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# Performance comparison of combined cooling heating and power system in different operation modes

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ABSTRACT

Operation mode of combined cooling heating and power (CCHP) system determines its energetic and environmental performances. This paper analyzes the energy flows of CCHP system and separated production (SP) system. The fuel energy consumptions of CCHP system following electrical demand management (EDM) and thermal demand management (TDM) are deduced respectively. Three indicators: primary energy saving, exergy efficiency and $CO_2$ emission reduction, are employed to evaluate the performances of CCHP system for a commercial building in Beijing, China. The feasibility analysis shows that the performance of CCHP system is strictly dependent upon building energy demands. The selection of CCHP operation modes is systemically based on building loads, CCHP system and local SP system. The calculation results conclude that CCHP system in winter under EDM achieves more benefits than in summer. The sensitivity discussion indicates that the coefficient of performance for cooling and the efficiency of electricity generation are the most sensitive variables to the energetic and environmental performances of CCHP system.



## 1. Introduction

Combined cooling heating and power (CCHP) system, also called trigeneration system, is broadly defined as the energy supply system by generating electricity onsite near the load and recycling the exhaust gas for heating, drying, cooling, or dehumidifying [1,2]. It is identified as an alternative for the world to meet and solve energy-related problems, such as increasing energy demands, increasing energy cost, energy supply security, and environmental pollution [1,3–7].

Many researchers have studied CCHP systems from different aspects such as model [3,8–17], optimization [14,16,18–26], feasibility analysis [11,18,27–37], and evaluation [3,4,38–50] to meet the development goal of sustainable energy. A good CCHP system must yield economic savings, but more importantly must yield primary energy savings as well as reducing the emission of pollutants. Generally, primary energy consumption [3,38], primary energy saving (PES) [39–41], fuel energy saving ratio [42], energy-efficiency [43] are employed to show the energetic performance of CCHP system. The environmental impacts of CCHP system are often evaluated in the amounts of $CO_2$ emission [3], and the reduction of $CO_2$ emission and/or other greenhouse gases [39,41,44–46].

The performances of CCHP system are closely related to its design, and more importantly the operation mode determines its energetic and environmental performances. The most distinctive operation modes are the following [3,51,52].

### 1.1. Electric demand management (EDM)

The generated electricity of CCHP system at any moment in time is equal to the electrical load. If the co-generation heat is lower than the thermal load, the supplementary heat is needed; if it is higher, excess heat is rejected to the environment through coolers or exhaust gases.

### 1.2. Thermal demand management (TDM)

The useful thermal output at any moment in time is equal to the thermal load. If the generated electricity is higher than the load, excess electricity is sold to the grid or stored; if it is lower, supplementary electricity is purchased from the grid.

In the utility sector, the mode of operation depends on the building load, the availability of power plants and the commitments of the utility towards customers regarding the supply of electricity and heat. To discuss the application rules of operation strategies, Mago et al. [3] developed a CCHP operation model following thermal or electrical load and compared the primary energy consumptions (PEC) and the $CO_2$ emissions of four CCHP systems in

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**Nomenclature**

| | |
|---|---|
| CCHP | combined cooling heating and power |
| CHP | combined heating and power |
| $CO_2E$ | $CO_2$ emission |
| $CO_2ER$ | $CO_2$ emission reduction |
| COP | coefficient of performance |
| EDM | electric demand management |
| PEC | primary energy consumption |
| PER | primary energy ratio |
| PES | primary energy saving |
| PGU | power generation unit |
| SP | separated production |
| TDM | thermal demand management |

*Symbols*

| | |
|---|---|
| *BV* | vector of building energy consumption |
| *CV* | vector of CCHP system parameters |
| *E* | electricity |
| *EX* | exergy |
| *Q* | heat |
| *F* | fuel |
| *HHV* | high heating value |
| *LHV* | low heating value |
| *SV* | vector of SP system parameters |
| *T* | temperature |
| *V* | volume |
| $\eta$ | efficiency |
| $\mu$ | conversion factor |

