# Energy and Exergy Analysis on China's Natural Gas Urban District Heating Systems for Replacing Coal: A Case Study of Beijing

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ABSTRACT

China has been vigorously developing natural gas-based urban district heating (UDH) for years to reduce air pollution. Various UDH systems are proposed for a case in the urban area of Beijing. This study investigates the effects of load percentages of different prime movers on the technical performances of several UDH systems at different ambient temperatures. A decrease in the gas turbine load percentage results in an obvious decrease in the exergy efficiency of the UDH system. The calculation results of heating and power outputs, energy and exergy inputs, and exergy efficiency of the UDH systems under different working conditions are presented. The heating association of distributed energy system and on-demand heat pump heating can reach the highest average-exergy-efficiency among the UDH systems. This optimal natural gas-based UDH system should be promoted in China instead of natural gas-fired heating boilers to replace coal-based UDH.

**Keywords**: CHP, urban district heating, distributed energy system, heat pump heating, exergy efficiency, combined cycle.

## INTRODUCTION

Energy and environmental issues have become increasingly prominent in the world [1,2]. Buildings comprise 40% of the global energy consumption and 40% to 50% of $CO_2$ emissions worldwide [3,4]. The total building area in China ranks first worldwide and continues to grow dramatically [5]. $CO_2$ emission from urban district heating (UDH), which has an average annual growth rate of 10.3%, was responsible for 4.4% of China's total $CO_2$ emission in 2009 [6]. Coal is the primary energy source for UDH in China [6,7]. The oxides of sulfur and nitrogen and inhalable particles released from coal combustion are the predominant sources of air pollution in China [7,8]. The coal-based UDH is particularly related to extraordinarily heavy air pollution and PM2.5 aerosols in winter in northern Chinese Cities including Beijing [9,10].

In the past decade, Chinese authorities began to promote natural gas-fired heating boilers instead of coal-fired heating boilers in major cities to mitigate the effects of urban air pollutants emitted by coal-based UDH [7,11,12,13]. The natural gas-fired heating boilers can reach a thermal efficiency of approximately 90%, which is higher than that of the coal-fired ones. The thermal efficiency is based on the first law of thermodynamics. In addition to this, exergy analysis based on energy grade is also needed to explore the avenues of replacing coal-based UDH with natural gas [14,15,16]. In reality, the majority of the exergy of natural gas is destructed when the high valued primary energy is used by the natural gas-fired heating boilers to provide low valued energy [17].

Distributed energy systems (DESs) are located in vicinity of load centers, and effectively reduce energy transport losses and environmental impacts. Meanwhile, DESs can realize energy cascade utilization of natural gas by using this primary energy to provide high-quality electricity as well as low-exergy steam and hot water [2,18]. Approximately 1000 natural gas-based distributed energy projects are expected to be developed as part of China's 12th Five-Year Plan (from 2011 to 2015). By 2020, natural gas-based DESs will have been implemented in most large-scale cities in China to increase energy unitization efficiency and reduce $CO_2$ emissions [19].

Various UDH systems are proposed for the University of Science and Technology Beijing (USTB), which is located in the urban area of Beijing. This study investigates the effects of load percentages of prime movers on the system efficiencies of several UDH systems. The objective of this study is maximization of the average-exergy-efficiency of the UDH system in an entire heating season. The constraints associated with this system integration and optimization mainly include types of prime movers, peak-shaving heating means, heat-to-power ratio, ambient temperatures, and operation hours at different ambient temperatures.

## SYSTEM DESCRIPTION

As shown in Figure 1, the DES studied in this study can use natural gas to simultaneously provide power, steam, and hot water. Natural gas fuels a gas turbine (GT) to generate power. GT exhaust waste heat is recovered to produce main steam through a heat recovery steam generator (HRSG). The main steam is supplied into a steam turbine to generate power. Low pressure steam can be extracted from the steam turbine and utilized for heating. This system is also called a combined cycle because it integrates a topping cycle (the GT primary output is power) and a bottoming cycle (the HRSG primary output is main steam to be expanded in a steam turbine). Next a hot water heater is added at the rear section of the HRSG to produce hot water by reducing flue gas temperature from approximately 120°C to 90°C. The hot water is also used for heating.

