Comparative Study on Heating and Cooling Systems Integrated with Energy Storage

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Abstract. Taking a commercial building in Shanghai as an example, a list of cooling and heating systems are established and operation strategies are formulated. Based on the precondition that the excess electricity can be sold to the grid, the primary energy utilization rate and economices of the energy supply schemes are analyzed. The results show that compared with the traditional heating and cooling supply method, the combined cooling, heating, and power systems have better energy-saving and economic benefits. Additionally, the inclusion of the thermal energy storage yields additional economic benefits (up to 36% reduction in the CO2eq emissions and up to the 21% reduction in the total annual cost). Under the following-electric-load operation mode, the role of the thermal energy storage is to alleviate the temporal mismatch between the electric demand and the heating or cooling demand. To be specific, in the combined cooling, heating, and power systems, the total annual cost is reduced by up to 5.8% and the annual carbon dioxide equivalent emissions are reduced by up to 2.4% when the thermal energy storage is used. While under the following-electric-price operation mode, the performance of the CCHP system is largely subject to the natural gas price. Last, although heat pump systems are often regarded as efficient systems owing to the relatively high coefficient of performance of the heat pump, the energy supply through the heat pump systems may be carbon-emission-intensive currently.

1 Introduction

Heating and cooling demands are expected to continuously increase considering the rising demand for the indoor thermal comfort across the world. With a variety of energy storage technologies becoming technically and economically feasible, such as sensible and latent heat storage, the energy-storage-integrated heating and cooling systems are expected to be widely adopted in the future.

Nomenclature

AC	Air conditioning
CCHP	Combined cooling, heating, and power
DHS	District heating system
FEL	Following electric load
FEP	Following electric price
FTL	Following thermal load
TES	Thermal energy storage

Plenty of previous studies have shown advantages of energy storage, particularly thermal energy storage (TES), when it is deployed in heating and cooling systems [2]. Long-term advantages include the avoidance of additional combustion chambers, peak generators, and the upgrade of the transmission and distribution network [1]. During daily operation, TES relieves the intermittence of renewables and the temporal mismatches of the energy supply and demand, thereby facilitating the integration of renewables or time-varying waste energy and enabling generators to operate under optimal conditions. Furthermore, the operation costs of the heating and cooling systems are expected to be reduced when TES is utilized to exploit the electricity price variations under time-of-use or real-time electric tariffs [11].

Recognizing the abovementioned benefits of the deployment of TES in the heating and cooling systems, a few previous studies have focused on the planning and

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operational optimization of the systems. Zheng et al. explored the potential roles that different energy storage technologies played in CCHP systems when three different operation strategies, i.e., following-heat-load, following-electric-load, and following-electric-price, were applied [5]. Nuytten et al. found that TES as a buffer exhibited a significant influence on the flexibility of the combined heating and power system [7]. Powell et al. developed a dynamic optimization method for optimally shifting loads by using TES in a combined cooling, heating, and power (CCHP) system [8]. In addition to the CCHP system, TES is also widely adopted in a heat pump system for enhancing the technical and economic performance of the system and the flexibility of the heating supply [10; 15]. In addition, distributed TES is installed in buildings to shift heating or cooling loads for reducing the operating costs of the heating, ventilation, and air conditioning systems [12]. Alternatively, TES systems are also deployed in the conventional district heating systems (DHS) to defer the upgrade of the generation, transmission, and distribution facilities, or replace low-efficient peak generators [13].

Although previous studies have investigated the planning for the energy-storage-integrated heating and cooling systems, few of them conducted extensive comparisons among them. Therefore, the present study aims to first explore the potential roles that energy storage technologies are going to play in different heating and cooling systems, and then provide comparative studies for a list of options.

2 Data and methods

2.1 System configurations

Four representative heating and cooling systems are investigated and compared in the present study, which are:

(i) CCHP system without energy storage (termed as CCHP);

(ii) CCHP system with TES (termed as CCHP-TES);

(iii) ground-source heat pump system with TES (termed as HP-TES);

and (iv) conventional natural-gas-fired district heating system and distributed air-conditioning (AC) system without energy storage (termed as DHS-AC).

