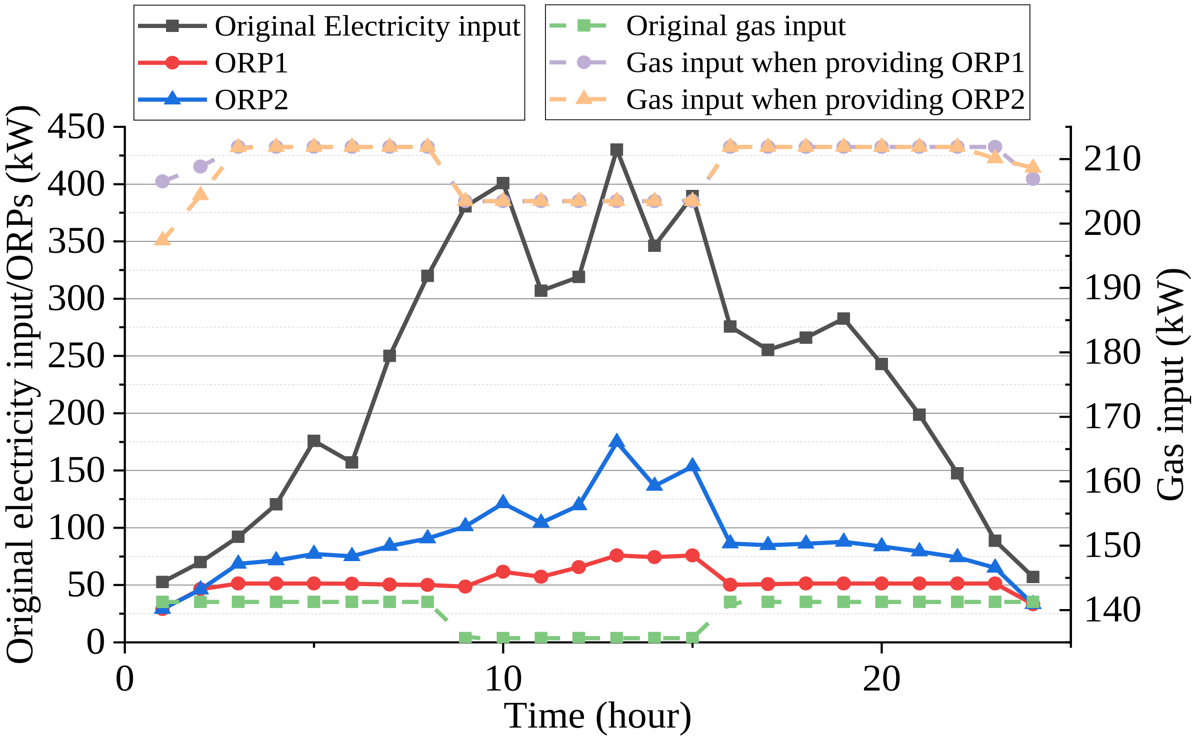

Fig. 9. Bi-level ORPs and their effects on the gas input

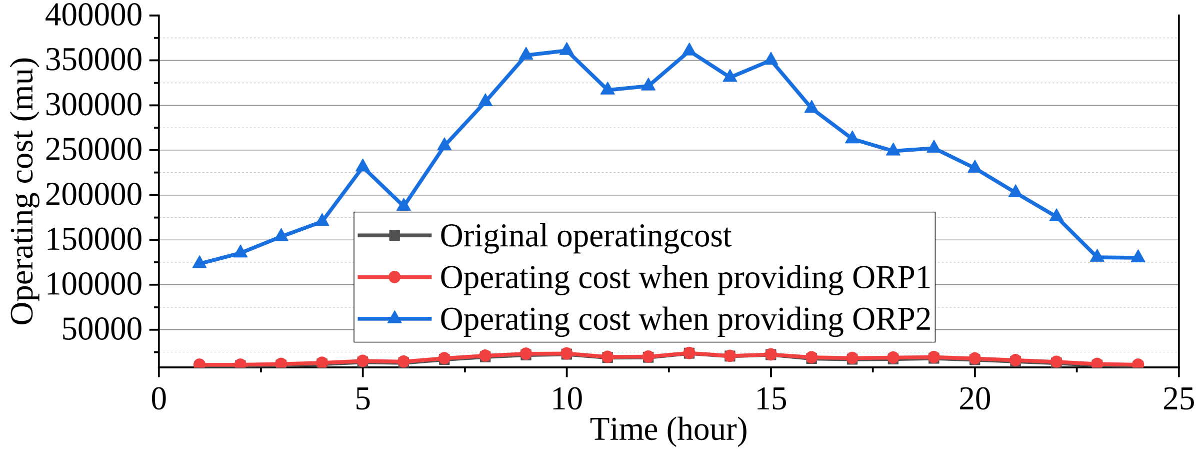

Fig. 10. Operating costs with different ORPs

- the average ORP1 is **53.42 kW**.
- During most of the off-peak time of the heating load, the ORP1 is around 50 kW.
- Influenced by the first level strategy, the mean gas consumption for the EH raises by **49.60%**
- By introducing the second level strategy, the average ORP2 is 88.92 kW, increased by **66.45%**.
- with only first level strategy does not increase much from that in the normal operating condition. However, the further increase of OR from ORP1 to ORP2 results in the dramatic increase of the operating cost.

Sensitivity analysis

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
CHP	EO_1 (kW)	50.00	50.00	91.55