Additional power can be generated as supplementary firing is adopted in the HRSG [20]. Adjusting the supplementary fuel flow based on an ambient temperature can enlarge the steam supply capability of the DES with a supplementary-fired HRSG (DES-SF) to meet peak heating demand.

National average ownership of air conditioner per 10000 urban households in China was already 12200 by the end of 2011 [21]. The number of air conditioners has laid a solid foundation for the formation of a heating association of the DES and heat pump heating (DES+HPH) to replace coal-based UDH in the regions south of 41°N latitude in China [6].

The current total building area at USTB is 859 thousand square meters. In 2001, three natural gas-fired hot water boilers with capacity of 14 MW were built to replace all the coal-fired heating boilers. A new natural gas-fired hot water boiler of 14 MW was installed in 2010 to meet increased heating demands.

Various UDH configurations are proposed to meet the design heating load of 50.4 MW (see Table 1). This study adopts proven thermal engineering software of Thermoflow [22] to build models of a conventional combined heating and power (CHP) system and six UDH systems with different GT prime movers.

As shown in Table 1, the three heating associations or combinations (i.e., DES+NHB, DES+HPH and DES-SF) include the DES and peak-shaving heating means such as natural gas-fired boilers, heat pumps, and HRSG supplementary firing. Base load heating is undertaken by

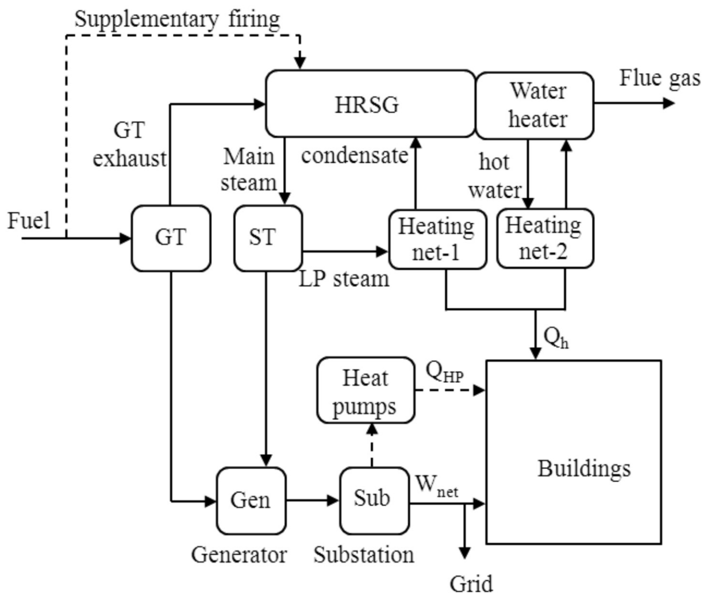



**Figure 1. Schematic diagram of distributed energy system**

the DES, while peak-shaving heating is supplied by additional heating means such as boiler, heat pump or supplementary HRSG firing.

China has a special provision that the on-grid electricity quotas assigned to a CHP project would be lowered when the CHP project does not reach the predetermined annual thermal efficiency and heat-to-power ratio. Moreover, when the CHP project generates more power than the on-grid electricity quotas, the power grid corporation dispatches such excess power with no payment to the CHP project [23]. The minimum heat-to-power ratio in this study is 0.6.

## METHODS

### Energy Analysis

The energy balance equation for a UDH system can be expressed as follows:

$$Q_{\mathrm{air}} + Q_{\mathrm{f}} + W_{\mathrm{in}} = W_{\mathrm{out}} + \sum Q_{\mathrm{h}} + Q_{\mathrm{l}} \tag{1}$$

