Comparison and Error Analysis of Off-design and Design Models of Energy Hubs

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***Abstract*—The accuracy of the simulation model has a profound impact on the optimal operation of the energy hubs (EHs). However, in many articles, the constant model of the efficiency of equipment is adopted to formulate the operation system, which would probably lead to a simplification of the simulation models. But, EHs are typically operated under off-design condition due to the fluctuations in cooling, heating, electricity requirement. Moreover, even though the off-design characteristics are considered, few studies have suggested comparing the differences between those two models by considering the operation cost. In order to assess the effect of the off-design characteristics of EH on the optimal operation accuracy in this paper, two test cases are performed on the fixed and variable load conditions, respectively.**

In addition, the individual effect of off-design characteristics of each equipment on the optimal operation cost of the EH is also investigated through four optimization runs. It is worth mentioning that the optimal operation problem of the EH considering the off-design characteristics and on-off status of the equipment is a mixed integer non-linear programming problem (MINLP). By testing the design and off-design models on the two cases, the results of simulation demonstrate that the optimal operation cost for the off-design model is larger than that for the design model. Nonetheless, in the aspect of the authenticity of the system operation strategy, the off-design model performs better than the design model. Furthermore, a larger relative error of the system operation cost between the two models can be observed when the EH is operated under a relatively lower load condition, revealing that the influence of off-design characteristic on the optimal operation of EHs is too significant to be neglected.

***Index Terms*—Design, energy hubs, MINLP, off-design, optimal operation.**

NOMENCLATURE

C	Energy price.
COP	Coefficient of performance.
EHs	Energy hubs.
ESB	Energy storage battery.
K	Parameters of equipment efficiency.
L	Load, kW.
LHV	Lower heating value, $\mathrm{kJ/m^3}$.
MINLP	Mixed integer nonlinear program.
C_{OC}	Operation cost, ¥.
P	Electric power, kW.
Q	Thermal power, kW.
SOC	State of charge.
t	Time, h.
V	Gas consumption, $\mathrm{m^3}$/s.
α	Minimum load factor.
δ	Units on/off status.
η	Efficiency.
max	Maximum.
min	Minimum.
AB	Afterburning.
AC	Absorption chiller.
ACin	Input of absorption chiller.
c	Charging.
C	Cooling.
d	Discharging.
E	Electricity.
EC	Electric chiller.
f	Discharge rate of ESB.
GT	Gas turbine.
H	Heating.
HE	Heat exchanger.
HEin	Input of heat exchanger.
HEout	Output of heat exchanger.
HRSG	Heat recovery steam generator.
i	i-th parameter of equipmen.t efficiency
N	Rated value.
NG	Natural gas.
S	Solar.
sold	Sold.
pur	Purchase.

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I. INTRODUCTION

OVER the past years, due to the exponential growth in energy demand, the comprehensive utilization of energy resources has increasingly attracted researchers' attentions [1]–[3]. Energy hub, which is a indispensable part as an interconnection point linking the various energy networks and the energy components in constructing the integrated energy system, have been proposed recently. Until now, the concept of energy hub has been used to facilitate some researchers analyzing the multiple energy carrier flows and their interactions [4]–[6]. In most researches, EH is regarded as a component which achieves the same energy conversion function as Combined Cooling Heating and Power (CCHP) system. The reason for this is that the EHs are commonly used in regional energy systems which supplies energy to end users directly. For instance, human comfort factor is first considered in the mathematical optimization model of the residential EHs in [7], while minimizing the total cost of natural gas and electricity simultaneously. Next, based on the research results of previous papers, a new concept named Smart Energy Hub is put forward by authors of [8]. In Smart Energy Hub, the customers aims to maximize their daily payoff by selecting different power supply pattern in the integrated demand response (IDR) program. Furthermore, [9] and [10] took comprehensive consideration of renewable energy and some uncertainties when operating a residential EH. In recent years, the energy hub has received a lot of attention from researchers, involving many aspects. [11] illustrated EH models for typical integrated energy systems and summarized the key issues of EH research and the potential research topics. In terms of models, the authors of [12] proposed a standardized matrix modeling method based on the concept of the EHs, which leads to a compact formulation of the characteristics on the energy converters and their connections in 2017. In terms of algorithms, [13] proposed a new optimization algorithm which can effectively solve Energy Hub economic dispatch problems. In terms of configuration planning, Y. Wang *et al*. proposed a graph theory based optimal configuration planning model for EH starting from scratch in [14]. In terms of optimal operation of EHs, [15] imagines an innovative methodology that obviously increases the synergy between structural and operation optimization and targets the system's cost affordability. In 2017, Thanh Tung Ha proposed a mathematical model aiming to optimize the total energy costs of the extended EH models considering the involvement of a battery energy storage system, solar heat exchanger, and solar photovoltaic generation in [16]. What's more, in 2018, the EH model was introduced to optimize energy cost with considering the uncertainty of the loads (cooling, heating and electricity) and electricity price in [17] by V. V. Thang *et al*. It can be seen from the above references that research on EHs has become a hot issue now.

However due to fluctuating energy requirement for the EH model, the operation of EH brings many challenges. As mentioned above, most of studies established various mathematical models of EH, in which the energy converters are often modeled simply, to achieve the optimal economic performance of it. This leads to the fact that these studies all ignored the impact of off-design characteristics of EH components on EH which is the motivation of this article. For example, while EHs operate at off-design condition, the variations of coefficient of performance (COP) and efficiency are often neglected by most models. Reference [18] treated the equipment efficiencies as constants and then solved the hourly trigeneration problem using the proposed Tri-Commodity Simplex (TCS) algorithm. What's more, a linear programming model with the lowest variable cost was provided in [19] and the simulation results for different demands of operation modes and energy services were also explored and analyzed.

Actually, the assumption in most researches shows that the equipment efficiencies are constant, which may leads to inaccurate results depending on different systems operation conditions. Therefore, with the purpose of ensuring a more accurate performance evaluation, some researchers have developed more accurate and complex models, taking into account the off-design characteristics of the equipment. As a result, the original linear programming (LP) model has been converted into complex non-linear programming model (NLP) [20]–[22]. Nonetheless, the LP and NLP models are still difficult to be used to accurately describe the discrete characteristics of the simulation model. So, in order to handle the problem of the equipment's start-up status, mixed integer linear programming model (MILP) and MINLP model were proposed. In Reference [23], a detailed MILP model is developed to plan short-term operation of the distributed energy system. Reference [24] put forward two mathematical models, which include design model and off-design model for the optimal operation of the constructed CCHP model. And the results of this paper show that the negative effects of using the constant efficiency model can be reduced when employing the thermal storage facilities. In [25], the trigeneration system was modeled by an MINLP model, which can reflect the realistic operation of equipment. However, due to the nonlinear nature, the MINLP models pose significant computational challenges. Thus, [23], [24], [26], [27] proposed numerous approaches for converting the MINLP model into MILP model. In [23], the non-linear characteristics of the performance curves have been dealed with using appropriate piecewise linear approximation, which involve 5-20 intervals. The results showed that it is sufficient to obtain a more accurate objective function estimate when using 10 intervals.