Although a variety of TES technologies are technically feasible, only short-term sensible heat storage, e.g., water tank, is considered in the present study considering the technology readiness level [2]. In addition, the long-term benefits of TES as virtual peak generators are not considered.

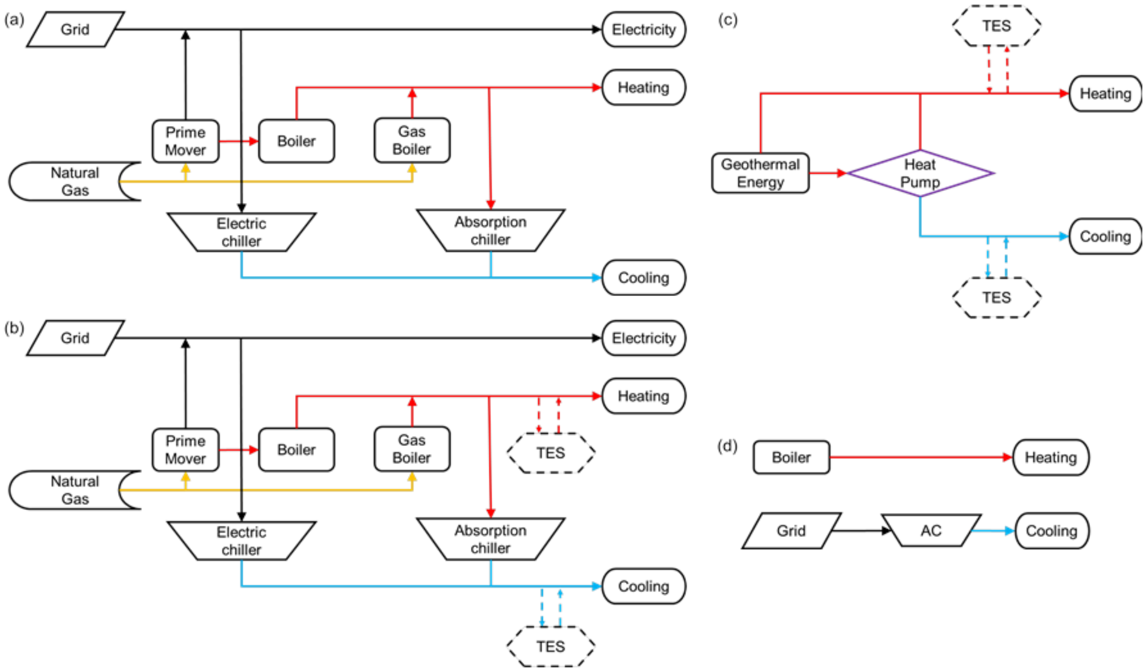

Fig. 1. System diagrams of investigated energy supply systems: (a) CCHP, (b) CCHP-TES, (c) HP-TES, and (d) DHS-AC

The investigated CCHP system (as illustrated in Fig. 1a) is assumed to be operated under the following-thermal-load (FTL) mode. It is assumed that the excess electricity generated by the CCHP system can be sold back to the grid. Under the FTL mode, there is no excess electric product and thus no need for energy storage. With the inclusion of the TES (both heat and cold energy storage devices included), the CCHP system (Fig. 1b) is either operated under the following-electric-load (FEL) mode or the following-electric-price (FEP) mode. Under the FEP mode, the prime mover is turned off when the electric price is low and dispatched at its full capacity during peak hours. Excess heat and cold energy is stored in the heat and cold energy storage, respectively, and supplied to the consumers when needed. Similarly, the dispatch of the heat pump is such that it operates at the optimal coefficient of performance during off-peak hours and the excess heating and cooling products are stored in the TES (Fig. 1c). The DHS-AC system is illustrated in Fig. 1d.