**Table 1. Candidate UDH systems proposed for USTB and their power-gen installation capacities**

| UDH system | Abbreviation | UDH configuration proposed for USTB | Power-gen installation capacity (MW) |
|---|---|---|---|
| natural gas-fired boilers | | 4 sets of 14 MW natural gas-fired hot water boilers | |
| natural gas-based CHP | | 1 set of natural gas-fired boiler, 1 set of steam turbine | 30 |
| DES including 1 set of small-scale heavy-duty GT and steam turbine | SHD DES | 1 set of 40 MW class small-scale heavy-duty GT and HRSG, 1 set of steam turbine | 60 |
| DES including 2 sets of aero-derivative (aero) GTs and 1 set of steam turbine | 2-on-1 DES | 2 sets of 30 MW class aero GTs and HRSGs, 1 set of steam turbine | 87 |
| association of DES and natural gas-fired hot water boilers | DES+NHB | 1 set of 30 MW class aero GT, HRSG and steam turbine, two sets of natural gas-fired hot water boilers | 40 |
| association of DES and heat pump heating | DES+HPH | 1 set of 30 MW class aero GT, HRSG, and steam turbine, heat pumps | 40 |
| DES with a supplementary fired HRSG | DES-SF | 1 set of 30 MW class aero GT, supplementary fired HRSG and steam turbine | 40 |

where $Q_{air}$ represents the heat transfer rate of inlet air flow of the GT or boilers, $Q_f$ is the energy input of consumed natural gas, $W_{in}$ indicates total power input consumed by the UDH system (generation losses), $W_{out}$ denotes total power output generated by the UDH system, $\sum Q_h$ represents overall heating outputs given by all the available heating means within the UDH system, and $Q_l$ represents various distribution energy losses in the UDH system. See Table 2 for the detailed expressions on the $W_{in}$, $W_{out}$ and $\sum Q_h$ of different UDH systems.

**Table 2. Power inputs, power outputs, and heating outputs of different UDH systems**

| UDH system | $W_{in}$ | $W_{out}$ | $\sum Q_h$ |
|---|---|---|---|
| natural gas-fired boilers | ignored | 0 | $Q_{NHB} \times \eta_p$ |
| natural gas-based CHP | $W_{aux,CHP}$ | $W_{ST,CHP}$ | $Q_{ps,CHP} \times \eta_p$ |
| SHD DES | $W_{aux,CC}$ | $W_{GT,SHD}+W_{ST,CC}$ | $(Q_{ps,CC}+Q_{hw,CC}) \times \eta_p$ |
| 2-on-1 DES | $W_{aux,CC}$ | $W_{GT,aero}+W_{ST,CC}$ | $(Q_{ps,CC}+Q_{hw,CC}) \times \eta_p$ |
| DES+NHB | $W_{aux,CC}$ | $W_{GT,aero}+W_{ST,CC}$ | $(Q_{ps,CC}+Q_{hw,CC}+Q_{NHB}) \times \eta_p$ |
| DES+HPH | $W_{aux,CC}+W_{HP}$ | $W_{GT,aero}+W_{ST,CC}$ | $(Q_{ps,CC}+Q_{hw,CC}) \times \eta_p+Q_{HP}$ |
| DES-SF | $W_{aux,CC}$ | $W_{GT,aero}+W_{ST,CC}$ | $(Q_{ps,CC}+Q_{hw,CC}) \times \eta_p$ |

In Table 2, $W_{ST,CHP}$ refers to the gross power generated by the steam turbine of natural gas-based CHP, $W_{aux,CHP}$ represents the overall power consumed by auxiliary equipment (i.e. pumps and fans) of natural gas-based CHP, $Q_{ps,CHP}$ indicates the heat transfer rate of steam provided for heating by natural gas-based CHP. $\eta_p$ is the energy transport loss rate of heating piping system at 10%.

$Q_{NHB}$ indicates the heat transfer rate of hot water provided by natural gas-fired boilers.

$W_{GT,SHD}$ indicates the work done by a small-scale heavy-duty GT, $W_{GT,aero}$ indicates the power generated by the aero-derivative GTs, $W_{ST,CC}$ represents the power provided by a combined cycle steam turbine, and $W_{aux,CC}$ indicates the work consumed by the auxiliary equipment of a combined cycle unit.

$Q_{ps,CC}$ indicates the heat transfer rate of steam provided for heating by the combined cycle unit, $Q_{hw,CC}$ indicates the heat transfer rate of hot water produced for heating by the stack water heater at the rear section of HRSG, $Q_{HP}$ indicates the heat transfer rate supplied by the heat pumps, and $W_{HP}$ is the power consumed by the heat pumps.