As previously mentioned, a suitable and accurate simulation model has a profound impact on the optimal operation of EHs. As far as we can see, the design models of EHs are more widely used than the off-design models owing to the superiority of computation. However, EHs are often operated under the off-design condition, implying that the equipment efficiencies also vary with the different load levels. Therefore, the simplification of the simulation model may lead to the reduction of accuracy of the operation strategy. Occasionally, the MINLP model considering the off-design characteristics of the equipment can be transformed into an MILP model by using the appropriate piecewise linear approach. Nonetheless, it was founded that not all of the MILP solvers could dispose the linearized variables [27]. Although the off-design characteristics have been proved to have the advantage of improving the accuracy of simulation models [24]–[29], there are few literatures to compare the difference between the design model and off-design model by means of considering the operation cost.

Unlike some previous researches, the novelty of this paper is that we not only present two mathematical models of the equipment for the EH's optimal operation with the aim of minimizing the daily operation cost, but also compare the differences of operation strategy and relative error of the optimal operation costs between the two models. It should be emphasized that the considered EHs in our paper are directly applied to the end users with representative structures while providing cooling, electricity and hot water simultaneously. In addition to traditional energy technologies, photovoltaic generation and energy battery storage are also considered in the EH. For comparison purposes, one model with constant energy conversion efficiency is established to represent the performance characteristic of EH when it runs at design levels. The other model considers all key equipment of the EH under off-design condition for comparison. Moreover, two test cases have been conducted to compare the difference of the optimal operation results between those two models. One of the case is carried out under the fixed load condition to compare the difference of the optimal operation strategy between the two models. Furthermore, four numerical examples are implemented to investigate the individual effect of the off-design characteristics of each equipment on the optimal operation cost of EH. In the other case, EH is operated under various load conditions in form of ratios for the cooling load to electricity load (C2E) and the hot water load to electricity load (H2E), for the comparison of design and off-design models. Firstly, the ratios of C2E and H2E are both taken as 1.5, 1 and 0.5, which forms 9 cases (3 × 3). Then, the electricity load is taken as 100%, 75% and 50% of the initial electricity load in order to assess the impacts of electricity load variations on EH's optimal operation cost. Thereby, a total number of 27 optimization calculations (3 × 3× 3) is performed.

The remainder of this paper is structured as follows. Section II describes the structure of the proposed EH. The detailed mathematical models of equipment in the EH are presented in Section III. The MINLP problem as well as some constraints is introduced in Section IV. The difference of optimal operation strategy and relative error of operation costs between detailed and simplified models are compared in Section V. Finally, Section VI contains some concluding remarks.

II. System Description

The framework of typical EH in our paper is illustrated in Fig. 1. The EH includes energy supply sides, energy conversion equipment sides and end user sides. Utility grid, photovoltaic generation and natural gas form the energy supply sides. As for energy conversion equipment sides, it consists of several component like gas turbine (GT), PV panel, energy storage battery (ESB), heat recovery steam generator (HRSG) with afterburning (AB), absorption chiller (AC), heat exchanger (HE) and electric chiller (EC). Besides, the end user sides are composed of the electric load demand, hot water demand and cooling demand.

In EH, GT, which can produce electricity and recoverable heat simultaneously, is applied as a power generator unit in the system. On the one hand, the electricity is applied to not only satisfy part electricity demand but also drive the EC, while the electricity power provided by the GT is insufficient; the shortage part will be supplied by PV panel and public grid. Conversely, when the electricity power GT provided exceeds the requirement, the excess electricity power will be stored in the battery or sold back to the public grid. On the other

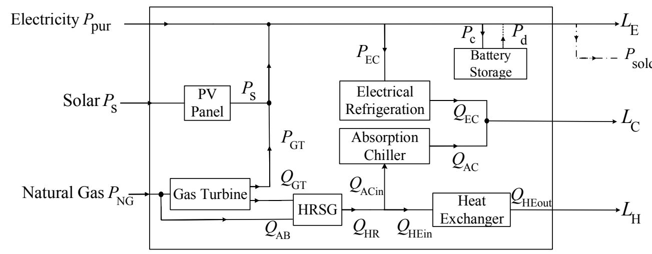


Fig. 1. Schematic diagram of an EH.

hand, recovered heat is divided into two parts. One part is transformed by the HE to meet the hot water requirement of end users. The other part is applied to drive the AC to work normally to generate the required cooling load. Once the hot water obtained by heat exchanger can not completely meet the hot water requirement, the rest requirement will be provided by the HRSG. In terms of the cooling requirement, it can be gained from two ways: EC and AC respectively.

III. Mathematical Model

The optimal operation of EH is very complicated and has a relationship with each component inside. In some articles, they generally design various kinds of equipment in the EH as a constant efficiency model to simplify the model, which is not accurate in the simulation. Therefore, we developed two mathematical models which have the same structure but different specifications for comparing the difference of optimal operation. One model is formulated using constant efficiency assumption for the equipment called design model. And another model considers the off-design features of all key equipment in EH called off-design model. So, it is necessary to have a clear understanding of each component of EH and operation mechanism before establishing the optimization models. Performance curves for equipment in EH can be acquired from these documents [25], [30], [31]. The next step is to describe the general form of each part of EHs in detail.

A. Gas Turbine

GT, which provides electricity and recoverable heat simultaneously, is regarded as power generation unit. When considering the off-design characteristic of GT, the output of electricity, the amount of thermal output, and the amount of gas fuel consumption have a coupling relationship. And the output of electricity, the gas fuel consumption are completely determined by the thermal output. Hence, the characteristic performance of GT based on off-design model is expressed below [30]:

$$P_{\mathrm{GT}}(t) = K_1 Q_{\mathrm{GT}}^2(t) + K_2 Q_{\mathrm{GT}}(t) + K_3 \tag{1}$$

$$P_{\mathrm{NG}}(t) = K_4 Q_{\mathrm{GT}}^2(t) + K_5 Q_{\mathrm{GT}}(t) + K_6 \tag{2}$$

$$V_{\mathrm{GT}}(t) = \frac{P_{\mathrm{NG}}(t)}{\mathrm{LHV}} \tag{3}$$

where NG refers to natural gas, LHV indicates lower heating value.