2.2 Models

The energy (heating, cooling, and power) balance of the investigated systems are as follows:

(i) CCHP

$$\begin{aligned} H(t) &= G_{ICE,heat}(t) + G_{GB}(t) \\ C(t) &= G_{ABS}(t) + G_{EC}(t) \\ E(t) + P_{EC}(t) &= P_{ICE,ele}(t) + P_{grid}(t) \end{aligned} \tag{1}$$

(ii) CCHP-TES

$$\begin{aligned} H(t) &= G_{ICE,heat}(t) + G_{GB}(t) + P_{TES}(t) \times \eta_{TES} \\ C(t) &= G_{ABS}(t) + G_{EC}(t) + P_{TES}(t) \times \eta_{TES} \\ E(t) + P_{EC}(t) &= P_{ICE,ele}(t) + P_{grid}(t) \end{aligned} \tag{2}$$

(iii) HP-TES

$$\begin{aligned} H(t) &= G_{HP}(t) + P_{TES}(t) \times \eta_{TES} \\ C(t) &= G_{HP}(t) + P_{TES}(t) \times \eta_{TES} \\ E(t) + P_{HP}(t) &= P_{grid}(t) \end{aligned} \tag{3}$$

(iv) DHS-AC

$$\begin{aligned} H(t) &= G_{DHS}(t) \\ C(t) &= G_{AC}(t) \\ E(t) + P_{AC}(t) &= P_{grid}(t) \end{aligned} \tag{4}$$

Where, $H(t)$, $C(t)$, and $E(t)$ denote the heating, cooling, and power demands at time step t, respectively; $G_{ICE,heat}(t)$, $G_{GB}(t)$, $G_{HP}(t)$, and $G_{DHS}(t)$ denote the heat generation of the prime mover (internal combustion engine in the present study), the gas boiler, the heat pump, and the district heating system at time step t, respectively; $G_{ABS}(t)$, $G_{EC}(t)$, $G_{HP}(t)$, and $G_{AC}(t)$ denote the cold generation of the absorption chiller, the electric chiller, the heat pump, and the AC at time step t, respectively; $P_{EC}(t)$, $P_{HP}(t)$, and $P_{AC}(t)$ denote the power consumption of the electric chiller, the heat pump, and the AC at time step t, respectively; $P_{TES}(t)$ denote the charge (negative value) and discharge (positive value) energy of the TES, at time step t; and η_{TES} denotes the discharge efficiency (the inverse of the charge efficiency during the charge process) of the TES.

The sizing of the key devices in the CCHP system is determined by using the NSGA-II method with the three optimization objectives, which are (i) to reduce the annualized total cost (including annualized capital cost and yearly operation cost, as defined in the following equation), (ii) to reduce equivalent carbon dioxide emissions, and (iii) to increase the primary energy rate of the CCHP system [6]:

$$TAC = \frac{IR \times (1+IR)^n}{(1+IR)^n - 1} \sum CC_k + \sum [P_{grid}(t) \times PC_E(t) + NG(t) \times PC_{NG}] \tag{5}$$

Where, TAC denotes the total annualized cost; IR denotes the interest rate (10%); n denotes the lifetime of the system (20 years); CC_k denotes the capital cost of the device k; $P_{CE}(t)$ and PC_{NG} denotes the tariff rate of the electricity and the natural gas, respectively; and $NG(t)$ denotes the consumption of the natural gas at time step t.

Although the power demand is not the focus of the present study, considering that electricity is one of the essential products of the CCHP system, the electricity tariff costs for meeting the power demand in addition to the electricity consumed by the heat pump and the AC are included in the operating costs of the HP-TES and the DHS-AC systems for providing fair comparisons among the investigated four systems. The income obtained through the sell of the excess electricity back to the grid at the flat electricity price (see Table 1), if any, is taken off from the *TAC* of the CCHP system.