The heating capacity of an air-sourced electric-driven heat pump can be calculated as follows:

$$Q_{HP} = COP_h \times W_{HP} \quad (2)$$

where $COP_h$ and $W_{HP}$ represent a heating coefficient of performance and power consumption of the heat pump, respectively. The $COP_h$ is the ratio of heat rate delivered by the heat pump and power input of the heat pump at a specific ambient temperature. The values of $COP_h$ of the heat pump at different ambient temperatures of -9, -1.6, and +5°C were calculated to be 3.3, 3.6, and 4, respectively (see Table 3).

**Table 3. The heating coefficients of performance of the heat pump at different ambient temperatures***

| Brand | Type | Ambient Temperature (°C) | Rate of heat delivered† (kW) | Rate of energy input† (kW) | $COP_{heating}$ (kW/kW) |
|---|---|---|---|---|---|
| Tsinghua Tongfang | FS-L-R | -9 | 58 | 17.5 | 3.3 |
| | | -1.6 | 66 | 18.3 | 3.6 |
| | | +5 | 74 | 18.5 | 4 |

*Refer to Tsinghua Tongfang Artificial Environmental Corporation's product brochure on air source heat pump unit (I-CABB-G, 2011).
†The values are derived from performance curves at different ambient temperatures published in the product brochure.

The net power output of a UDH system is calculated as follows:

$$W_{net} = W_{out} - W_{in} \quad (3)$$

The electricity efficiency of a UDH system can be calculated as follows:

$$\eta_e = W_{net} / Q_f \quad (4)$$

The system thermal efficiency of a UDH system is calculated as follows:

$$\eta_t = (W_{net} + \sum Q_h) / Q_f \quad (5)$$

Currently, it is not practical for centralized heating plants in China to adjust to the heating load according to indoor temperatures of individual rooms and end-users' demand. Thus, alternatively, on-demand heating can be achieved by the economic operation of heat pumps. Heating time and capacity can be controlled according to indoor temperature, and heat pumps can be shut down if users need suspend the heating. For the on-demand heat pump heating (HPH), energy consumption per unit floor area is calculated using Eq. 6 [6]:

$$E_{\mathrm{he}} = E_{\mathrm{h24}} \times (1-\varepsilon) \times \delta_{\mathrm{p}} + E_{\mathrm{h24}} \times \varepsilon \times \delta_{\mathrm{r}} \tag{6}$$

where $E_{he}$ is the average annual energy consumption per unit floor area of the economic operation of HPH, $\varepsilon$ is the ratio of urban residential area to urban building area in the region feasible for replacing UDH with HPH at 0.894 [6], $\delta_p$ is the ratio of the average annual energy consumption per unit floor area of the economic operation of HPH in public buildings to that of the 24-h operation of HPH at 0.7, and $\delta_r$ is the ratio of the average annual energy consumption per unit floor area of the economic operation of HPH in residential buildings to that of the 24-h operation HPH at 0.4.

$$\delta_{\mathrm{p}} = \varepsilon_{\mathrm{r}} \tag{7}$$

$$\delta_{\mathrm{r}} = \theta_{\mathrm{r65}} \times [(1-\varepsilon_{\mathrm{s}}) + \varepsilon_{\mathrm{s}} \times \theta_{\mathrm{b}}] + (1-\theta_{\mathrm{r65}}) \times [\varepsilon_{\mathrm{s}} \times \theta_{\mathrm{b}} + (1-\varepsilon_{\mathrm{w}} - \varepsilon_{\mathrm{s}})] \tag{8}$$

where $\varepsilon_r$ is the ratio of regular heating time per day to 24 h per day at 0.42, $\varepsilon_s$ is the ratio of sleeping hours per day to 24 h per day at 0.3, $\varepsilon_w$ is the ratio of working hours per day to 24 h per day at 0.33, $\theta_{r65}$ is the ratio of the urban residential area of people aged 65 and over to the urban residential area in the region feasible for replacing UDH with HPH at 0.097, and $\theta_b$ is the ratio of the bedroom area of urban residential buildings to the urban residential area in the region feasible for replacing UDH with HPH at 0.5.