	HO_1 (kW)	90.00	90.00	95.19
GB	HO_2 (kW)	20.00	54.00	26.05
EB	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

- OR = 40 kW, the electricity reduction is realised by **substituting the heating production of EB with the GB**.
- OR = 100 kW, 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.
- 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.

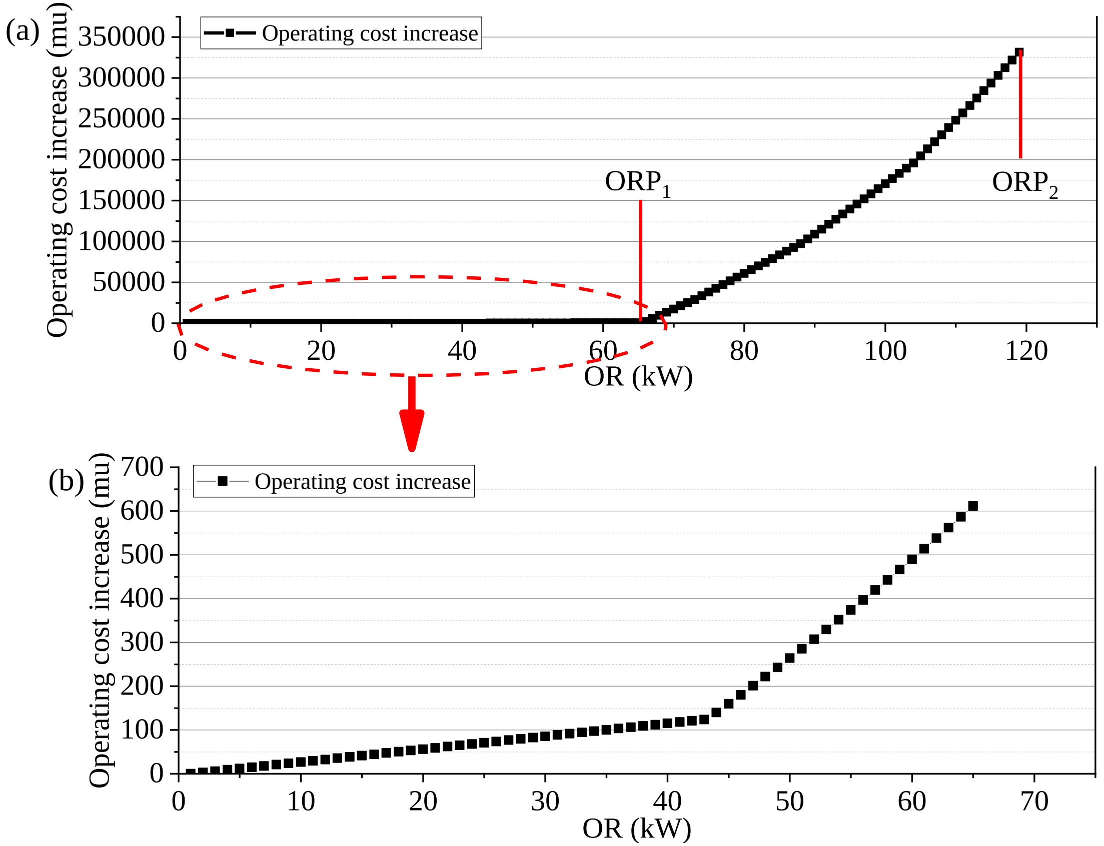

Fig. 11. Operational cost with the increasing OR

- Before ORP1, the cost increases due to the gas and electricity purchasing cost; Between the ORP1 and ORP2, the cost increases rapidly due to the **interruption costs** for load curtailments.
- At the segment before ORP1, 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.

Thanks!

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