The optimal solution is selected by using the technique for order preference by similarity to ideal solution method with the weighting of the three optimization objectives being determined according to the corresponding information entropy values [6]. Based on the preliminary results, the crossover and mutation rates of the NSGA-II method are set as 0.7 and 0.1, respectively, to guarantee the convergence of the optimization results within 300 generations. The economic and technical parameters of the devices involved are provided in Table 1.

In addition, the capacities of the ground-source heat pump and the TES are optimized for reducing the *TAC* of the system. The sizes of the DHS and the AC in the DHS-AC system ire determined according to the maximum heating load and the maximum cooling load, respectively.

2.3 Case study

To illustrate the roles of the TES in different heating and cooling systems, a case study is conducted for a commercial building in Shanghai, China [6]. Detailed demand profiles are provided in Fig. 2. The time-varying electric tariffs are provided in Table 1 and the tariff of the natural gas is set as 2.8 RMB/m³. Some other essential economic and technical parameters are also provided in Table 1. The remaining parameters can be found in the reference [6].

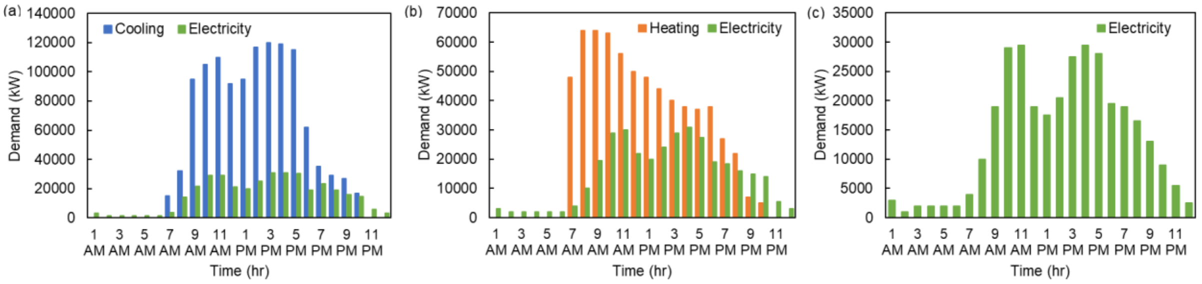

Fig. 2. Demand profiles for a commercial building in Shanghai, China: (a) cooling season, (b) heating season, and (c) transition season.

Table 1. Economic and technical parameters.

Parameters	Value	Unit
Efficiency of boiler	0.8	/
Coefficient of performance of absorption chiller	1.2	/
Efficiency of gas boiler (incl. DHS)	0.9	/
Coefficient of performance of electric chiller (incl. AC)	3	/
Coefficient of performance of heat pump (cooling mode)	3	/
Coefficient of performance of heat pump (heating mode)	4	/
Charging efficiency of TES	0.9	/
Discharging efficiency of TES	0.95	/
Natural gas price	2.8	RMB/m³
Flat electricity price	0.7912	RMB/kWh
Peak electricity price (7 PM to 9 PM)	1.3688	RMB/kWh
Parity electricity price (8 AM to 11 AM, 1 PM to 7 PM, and 9 PM to 10 PM)	1.0207	RMB/kWh
Valley electricity price (1 AM to 8 AM, 11 AM to 1 PM, and 10 PM to 24 PM)	0.4273	RMB/kWh
Tax rate	0.0615	/
Cost of the prime mover (small-scale internal combustion engine)	4000	RMB/kW
Cost of boiler	300	RMB/kW
Cost of absorption chiller	1202.5	RMB/kW
Cost of gas boiler	300	RMB/kW
Cost of electric chiller	968.5	RMB/kW
Cost of TES	200	RMB/kWh
Equivalent carbon dioxide emissions coefficient of the grid power	0.968	kg/kWh
Equivalent carbon dioxide emissions coefficient of natural gas	0.22	kg/kWh
Heating days (no cooling loads) per year	90	days
Cooling days (no heating loads) per year	122	days
Transition days (no heating and cooling loads) per year	153	days

3 Results and discussion

The optimized system configurations are presented in Fig. 3 along with the corresponding *TAC*s, annual operating costs, and annual equivalent carbon dioxide emissions being displayed in Fig. 4.