**Exergy Analysis**

The general exergy balance equation for a UDH system can be expressed as follows:

$$Ex_{\mathrm{air}} + m \times ex_{\mathrm{f}} = Ex_{\mathrm{w}} + \sum Ex_{\mathrm{h}} + I \tag{9}$$

with

$$Ex_{\mathrm{h}} = (1 - T_0 / T) \times Q_{\mathrm{h}} \tag{10}$$

$$Ex_{\mathrm{w}} = W_{\mathrm{net}} \tag{11}$$

$$ex_{\mathrm{f}} = ex_{\mathrm{ph}} + ex_{\mathrm{ch}} \tag{12}$$

where $Ex_{air}$ represents the rate of exergy transferred within inlet air flow to a control volume, m indicates mass flow of fuel, $ex_f$ represents the exergy flow per unit fuel input into the control volume, $Ex_w$ denotes the net power rate across the boundary of the control volume, $\sum Ex_h$ refers to the total rate of exergy transferred by means of heating fluids across the boundary, and I indicates exergy destruction. Moreover, $ex_{ph}$ indicates the physical exergy flow per unit fuel input into the control volume, and $ex_{ch}$ represents the chemical exergy flow per unit fuel input.

The physical exergy of unit fuel can be calculated as follows:

$$ex_{\mathrm{ph}} = h - h_0 - T_0 \times (s - s_0) \tag{13}$$

where h and s refer to the enthalpy and entropy of fuel, respectively. The subscript 0 refers to the reference state condition. In this study, the reference state condition is set to be 273.13 K (0°C) and 0.1013 MPa.

The chemical exergy of unit gaseous mixtures can be calculated as follows:

$$ex_{\mathrm{ch}} = \xi \times Q_{\mathrm{L}} \tag{14}$$

where $Q_L$ is the lower heating value of natural gas at 44936 kJ/kg, ξ indicates the ratio of chemical exergy to $Q_L$. ξ can be obtained from a general gaseous fuel with composition $C_xH_y$ calculated according to the following experimental correlation [24]:

$$\xi = 1.033 + 0.0169 \times y / x - 0.698 / x \tag{15}$$

The exergy efficiency of a UDH system is calculated as follows:

$$\psi = (Ex_{\mathrm{w}} + \sum Ex_{\mathrm{h}}) / (m \times ex_{\mathrm{f}}) \tag{16}$$

## RESULTS AND DISCUSSION

### Sizing UDH Systems

Sizing the UDH system at USTB is performed to provide a heating capacity of 50.4 MW at the design ambient temperature of -9ºC. As shown in Table 4, the UDH system including 4 sets of natural gas-fired hot water boilers reaches a thermal efficiency of 81%. However, its exergy efficiency is much lower than those of the other UDH systems. Approximately 80% exergy of its natural gas consumption is destructed. This portion of exergy can be efficiently converted to power prior to the generation of a low temperature heating fluid. While undertaking the same heating load of 50.4 MW, SHD DES generates more electricity by 45% with 9% less fuel consumption than natural gas-based CHP. 2-on-1 DES can provide 2.1 times the net power output of natural gas-based CHP by consuming 14% more natural gas. It is observed that the exergy efficiencies of the UDH systems with GT prime movers are in the range of 45.9%-51.1%, and are significantly higher than those of the natural gas-fired boilers and conventional CHP.

Equivalent fuel flows are required for both DES-SF and DES+NHB to undertake peak heating load at the ambient temperature of -9 ºC (see Table 4). DES-SF can deliver 7.6% more power (approximately 3 MW) at this working condition than DES+NHB. This difference shows that high-grade energy of the supplementary natural gas can be exploited by HRSG supplementary firing to increase power output, while the corresponding exergy is destructed in the natural gas-fired heating boilers.

DES+HPH can leverage the heat pumps to shave peak heating load, and ensures the DES to efficiently operate at full load in the entire heating season. The natural gas consumption of DES+HPH is much lower than that of any other UDH system except natural gas-fired boilers (see Table 4). As shown in Figure 1, the electricity consumption of HPH can be provided directly by the DES with the least power transmission loss. Thus, the electricity cost of HPH can be obviously reduced, compared with commercial electricity purchased from a central power grid.