B. Energy Storage Battery

For the purpose of shaving the peak demand and compensating the fluctuation of renewable energy, ESB is employed in the EH. What's more, in this paper, we choose the Lithium-ion (Li-ion) battery because of its best energy-to-weight ratio and the slow loss of charge without using [32]. The state of charge (SOC) is its unique state variable. Since charging and discharging cannot be performed simultaneously, $P_{\mathrm{c}}(t)$ and $P_{\mathrm{d}}(t)$ have the mutually exclusive relationship which can be expressed through two binary variables $\gamma_{ESB.t}^{\mathrm{ch}}$ and $\gamma_{ESB.t}^{\mathrm{dis}}$. In this way, the equations about charge and discharge can be formulated below [33]:

$$\begin{aligned} SOC(t+1) &= (1-f)SOC(t) + \frac{\eta_{\mathrm{c}} P_{\mathrm{c}}(t)}{\mathrm{E}}\gamma_{ESB.t}^{\mathrm{ch}} \\ &\quad - \frac{P_{\mathrm{d}}(t)}{\eta_{\mathrm{d}}\mathrm{E}}\gamma_{ESB.t}^{\mathrm{dis}} \\ \gamma_{ESB.t}^{\mathrm{ch}} &+ \gamma_{ESB.t}^{\mathrm{dis}} = 1 \quad \forall t \in T \end{aligned} \tag{4}$$

where T is total number of hours a day (24 h).

C. Heat Recovery Steam Generator with Afterburning

The HRSG, which has the ability of significantly improving the energy efficiency by recovering the high-grade waste heat, is more and more widely applied in cogeneration cycle systems [34]. Generally speaking, HRSG turns the ordinary water into hot water we need by recovering the waste heat generated from the GT. During shutdown times of the GT, the hot water demand is supplied by the thermal of complemental burning of natural gas. In actual operation, owing to the difference in users' need for steam temperature, HRSG is often operated under different parameters. Therefore, The efficiency and rated value of the HRSG are usually different, which will affect the operation performance of the entire EH. In order to simplify the complexity of the model, in this article, we considered the thermal characteristics of the HRSG to be related to its rated thermal output Q_{HRN} and its rated thermal efficiency η_{HRN}. The relation can be described as [30]:

$$\frac{\eta_{\mathrm{HR}}(t)}{\eta_{\mathrm{HRN}}} = K_7\left(\frac{Q_{\mathrm{HR}}(t)}{Q_{\mathrm{HRN}}}\right)^2 + K_8\left(\frac{Q_{\mathrm{HR}}(t)}{Q_{\mathrm{HRN}}}\right) + K_9 \tag{5}$$

$$Q_{\mathrm{HRin}}(t) = Q_{\mathrm{AB}}(t) + Q_{\mathrm{GT}}(t) \tag{6}$$

$$Q_{\mathrm{AB}}(t) = V_{\mathrm{AB}}(t)\mathrm{LHV} \tag{7}$$

D. Absorption Chiller

AC has been studied by the majority of researchers due to its reliability and full utilization in the low grade heat of waste heat. Until now, there are three types of absorption chillers for providing users with cooling requirement which is single-, double-, and triple-effect chillers. Furthermore, the temperature of heat resource is the key factor to be considered when choosing the chiller. The thermal characteristics performance of AC can be presented below when the off-design characteristics of AC is considered in the model [25]:

$$\frac{\mathrm{COP}_{\mathrm{AC}}(t)}{\mathrm{COP}_{\mathrm{ACN}}} = \frac{\frac{Q_{\mathrm{AC}}(t)}{Q_{\mathrm{ACN}}}}{K_{10}\left(\frac{Q_{\mathrm{AC}}(t)}{Q_{\mathrm{ACN}}}\right)^3 + K_{11}\left(\frac{Q_{\mathrm{AC}}(t)}{Q_{\mathrm{ACN}}}\right)^2 + K_{12}\left(\frac{Q_{\mathrm{AC}}(t)}{Q_{\mathrm{ACN}}}\right) + K_{13}} \tag{8}$$

$$Q_{\mathrm{AC}}(t) = \mathrm{COP}_{\mathrm{AC}}(t)Q_{\mathrm{ACin}}(t) \tag{9}$$

where ACin is defined as input of absorption chiller.

E. Electric Chiller

Unlike AC which can only be driven by the low-quality of waste heat, EC can generates cooling by means of consuming electricity. Therefore, it is obvious that the COP of EC is higher than AC on account of the consumption of high quality electricity. The thermal performance of EC is formulated as follows when considering the off-design characteristics of EC [25]:

$$\frac{\mathrm{COP}_{\mathrm{EC}}(t)}{\mathrm{COP}_{\mathrm{ECN}}} = \frac{\frac{Q_{\mathrm{EC}}(t)}{Q_{\mathrm{ECN}}}}{K_{14}\left(\frac{Q_{\mathrm{EC}}(t)}{Q_{\mathrm{ECN}}}\right)^2 + K_{15}\left(\frac{Q_{\mathrm{EC}}(t)}{Q_{\mathrm{ECN}}}\right) + K_{16}} \tag{10}$$

$$Q_{\mathrm{EC}}(t) = \mathrm{COP}_{\mathrm{EC}}(t)P_{\mathrm{EC}}(t) \tag{11}$$

F. Heat Exchanger

Since the thermal efficiency of HE is basically the same under different thermal load condition, then in this paper we considered a fixed thermal efficiency which is represented as:

$$\eta_{\mathrm{HE}}(t) = \eta_{\mathrm{HEN}} = \frac{Q_{\mathrm{HEout}}(t)}{Q_{\mathrm{HEin}}(t)} \tag{12}$$

where $\mathrm{HE}_{\mathrm{in}}$ and $\mathrm{HE}_{\mathrm{out}}$ represent the input and output of heat exchanger, respectively.

G. Photovoltaic Generation

Solar photovoltaic systems convert solar irradiation into electricity we need through photoelectric effects. And the basic building block of solar photovoltaic power is either solar cells or photovoltaic cells [35]. In this paper, photovoltaic cell is operated in accordance with the predictive output $P_{\mathrm{S}}(t)$.