3.1 CCHP systems

The resulting primary energy utilization rates of the CCHP system under the FTL mode, the CCHP-TES system under the FEL mode, and the CCHP-TES system under the FEP mode are 0.6213, 0.6616, and 0.5964, respectively, which are significantly higher than the typical primary energy utilization rate of a traditional energy supply system.

Although the optimized capacities of the TES (both heat and cold energy storage) are relatively small in the CCHP-TES system under the FEL mode, it can be found that the inclusion of the small TES devices drives the significant reductions in the resulting *TAC*s and carbon dioxide equivalent emissions as compared to those values obtained for the CCHP system (FTL mode). Here, the role of the TES is to alleviate the temporal mismatch between the electric demand and the heating or cooling demand. During the cooling and heating seasons and under the FEL mode, when the cooling demand is beyond the generation capacity of the prime mover, the insufficient cooling supply is met by the supplementary electric chiller. By contrast, the recovered heat from the prime mover is more than the needed energy for meeting the cooling demand through the absorption chiller, thereby leading to the wasted energy. This part of the wasted energy can be recovered by the TES. To this end, the overall *TAC* is reduced by up to 5.8% and the annual carbon dioxide equivalent emissions are reduced by up to 2.4% when the TES is used. It should also be noted that the gaps are relatively small during the heating and cooling seasons. Therefore, the needed TES capacity is relatively small for this specific case.

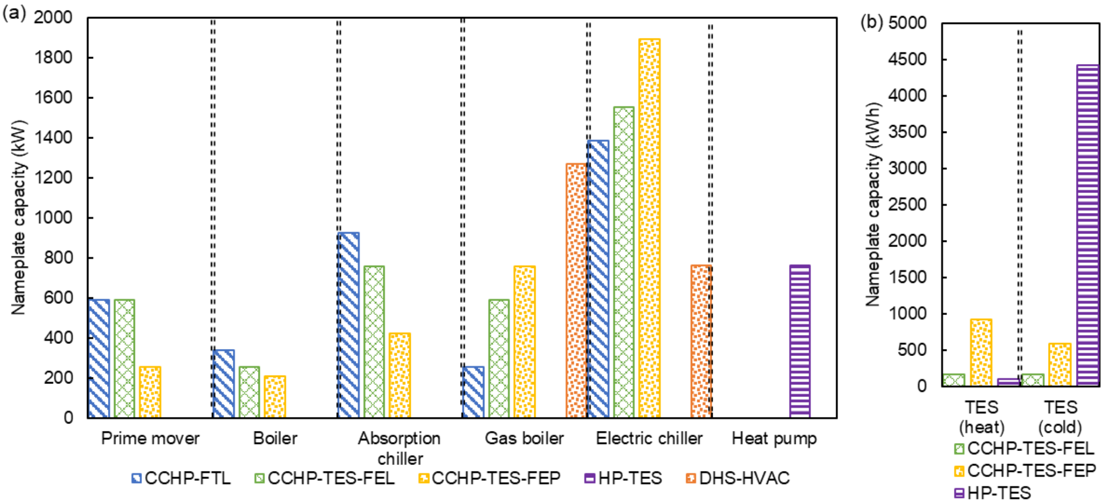

Fig. 3. Optimized capacities of key devices in the investigated heating and cooling supply systems: (a) prime mover, boiler, absorption chiller, gas boiler, electric chiller, and heat pump; and (b) heat energy storage and cold energy storage.

