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# A new operation strategy for CCHP systems with hybrid chillers

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ABSTRACT

Performance and economical efficiency of the combined cooling, heating and power (CCHP) system mainly depend on the system structure, operation strategy and choice of facility capacity. This paper proposes a structural configuration of the CCHP system with hybrid chillers, consisting of a combined electric and absorption chiller, whose electric cooling to cool load ratio varies according to different electric and thermal loads in every hour. A new operation strategy, based on the variational electric cooling to cool load ratio, for the CCHP system with unlimited and limited power generation unit (PGU) capacity is investigated. Given the proposed operation strategy, an optimization algorithm is adopted to determine the optimal PGU capacity. In addition, a case study of a hypothetical hotel in Victoria, BC, Canada is conducted to verify the feasibility of the proposed CCHP system structure and the corresponding optimal operation strategy.



## 1. Introduction

Combined cooling, heating and power (CCHP) systems, which can also be referred to the trigeneration systems, are broadly employed in small-medium scale power systems in order to achieve economical efficiency and less contamination [1–3]. The main idea of the CCHP system is to make use of the excess heat rejected from the power generation unit (PGU) to regenerate thermal energy that can be used to compensate for the building energy demand gap [4–6]. CCHP systems have been widely introduced into various kinds of buildings, such as office buildings, hotels and hospitals [7,8].

Classical CCHP systems adopt PGUs to generate electricity, and the rejected heat from a PGU is recovered by the heating recovery system to provide the prime energy for the cooling and heating load. Thermally activated technology is adopted in the CCHP system. The absorption chiller is installed to absorb and adsorb the recovered heat to meet the cooling demand [9,10]; the heating unit reheats the recovered heat to meet the heating demand. The CCHP system can be regarded as a general model of the combined heating and power (CHP) system – a proven and reliable technology [11,12]. When operating in winter, with no chiller running, the CCHP system degrades to the CHP system. The goal of designing CCHP systems is to reduce the primary energy consumption, the annual cost and the carbon dioxide emission as much as possible. To achieve this, the following issues should be incorporated into the design consideration: The system operation strategy, the individual component efficiencies, and the building demand for power, heating, and cooling [13].

Typically, there are two basic operation strategies: Following the thermal load (FTL) and following the electric load (FEL) [14,15]. They can also be referred to the thermal demand management (TDM) and the electric demand management (EDM) [16]. The comparisons and analyses of these two strategies are investigated in [16–22]. When operating at FTL mode, the CCHP system satisfies the building's thermal load first; if the by-product electricity cannot meet the electric demand, additional electricity should be purchased from the local grid. When operating at FEL mode, it provides sufficient electricity for the building first, and then if the by-product heat cannot meet the thermal demand, an auxiliary boiler, combusting the fuel, will be activated. However, both FEL and FTL strategies will inherently waste energy. Some operation strategies based on different evaluation criteria are discussed in [23–25]. As stated in [26], CCHP systems operate at peak efficiency when the thermal and electric loads are well-matched. Thus, one of the objectives of this paper is to design an operation strategy to meet the thermal and the electric loads with less energy consumption and carbon dioxide emission. The strategy design depends on the building's energy consumption, and also electricity and fuel rates.

In [27,28], the authors propose a new CCHP system structure different from the conventional CCHP system structure, whose cooling load all lands on the absorption chiller. The new structure adopts a combination of absorption and electric chillers. An electric chiller has a high coefficient of performance (COP) to be around 3, which leads to a high cooling efficiency. However, taking the high rates of the electricity into account, an operation strategy needs to

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**Nomenclature**

| | |
|---|---|
| CCHP | combined cooling, heating and power |
| CDE | carbon dioxide emission |
| CDER | carbon dioxide emission reduction |
| COP | coefficient of performance |
| EC | evaluation criteria |
| FEL | following the electric load |
| FTL | following the thermal load |
| HTC | hourly total cost |
| HTCS | hourly total cost savings |
| PES | primary energy savings |
| PGU | power generation unit |
| SP | separation production |

*Symbols*

| | |
|---|---|
| $C$ | cost |
| $E$ | electricity |
| $F$ | fuel |
| $L$ | facility life |
| $N$ | installed power |
| $Q$ | thermal energy |
| $x$ | electric cooling to cool load ratio |
| $\eta$ | efficiency |
| $\mu$ | carbon conversion factor |