IV. Optimal Operation of the EH

A. Objective Function

The daily operation cost under the premise of meeting the electricity, hot water and cooling demands is used as the objective function. The expression of the objective function can be written as follows:

$$\begin{aligned} \mathrm{MinC_{OC}} = \sum_{t=1}^{24} \{ & 3600 C_{\mathrm{NG}}[V_{\mathrm{AB}}(t) + V_{\mathrm{NG}}(t)] \\ & + C_{\mathrm{E}}(t)[P_{\mathrm{pur}}(t) - P_{\mathrm{sold}}(t)]\} \end{aligned} \tag{13}$$

As shown in (13), the daily operation cost C_{OC} represent the sum of the consumed natural gas costs and the daily electricity costs. The first part of the operation cost in the equation is the consumed natural gas costs of EH, which is written as the product of natural gas prices and natural gas usage at the time t. There are two sources of natural gas consumed during time t, one from GT and the other from HRSG. In terms of daily electricity costs, it is noteworthy that the excessive electricity can be transferred to the public power grid. Thus, the daily electricity cost at the time t also has two sources, which are the cost of purchasing electricity $P_{\text{pur}}(t)$ and the revenue of selling electricity $P_{\text{sold}}(t)$ respectively. In this paper, we assumed the prices of purchasing and selling electricity are the same.

B. Constraints

As Fig. 1 shows, the EH consists of various kinds of energy conversion equipment. Therefore, the energy balance, capacity and opposite condition constraints will be discussed.

1) Energy Balance Relationships

At any time t, the electricity balance needs to be satisfied which is formulated as:

$$P_{\text{GT}}(t) + P_{\text{s}}(t) + P_{\text{d}}(t) + P_{\text{pur}}(t) - P_{\text{c}}(t) - P_{\text{EC}}(t) - P_{\text{sold}}(t) - L_{\text{E}}(t) = 0 \tag{14}$$

In (14), the sum of power generated and purchased is equal to the sum of the power used and sold to the grid.

The thermal load balance at the time t is expressed as follows:

$$Q_{\text{HR}}(t) - Q_{\text{HEin}}(t) - Q_{\text{ACin}}(t) = 0 \tag{15}$$

Equation (15) indicates that the output thermal energy of HRSG is given by the sum of thermal energy consumption of AC and HE.

The cooling load balance at the time t which cannot be ignored is defined as:

$$Q_{\text{EC}}(t) - Q_{\text{AC}}(t) - L_{\text{C}}(t) = 0 \tag{16}$$

It can be observed from (16) that the cooling load is supplied by both the AC and the EC.

2) Operation Limit

The output of equipment in the EH should not exceeds its operation limit. In addition, its on-off status is constrained as well owing to the binary variables.

$$\delta_{\text{GT}}\alpha_{\text{GT}}P_{\text{GTN}} \leq P_{\text{GT}}(t) \leq \delta_{\text{GT}}P_{\text{GTN}}, \delta_{\text{GT}} \in \{0,1\} \tag{17}$$

$$\delta_{\text{HR}}\alpha_{\text{HR}}Q_{\text{HRN}} \leq Q_{\text{HR}}(t) \leq \delta_{\text{HR}}Q_{\text{HRN}}, \delta_{\text{HR}} \in \{0,1\} \tag{18}$$

$$\delta_{\text{EC}}\alpha_{\text{EC}}Q_{\text{ECN}} \leq Q_{\text{EC}}(t) \leq \delta_{\text{EC}}Q_{\text{ECN}}, \delta_{\text{EC}} \in \{0,1\} \tag{19}$$

$$\delta_{\text{AC}}\alpha_{\text{AC}}Q_{\text{ACN}} \leq Q_{\text{AC}}(t) \leq \delta_{\text{AC}}Q_{\text{ACN}}, \delta_{\text{AC}} \in \{0,1\} \tag{20}$$

Furthermore, the capacity of ESB is constrained by its state of charge, the charging power and the discharging power. The initial level of electricity storage in the day is equal to the final level of the electricity stored in the day. Moreover, the heat exchanger has its capacity limit as well.

$$SOC^{\min} \leq SOC(t) \leq SOC^{\max} \tag{21}$$

$$0 \leq P_{\text{c}}(t) \leq P_{\text{c}}^{\max} \tag{22}$$

$$0 \leq P_{\text{d}}(t) \leq P_{\text{d}}^{\max} \tag{23}$$

$$SOC(1) = SOC(24) \tag{24}$$

$$0 \leq Q_{\text{HEout}}(t) \leq Q_{\text{HEN}} \tag{25}$$

C. Solution Method

The formulations of the model aforementioned result in an MINLP problem due to the introduced on-off status and non-linear terms of the optimization problem. The off-designed model of EH is a MINLP problem which can be solved on the platform of GAMS with Baron. This method can effectively solve linear and nonlinear optimization problems involving large scale variables. For more information on the solver and its availability, please refer to [36]. The settings of Baron's detail optimization parameters in this article are shown in Table I.

TABLE I
THE SETTINGS OF BARON'S DETAIL OPTIMIZATION PARAMETERS.

Parameter settings	Values
Absolute integer feasibility tolerance	1e-5
Absolute constraint feasibility tolerance	1e-5
Mixed-integer optimality gap	1e-8
Time limitation	50

V. CASE STUDY

EHs can have various applications, such as a factory, a hotel and residential areas. As shown in Fig. 1, the EH consisting of natural gas, electricity and solar energy as inputs and electricity, cooling and hot water as outputs is used as the test system in this study. In addition, the price of natural gas and electricity are important factors affecting the optimal operation of the considered EH. The electricity price is reported in Table II, showing that the electricity prices change over time while natural gas prices are set as a constant value of 3.5 $¥/\text{m}^3$ in this paper [29].

In this section, we evaluate the off-design and design models on two test cases characterized by different load conditions. For the first case study, a fixed load condition is utilized to compare the difference between the optimal operation results obtained by those two models while various load conditions are used for the second case study. In the latter case, for the purpose of comparing the relative error of operation costs obtained by design and off-design models, 27 optimization runs in which the electricity load, cooling load and hot water load are taken as different values are carried out firstly. Then, a realistic load case which is a hotel in Beijing is implemented to verify the validity of the conclusions observed from above 27 optimization runs. The two test cases are described in detail below.

A. Case A

A fixed load condition is applied to the off-design and design models of the EH in this case study. For the sake of comparison, the demand of end users is considered the same for those two models. The various demands of a residential

TABLE II
REAL-TIME ELECTRICITY PRICE.

Time	1	2	3	4	5	6	7	8	9	10	11	12
Price (¥/kWh)	0.23	0.2	0.18	0.17	0.17	0.2	0.25	0.32	0.43	0.62	0.72	0.96
Time	13	14	15	16	17	18	19	20	21	22	23	24
Price (¥/kWh)	1.02	1.08	1.19	1.01	0.87	0.66	0.72	0.78	0.89	0.79	0.6	0.42

area with multiple buildings on a typical day in summer are represented in Fig. 2, where the electricity and cooling demand exist all the day and the hot water load only occurs in daytime. Furthermore, the forecasting output of photovoltaic cell is also shown in Fig. 2. Other data concerning the EH including the capacity, rated efficiency and some dimensionless coefficients of the equipment in the EH are given in Table III. Moreover, Fig. 3 depicts the performance curves of various components in the EH based on the informations shown in Table III. It is noteworthy that both the efficiency and COP of components are distinct with their rated value, which implies that ignoring the off-design features of the components may lead to the inaccuracy result of EH's optimal operation.