*Subscripts*

| | |
|---|---|
| *b* | boiler |
| *c* | cool |
| *ch* | absorption chiller |
| *e* | electricity |
| *EX* | exergy |
| *f* | fuel |
| *grid* | electricity grid |
| *h* | heat |
| *p* | pump |
| pgu | power generation unit |
| *r* | recovery heat |
| *rc* | the part of recovery heat for cooling |
| *rec* | waste heat recovery system |
| *rh* | the part of recovery heat for heating |

*Superscripts*

| | |
|---|---|
| EDM | electric demand management |
| SP | separated production |
| TDM | thermal demand management |

USA. Jalalzadeh-Azar [52] studied a gird-independent EDM and TDM CHP models for an office building and analyzed the influence of the subsystem efficiencies on the total primary energy consumption. Moreover, some researchers proposed some special optimal operation strategies for CCHP systems. Fumo et al. [53] proposed emission strategy of CCHP system to minimize emission of pollutants. Cho et al. [54] optimized an operation scheme for CCHP system based on operational cost, PEC and $CO_2$ emission. Wang et al. [25] applied the optimal cooling ratio to operate CCHP system and maximized energy-saving, cost-saving and environment-protecting potentials. Ren and Gao [55] analyzed two different operation modes including minimum-cost operation and minimum-emission operation for residential micro combined heating and power (CHP) systems.

This investigation aims to analyze the energetic and environmental performances of CCHP system under EDM and TDM. The energetic performance is evaluated in PES and exergy efficiency. $CO_2$ emission reduction ($CO_2ER$) is employed to indicate the environmental performance of CCHP system compared to separated production (SP) system. The instantaneous performances of CCHP system with the instantaneous building loads are paid more attention. Moreover, the sensitivity of CCHP system to the technical parameters are analyzed to find out the improvement potential in systems and/or equipments.

## 2. SP system and CCHP system

### 2.1. SP system

The typical SP system providing cooling, heating, and power for building is shown in Fig. 1. The energy demands of building include: (1) electrical energy for lights and equipments in building, $E$; (2) thermal energy for space cooling, $Q_c$; (3) thermal energy for space heating and domestic hot water, $Q_h$; and (4) parasitic electrical energy in SP system such as the energy consumption of pumps and fans, $E_p^{SP}$. The electricity in SP system comes from the local electrical grid. The cooling system adopts electrical chiller. The gas boiler provides thermal energy and then the heat is distributed to users through heating coils.

The total electrical energy from the grid, $E_{grid}^{SP}$, is

$$E_{grid}^{SP} = E + E_c + E_p^{SP} \quad (1)$$

where $E_c$ is the electricity consumed by the electrical chiller and it can be replaced to

$$E_c = \frac{Q_c}{COP_e} \quad (2)$$

where $COP_e$ is the coefficient of performance (COP) of the electrical chiller.

Considered the energy loss in electricity transmission, the total electricity from grid is converted to the fuel energy consumption as follows

$$F_e^{SP} = \frac{E_{grid}^{SP}}{\eta_e^{SP}\eta_{grid}} \quad (3)$$

where $\eta_e^{SP}$ and $\eta_{grid}$ are the efficiency of electricity generation and the transmission efficiency of grid, respectively.

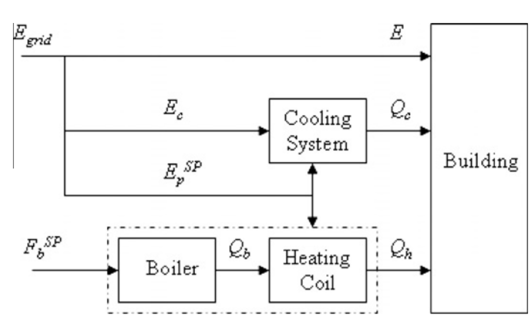


**Fig. 1.** General separated production system layout for building and energy flows.