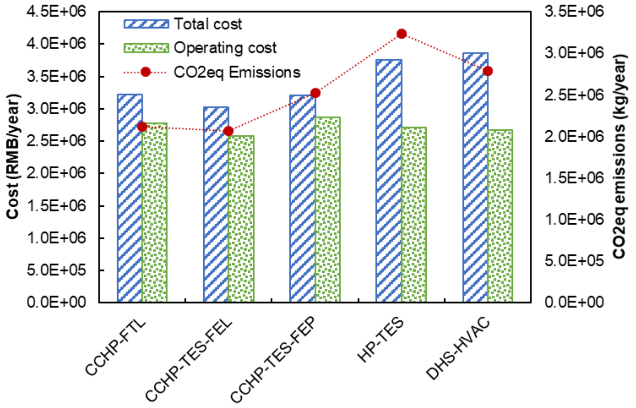

Fig. 4. Annualize total costs, annual operating costs, and CO2 emissions of the investigated heating and cooling supply systems.

The FEP dispatch strategy functions such as the prime mover is turned off when the grid electric price is relatively low (see valley price in Table 1). During off-peak hours, the auxiliary devices operate to meet the cooling and heating demands. And the TES is deployed to shift heating or cooling generation from off peak to peak hours (e.g., [9]). In this regard, the optimized capacities of the prime mover, the boiler, and the absorption chiller are significantly reduced. Nevertheless, under the given natural gas price, the FEP dispatch strategy yields the similar *TAC* as the CCHP-FTL case, and larger *TAC* as compared to the CCHP-TES-FEL case. Additionally, the use of the TES leads to charge and discharge losses, thereby yielding extra operating costs and CO_2eq emissions under the CCHP-TES-FEP case. Recognizing that the results are largely subject to the natural gas price, the impacts of the natural gas price on the performance of the three CCHP-related cases are addressed in the subsection 3.3.

3.2 HP systems

As shown in Fig. 4, the switch to the HP-TES system yields the increments in the *TAC* and the CO_2eq emissions. Under the given economic parameters and the emission factors of the grid power and the natural gas, the energy generation through the gas boiler and the electric chiller is less economic and more emission intensive than that through the prime mover, the boiler, and the absorption chiller. This hypothesis is verified by the DHS-AC system which leads to the highest *TAC* as compared to the CCHP systems (see Fig. 4). Regarding the CO_2eq emissions, the charge and discharge of the TES yields extra losses and thus increases the overall emissions. Moreover, the heat pump system is the only system that consumes grid electricity but no natural gas. Recognizing that the current grid electricity is less greenhouse-gas-intensive as compared to the natural gas, the system bases only on the electricity, i.e., HP-TES system in the present study, yields the highest CO_2eq emissions.

3.3 Impacts of natural gas price

As abovementioned, the superiorities of the investigated heating and cooling supply systems are largely subject to the natural gas price, which may span a wide range [14; 3]. Therefore, the present study investigates the impacts of the natural gas price by varying the natural gas price from 1.5 to 4 RMB/m^3. As shown in Fig. 5, overall, the natural gas price has minor impacts on the resulting CO_2eq emissions and the primary energy utilization rates of the CCHP system and the CCHP-TES system under the FEL mode. When the natural gas price increases, the *TAC*s under these two cases display stable increasing trends as shown in Fig. 5a.