TABLE III
PARAMETERS OF THE EQUIPMENTS AS FOR CASE A

Unit	Term	Value
GT	P_{GTN}	3500 kW
	η_{GTN}	0.276
	$\alpha_{\text{GT}}^{\min}$	0.2
	K_1	−0.000004
	K_2	1.0585
	K_3	−1448
	K_4	0.000001
	K_5	1.7751
	K_6	1474
HRSG	Q_{HRN}	3700 kW
	η_{HRN}	0.9
	$\alpha_{\text{HR}}^{\min}$	0.2
	K_7	−0.6249
	K_8	1.525
	K_9	0.0951
EC	Q_{ECN}	2800 kW
	COP_{ECN}	4
	$\alpha_{\text{EC}}^{\min}$	0.2
	K_{10}	0.75
	K_{11}	0.0195
	K_{12}	0.213
AC	Q_{ACN}	2800 kW
	COP_{ACN}	1.676
	$\alpha_{\text{EC}}^{\min}$	0.2
	K_{13}	0.66
	K_{14}	−0.915
	K_{15}	1.27
	K_{16}	0.015
ESB	E	3400 kW
	$P_{\text{c}}^{\max}$	1700 kW
	$P_{\text{d}}^{\max}$	1900 kW
	$SOC^{\max}$	0.9
	$SOC^{\min}$	0.2
	η_{c}	0.95
	η_{d}	0.95
	f	0.04

For the sake of assessing the effect of EH's simulation models on its optimal operation strategy, the optimal operation results calculated by the design and off-design models are graphically represented in Fig. 4–Fig. 6, which correspond to the electricity, heating and cooling optimal operation results, respectively. As for the optimal operation cost, the value obtained by the off-design model and design model is shown in Table IV. As we can see, the operation cost by off-design model is ¥ 66215.2, which is far higher than that obtained by design model, ¥ 60570.9, and the computational time is longer than the design model. However, the off-design model is more accurate than the design model.

Focusing on electricity optimal schedules, it can be observed

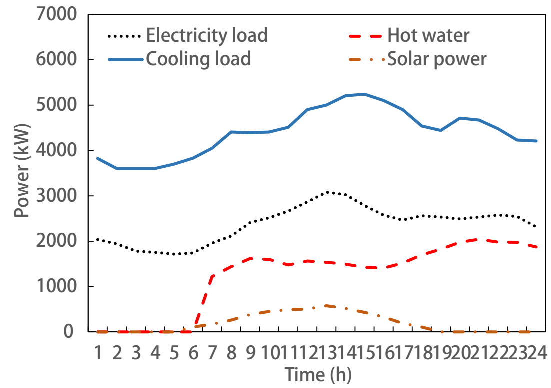


Fig. 2. Forecasting Output of Photovoltaic and Load demand of a typical day.

TABLE IV
THE RESULTS OBTAINED BY OFF-DESIGN AND DESIGN MODEL

Model type	Operation cost (¥)	Computation time (s)
Off-design model	66215.2	12.3431
Design model	60570.9	0.5325

from Fig. 4 that the operation strategy obtained from off-design model is similar to that obtained from design model. However, there are distinct differences in the concrete numerical results in terms of the unit output. For example, from 11:00 am to 22:00 pm, both the GT are switched on, while they are off when the real-time electricity prices are relatively lower. If inspected completely, higher output power of the GT based on the off-design model will be observed, comparing to the output based on the design model. This is due to the fact that the efficiency of GT varies with the load levels; then the GT output of off-design model is more than that of design model as to supply the equal quantity electricity demand. Moreover, at 15:00 pm and 21:00 pm, the generated electricity is more than the requirement. Hence, part of excess electricity is sold to public power grid. In the whole day time, ESBs achieve the function of peak averting and valley filling.

Concerning the heating optimal schedules, the steam out of HRSG is used to drive the AC and HE simultaneously. During the time period from 1:00 am to 6:00 am, the hot steam generated by both the HRSGs are totally supplied to AC because there is no hot water demand. Furthermore, it can be also observed from Fig. 5 (a)-(b) that the supplemental gas combustion of HRSG based on the off-design model is much more than the gas based on the design model. This is mainly for the reason that the efficiency of HRSG modeled based on off-design characteristics is relatively lower than the efficiency modeled based on design condition. In order to meet the same heating requirement, a larger amount of input gas of HRSG is needed. From the cooling optimal operation schedule point of view shown in Fig. 6, both the EC take on more cooling load than AC when electricity price is low. However, during the peak hours when electricity price is high, AC will take on more cooling load than EC due to the start-up of GT.

As discussed above, there exists apparently difference between the optimal operation strategy obtained by design and off-design models. However, the individual effect of each equipment on the optimal operation cost of EH can not be