*Subscripts*

| | |
|---|---|
| *ac* | absorption chiller |
| *annual* | annual value |
| *b* | boiler |
| *c* | cooling |
| *ca* | carbon |
| *e* | electricity |
| *ec* | electric chiller |
| *f* | fuel |
| *gap* | energy gap |
| *grid* | local grid |
| *h* | heating |
| *hour* | hourly value |
| *hrc* | recovered heat for cooling |
| *hrh* | recovered heat for heating |
| *hrs* | heat recovery system |
| *m* | total consumption |
| *p* | parasitic |
| *pgu* | power generation unit |
| *pgum* | PGU capacity |
| *r* | recovered |
| *red* | redundant |
| *user* | user |
| *userl* | lower bound of user |
| *useru* | upper bound of user |

*Superscripts*

| | |
|---|---|
| CCHP | CCHP system |
| SP | SP system |

be designed to determine the optimal effort of the electric chiller. A parameter called electric cooling to cool load ratio is the one to determine the effort. In the literature [27,28], this ratio is chosen to be fixed. However, in this paper, despite the same hybrid chillers are chosen, the ratio is optimized according to the variant energy consumption in every hour and the energy rates, which has not been investigated in other literatures.

Another most concerned problem in designing CCHP systems is the sizing problem, i.e. determining the capacities of facilities. Facilities' capacities in the SP system and chillers, heating unit and boiler in the CCHP system are easy to choose because their sizes depend on the corresponding energy load. Some cost-based sizing optimization approaches have been investigated in [1,7,29–33]. However, as a result of the complexity of operation strategies, the PGU capacity is hard to determine. Considering the prices of facilities, external electricity and fuel rates, and facilities' lives, some optimization approaches have been adopted to obtain the optimal PGU capacity, such as the particle swarm optimization [28], the genetic algorithm optimization [27,34] and the mixed integer nonlinear programming (MINLP) algorithm [35,36]. In this paper, the enumeration algorithm is adopted to determine the optimal value of PGU capacity.

This paper is organized as follows. A description of energy flow of the CCHP system, and the optimal operation strategies for the CCHP system with unlimited and limited PGU capacities are presented in Section 2. Evaluation criteria used in choosing different strategies constrained by primary energy rates are shown in Section 3. The last Subsection of Section 3 gives the mathematical model of the optimization problem. A case study in Section 4 verifies the feasibility of the proposed optimal operation strategies and optimal PGU capacity. Finally, Section 5 concludes the paper.

## 2. Optimal operation strategy

The system diagram of the CCHP system with hybrid chillers implemented is shown in Fig. 1. The solid line, dashed line and dot dashed line represent the thermal energy flow, primary energy flow and electricity flow, respectively.

The system equations and optimal operation strategies for CCHP systems are separated into the following two parts.

### 2.1. CCHP systems with unlimited PGU capacity

In this section, the scenario in which the PGU has no capacity limitation will be discussed. The idea of the optimal strategy is to make the electric demand and thermal demand match with each other [26]. The term '*match*' here means that all of the electric and thermal demand of the building is provided by the PGU, namely $F_b = 0$, $E_{grid} = 0$ and electric cooling to cool load ratio $x \in [0, 1]$. Most of the time, according to different energy consumption in different seasons and different hours in one day, the PGU cannot exactly provide the electricity and thermal energy for the building use. For example, following the FEL strategy, if the thermal load is less than that the PGU provides, energy waste is inevitable; if the thermal load is larger than the amount PGU provides, additional fuel should be purchased for the auxiliary boiler. For a fixed electric cooling to cool load ratio CCHP system, electric load, cooling load and heating load can only match at a point. However, by introducing the variational electric cooling to cool load ratio, the range for the energy loads to match with each other can be extended. By adjusting the electric cooling to cool load ratio, the electric load and thermal load can be accordingly tuned. Since $x$ can only vary in $[0, 1]$, there exists an appropriate range for the $E_{user}$ to vary to match with $Q_c$, $Q_h$ and $E_p$. This range can be obtained by two limiting situations.