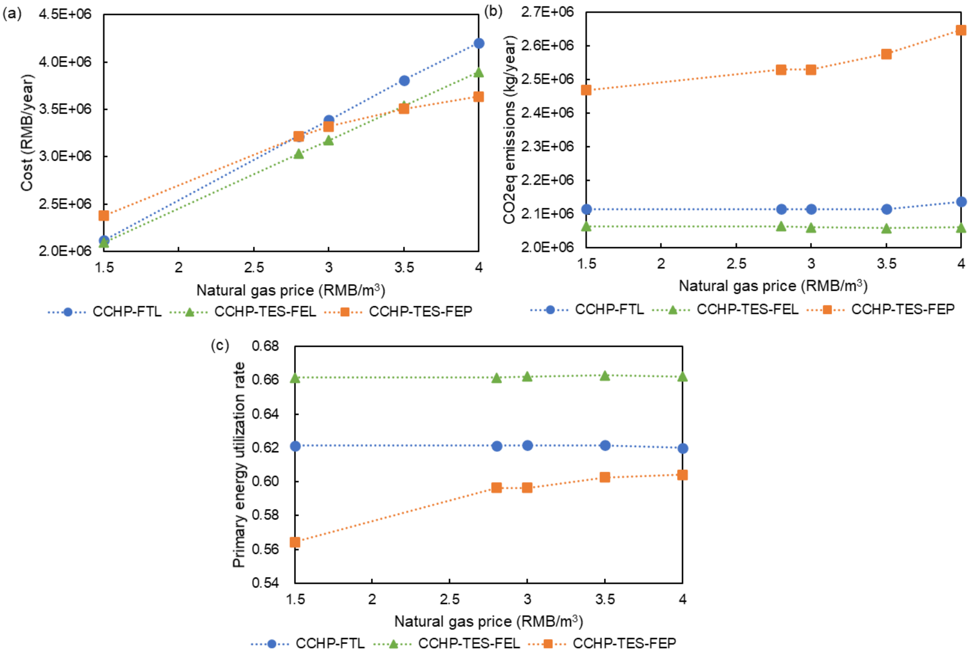

Fig. 5. (a) Annualize total costs, (b) CO_2 emissions, and (c) primary energy utilization rates of the investigated CCHP systems when the natural gas price spans the range from 1.5 to 4 RMB/m^3.

By contrast, the performance of the CCHP system under the FEP mode is largely subject to the natural gas price. To be specific, the TAC under the CCHP-TES-FEP case becomes less than that under the CCHP and the CCHP-TES-FEL cases when the natural gas price increases. At the natural gas price corresponding to 4 RMB/m3, the CCHP-TES-FEP case yields the lowest TAC, owing to that the strategy takes advantages of the relatively low electricity price during off-peak hours. Nevertheless, the CCHP-TES-FEP case yields the highest the CO2eq emissions due to the high utilization of the grid electricity.

It should be mentioned that when the natural gas price becomes 4 RMB/m3, the gaps with respect to the TAC among the CCHP systems and the HP-TES system are largely narrowed. Nevertheless, the benefits associated with the CCHP system remain when the reduction in the greenhouse gas emissions are taken into account, unless the emission factor of the grid electricity would be essentially reduced in the future.

4 Conclusions

To sum up, CCHP is an energy-saving and high-efficiency energy supply technology. The primary energy utilization rate can reach 66% during the cooling and heating periods. Compared with a traditional heating and cooling supply system, the CCHP system has better environmental (the CCHP-TES-FEL case yields the up to 36% reduction in the CO_2eq emissions compared to the DHS-HVAC system) and economic benefits (the CCHP-TES-FEL case yields up to the 21% reduction in the *TAC* compared to the HP-TES system).

Additionally, the inclusion of the TES yields additional economic benefits. Under the FEL mode, the role of the TES is to alleviate the temporal mismatch between the electric demand and the heating or cooling demand. Thereby, the sizing o the TES is subject to the specific cooling, heating, and electricity demands. The FEP mode functions such that the prime mover is turned off when the electric price is low and dispatched at its full capacity during peak hours. Under the such a mode, the performance of the CCHP system is largely subject to the natural gas price. At the natural gas price corresponding to 4 RMB/m^3, the CCHP-TES-FEP case yields the lowest *TAC*, owing to that the strategy takes advantages of the relatively low electricity price during off-peak hours. Nevertheless, the CCHP-TES-FEP case yields the highest the CO_2eq emissions due to the high utilization of the grid electricity.

Last, although heat pump systems are often regarded as efficient systems owing to the relatively high coefficient of performance, the energy supply through the heat pump systems may be carbon-emission-intensive when the emission factor of the grid power is relatively high.

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