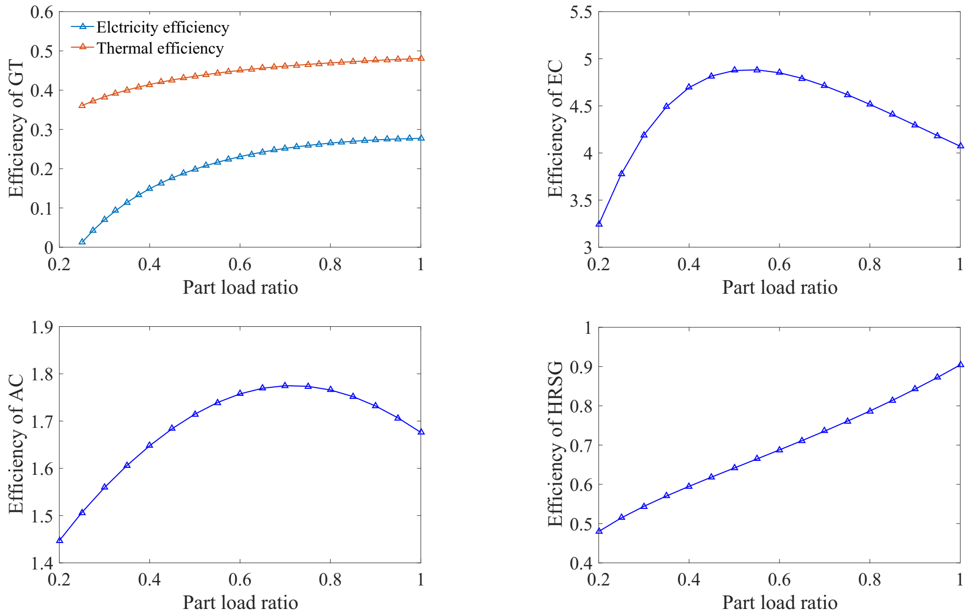
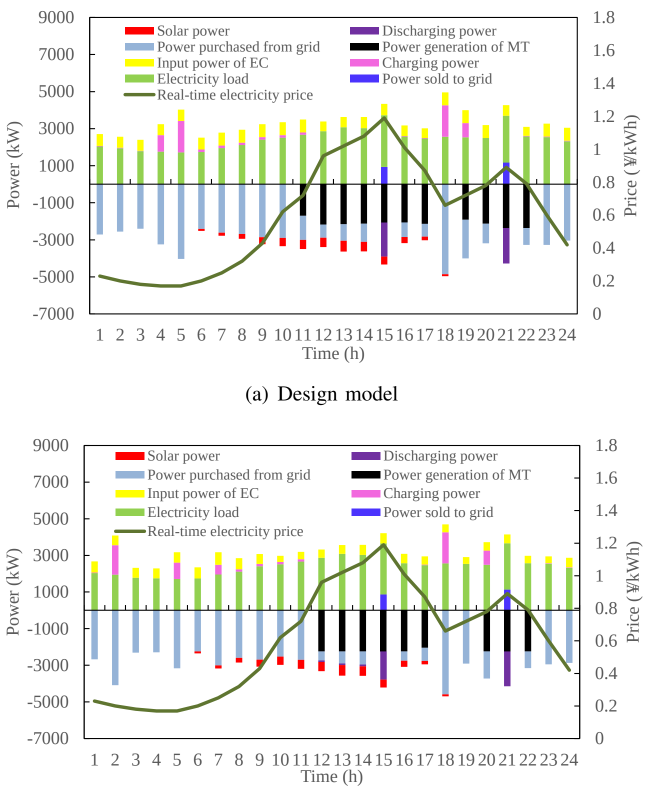


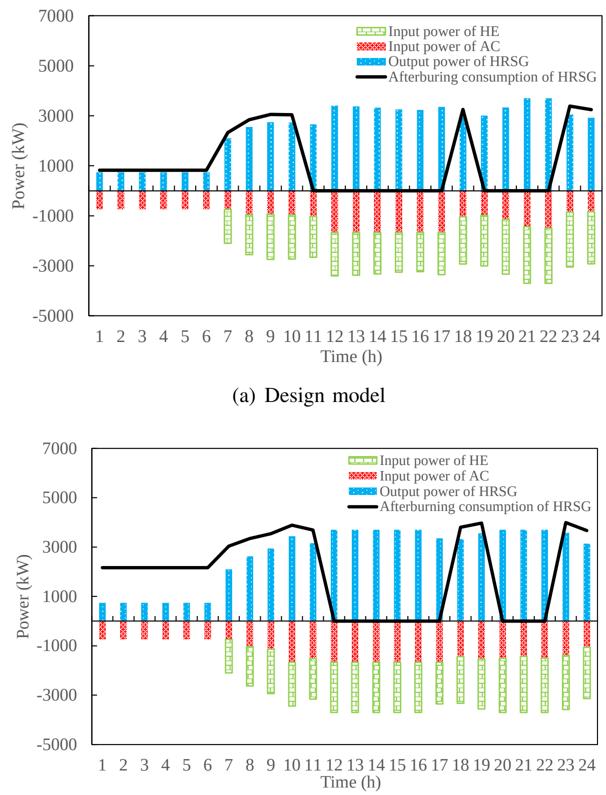
Fig. 3. EH's efficiency characteristic curves of each part GT, AC, EC and HRSG.



(a) Design model

(b) Off-design model

Fig. 4. Electricity optimization results as for design and off-design models.



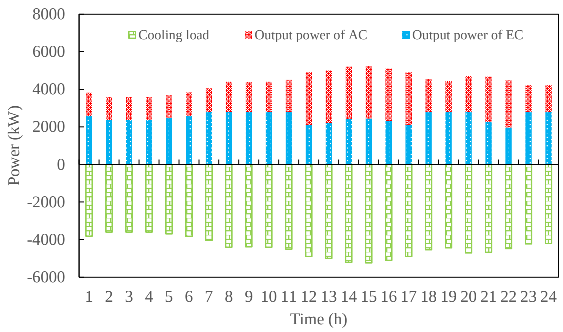
(a) Design model

(b) Off-design model

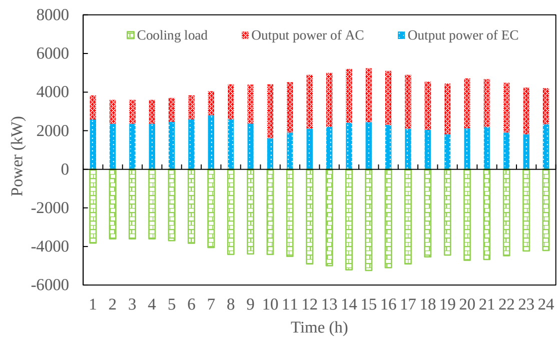
Fig. 5. Heating optimization results as for design and off-design models.

clearly figured out in the above analysis, while the off-design characteristic is considered. As a consequence, the off-design characteristics, belonging to a certain equipment of EH, will be taken into consideration in the following four optimization runs. The results of optimal operation costs and the relative errors between off-design and design models are summarized in Table V.

According to the information in Table V, the off-design characteristics of GT and HRSG have more noticeable impact on the optimal operation cost comparing to that of EC and AC. Moreover, the significant increase can also be observed when considering the off-design characteristics of HRSG rather than GT. Particularly, the operation costs obtained by model 3 and model 4 are slightly lower than that calculated by design



(a) Design model



(b) Off-design model

Fig. 6. Cooling optimization results as for design and off-design models.

model. This is a direct consequence of the higher COP of AC and EC, resulting in less consumption of heat and electricity. Moreover, the reason for the smaller error of operation cost calculated by model 3 and model 4 when compared to both the model 1 and 2 is that the fluctuating range of both EC and AC efficiency curves are higher than that of GT and HRSG efficiency curves.

Given the results of this case, it can be stated that the off-design characteristics of equipment are needed to be considered in the optimal operation of EHs. The relative error between the design model and off-design model is approximately 10% while it gets smaller when part of the equipment is modeled under off-design condition. Note that the efficiency of equipment under off-design condition is generally smaller than the rated efficiency, the optimal operation cost based on off-design model is consequently higher than design model. In particular, the COP of EC and AC are higher than the rated value under some part load ratios, leading to a lower operation cost than design model. Although the operation strategy difference between the design and off-design model is analyzed in this case, what the difference will be under various load conditions is yet to be solved, and this issue will be further investigated in Section V-B.

B. Case B

This case consists of the same equipment as case A, and in addition, applies to the case of various electricity, cooling and hot water load conditions. For the purpose of researching the effects of load variations on the relative error of the optimal operation cost, we assume that these loads are in the form of ratios for the C2E and the H2E. Firstly, the ratios of C2E and H2E are both taken as 1.5, 1 and 0.5, which forms 9 cases (3 × 3). Then, the electricity load are taken as 100%, 75% and 50% of the initial electricity load in order to assess the impacts of electricity load variations on EH's optimal operation. Thereby, a total number of 27 optimization calculations (3 × 3 × 3) are performed. It's worth mentioning that the benefits of this kind of load set are that the simulation result is not restricted to a special load type. Furthermore, the hourly electricity demand of a building is shown in Fig. 7. Since the capacity of the equipment in the EH refers to the actual load demand, the unit sizes used in case B are reported in Table VI. Under various load conditions, the deviations of the optimized operation cost change among these cases, as summarized in Table VII.

TABLE VI
PARAMETERS OF THE EQUIPMENT AS FOR CASE B.

Unit	Term	Value
GT	P_{GTN}	2000 kW
	η_{GTN}	0.24
	$\alpha_{\mathrm{GT}}^{\mathrm{min}}$	0.39
HRSG	Q_{HRN}	4500 kW
	η_{HRN}	0.9
	$\alpha_{\mathrm{HR}}^{\mathrm{min}}$	0.2
EC	Q_{ECN}	2300 kW
	$\mathrm{COP}_{\mathrm{ECN}}$	4.3
	$\alpha_{\mathrm{EC}}^{\mathrm{min}}$	0.2
AC	Q_{ACN}	2300 kW
	$\mathrm{COP}_{\mathrm{ACN}}$	1.79
	$\alpha_{\mathrm{EC}}^{\mathrm{min}}$	0.2
ESB	E	2000 kW
	$P_{\mathrm{c}}^{\mathrm{max}}$	1000 kW
	$P_{\mathrm{d}}^{\mathrm{max}}$	1000 kW

Figure 8 shows the data from Table VII in the style of a graph. Figures 8 (a)-(c) depict the relative errors under various C2E and H2E ratios as the electricity load is 100%, 75% and 50% of the initial electricity load, respectively. From the relative error point of view, Fig. 8 (a) shows that the increasing ratio of H2E leads to a smaller relative error on the basis of assuming the C2E ratio as a fixed value. Similarly, assuming that C2E ratio is a fixed value, the larger relative error can be also observed when decreasing the ratio of C2E. This is because the lower ratios of C2E and H2E, corresponding to the total less load demand, will result in the smaller efficiency

TABLE V
EFFECTS OF EACH EQUIPMENT ON THE OPTIMAL OPERATION COST CONSIDERING OFF-DESIGN CHARACTERISTICS

Model	GT	HRSG	EC	AC	Operation cost (¥)	Relative error (%)	Computation time (s)
1	√	–	–	–	63542.1	4.905	5.3421
2	–	√	–	–	64843.7	7.054	7.5418
3	–	–	√	–	59945.8	0.103	5.5682
4	–	–	–	√	60378.1	0.003	6.9405

Note: "–"denotes the off-design characteristics to be ignored, "√ "denotes the off-design characteristics to be considered.

TABLE VII
OPTIMAL OPERATION COST UNDER DIFFERENT C2E AND H2E RATIO

No.	E	C2E	H2E	Design model (¥)	Off-design model (¥)	Relative error (%)
1	1	1.5	1.5	51139.40	53782.10	5.16
2	1	1	1.5	47755.23	51220.83	7.25
3	1	0.5	1.5	44732.38	51143.06	14.30
4	1	1.5	1	42709.62	49637.41	10.58
5	1	1	1	40774.07	47499.07	24.15
6	1	0.5	1	37864.98	47009.51	27.61
7	1	1.5	0.5	36508.26	46620.55	28.52
8	1	1	0.5	33981.83	44321.82	29.83
9	1	0.5	0.5	31089.57	40373.11	6.22
10	0.75	1.5	1.5	44943.76	47739.62	7.72
11	0.75	1	1.5	41976.34	45216.14	14.92
12	0.75	0.5	1.5	39326.69	45194.86	15.96
13	0.75	1.5	1	36568.03	43330.22	19.41
14	0.75	1	1	34634.68	41359.61	28.96
15	0.75	0.5	1	31926.54	41173.32	35.32
16	0.75	1.5	0.5	30381.79	41111.98	40.12
17	0.75	1	0.5	27658.74	38758.62	45.03
18	0.75	0.5	0.5	26855.75	40232.92	50.01
19	0.5	1.5	1.5	38961.68	41650.49	6.91
20	0.5	1	1.5	35957.63	39200.14	9.01
21	0.5	0.5	1.5	33087.96	39667.09	19.82
22	0.5	1.5	1	30508.91	37532.48	22.43
23	0.5	1	1	28767.19	35457.71	23.25
24	0.5	0.5	1	25861.94	35720.89	38.10
25	0.5	1.5	0.5	24301.84	34483.56	41.06
26	0.5	1	0.5	21537.86	32623.22	51.47
27	0.5	0.5	0.5	20865.94	33188.95	55.12

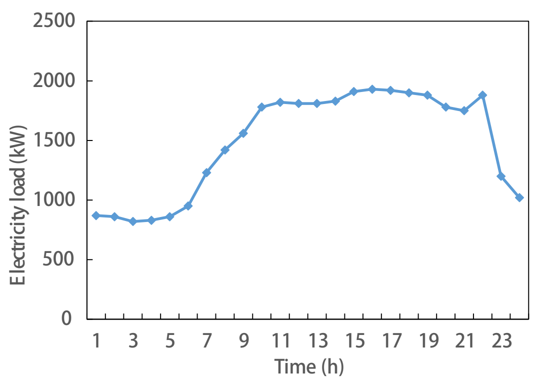


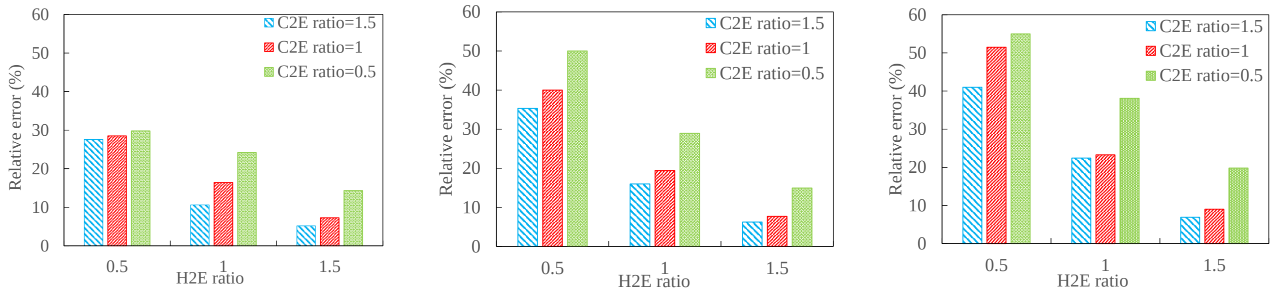
Fig. 7. The hourly electricity demand of a building.

of equipment. Consequently, the larger relative error of the operation cost between design and off-design models will be obtained. Despite these difference, we can also observe from Figs. 8 (a)-(c) that the relative error increases significantly with the reduction of electricity load, revealing that the relative error of optimal operation cost is not only influenced by the C2E and H2E ratio but also influenced by the electricity load set. According to Fig. 8 (c), we can observe that the relative error takes the maximum value when the electricity load is 50% of the original value, while it gets smaller with the increase of C2E and H2E ratio.

As mentioned above, we have analyzed the influence of various load conditions on relative error by calculating optimal operation cost between the design model and off-design model. The EH optimal operation cost decreases with the reduction of C2E and H2E ratio, while the relative error of the operation cost obtained by those two models increases when the EH is operated in low C2E and H2E ratios. Moreover, electricity load is another key factor affecting the relative error, and the error is shown to be a larger value when the electricity load is in the lower range. For the purpose of demonstrating the validity and facticity of the above conclusions, a case study is implemented in the following part.

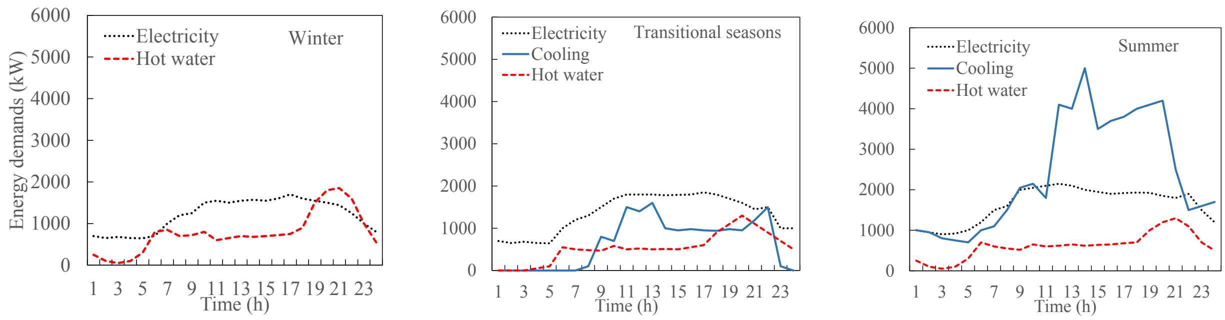
The hourly cooling, hot water and electricity requirements of three typical days in winter, transitional and summer seasons are shown in Fig. 9. As far as the actual load condition is concerned, it is worth noting that the energy demand is from a typical hotel, which covers an area of 60000 square meters in Beijing [24]. Concerning the load conditions of the three seasons, it is obvious that the hot water requirement and the electricity exist all year around, while the cooling demand is only appear in Summer and transitional seasons. In addition, the electricity demand remains relatively constant throughout all seasons, whereas the cooling and hot water requirements vary considerably depending on the type of the seasons.

Figure 10 illustrates the optimal operation costs and relative errors obtained by design and off-design models. As mentioned previously, the increase of operation cost can be observed when using the off-design characteristics rather than constants to model efficiencies. From the relative error point of view, it increases significantly when the EH is running in winter, where the cooling load is zero and H2E ratio is about equal to 0.5. We can see the relative error obtained by the day of summer is the minimum one, comparing to that obtained by the day of transitional seasons and winter. This is mainly for the reason that the electricity, cooling and hot water requirements in days of summer are close to the capacity of the equipments in the EH. Therefore, although the relatively higher energy demand leads to the maximum optimal operation cost, the minimum relative error can be obtained at the same time.



(a) Electricity load = 100% (b) Electricity load = 75% (c) Electricity load = 50%

Fig. 8. Relative error between the design model and off-design model.



(a) (b) (c)

Fig. 9. Energy demands of a hotel in Beijing.

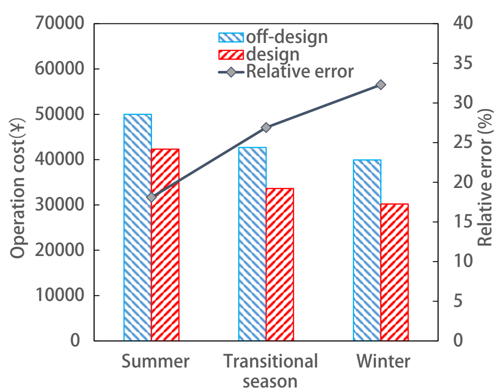


Fig. 10. The operation cost and relative errors of the costs obtained by design and off-design models.

VI. Conclusion

This paper have compared the difference of optimal operation strategy and the relative error of the operation cost between those two models. Moreover, the individual effect of the off-design characteristics of equipment on the optimal operation has also been evaluated and the simulation results have been verified.

The operation cost of off-design model is higher than that of the design model. But from the point of view of the optimal operation strategy, off-design model does better than the design model in terms of the authenticity of the operation schedule. Therefore, from a long-term perspective, simply using the design model for the optimal operation of EHs will have negative impact in the aspect of system planning and design.

As for the off-design characteristics of single equipment in the EH, the off-design characteristics of HRSG and GT have been proved to have a more significant effect on the operation cost than those of both AC and EC, which emphasizes the individual effect of off-design characteristics of HRSG and GT. Regarding to the relative error, it increases with the reduction of the electricity, cooling and hot water load. The largest relative error is approximately equal to 50%, implying that ignoring the off-design characteristic of EH's equipment will lead to an inaccuracy result for the optimal operation cost, especially when the load is small.

The results obtained by the two cases have provided some reference guide when simulating the optimal design and operation of EHs. In our future work, the impact of the off-design model on the capacity planning of EHs will be further studied.

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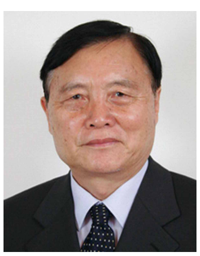

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