### Effect of Partially Loaded Prime Movers on System Performance

An increase in ambient temperature leads to a decrease in heating load. The heat-to-power ratios of 2-on-1 DES, SHD DES and natural gas-based CHP are observed to decrease to 0.4, 0.5 and 0.6, respectively, when the three UDH systems run at full load to undertake the heating load of 24.4 MW at an ambient temperature of 5ºC (see Figure 2b, 2d, and 2f). Therefore, the boiler/GT load percentages and net power outputs of these

**Table 4. Analysis results of different UDH systems for USTB at the ambient temperature of -9°C**

| Heating means | Natural gas-fired boilers | Natural gas-based CHP | SHD DES | 2-on-1 DES | DES+ NHB | DES+ 24-h HPH | DES-SF | DES+ on-demand HPH |
|---|---|---|---|---|---|---|---|---|
| Boiler/GT load percentage (%) | 100 | 100 | 100 | 97 | 100 | 100 | 100 | 100 |
| Thermal input (MW) | 62.2 | 158.5 | 144.3 | 176.4 | 112.7 | 90.5 | 113.3 | 90.5 |
| Power output (MW) | | 39.8 | 58 | 79.7 | 39.4 | 33.9 | 42.4 | 36.4 |
| Thermal output-steam (MW) | 50.4 | 50.4 | 43.9 | 41.6 | 27.9 | 27.9 | 48.7 | 27.9 |
| Thermal output-hot water (MW) | | | 6.5 | 8.8 | 22.3 | 4.3 | 1.7 | 4.3 |
| Thermal output-HPH (MW) | | | | | | 18 | | 9.7 |
| Heat-to-power ratio | | 1.3 | 0.9 | 0.6 | 1.3 | 1.5 | 1.2 | 1.4 |
| Electricity efficiency (%) | | 25.1 | 40.2 | 45.2 | 34.9 | 37.4 | 37.4 | 40.3 |
| Thermal efficiency | 81 | 56.9 | 75.1 | 73.8 | 79.5 | 93.1 | 81.9 | 86.6 |
| Fuel exergy input (MW) | 65.6 | 167 | 152 | 186.2 | 118.9 | 95.5 | 119.6 | 95.5 |
| Exergy output-steam (MW) | | 15.9 | 13.8 | 13.1 | 8.8 | 8.8 | 15 | 8.8 |
| Exergy output-hot water (MW) | | | 1.7 | 2.2 | 6.4 | 1.1 | 1 | 1.1 |
| Exergy output-HPH (MW) | 13.3 | | | | | 2.1 | | 1.1 |
| Exergy efficiency (%) | 20.3 | 33.3 | 48.4 | 51.1 | 45.9 | 48 | 49.1 | 49.7 |

UDH systems should be lowered to meet the minimum heating-to-power ratio.

It is observed that a decrease in the GT load percentage results in an obvious decline in the heat-to-power ratio, exergy and electricity efficiencies of 2-on-1 DES or SHD DES, and has a slight impact on the thermal efficiency (see Figure 2a-2d). At the ambient temperature of 5 °C, the exergy output of SHD DES at 40% load is reduced to be approximately 40% of that at full load. However, the fuel input exergy of SHD DES accounts for approximately 60% of that at full load. The GT load percentage of 2-on-1 DES is reduced to 41% to meet the minimum heating-to-power ratio (see Figure 2d). The low GT load percentage is equal to one set of GT being shut down and the other set operating at approximately 80% load. Thus, the annual GT equivalent full load hours are reduced considerably. Moreover, the operation profit of the DES declines and the corresponding investment payback period is prolonged.

**Overall Evaluation Under Multiple Operational Conditions**

System analysis is conducted under non-design working conditions. As shown in Table 5a and 5b, the GT load percentages of 2-on-1 DES at ambient temperatures of -1.6 and +5 °C decrease to 64% and 41%, respectively. Consequently, the exergy efficiencies of 2-on-1 DES at -1.6 and +5 °C are significantly reduced to be 46.1% and 43.6%, respectively. In contrast, the exergy efficiencies of DES-SF and DES+HPH at ambient temperatures of -1.6 and +5 °C are remained at a higher range of 50.6%-51.2%.

The weighted average seasonal efficiencies of the UDH systems are calculated according to the yearly meteorological records in Beijing [25]. 2-on-1 DES and SHD DES have large power-gen installation capacities of 87 MW and 60 MW, respectively (see Table 1). Their average system efficiencies are much lower than those of the heating associations (see Figure 3). This phenomenon can be explained by these two points: (a) The use of peak-shaving heating means can flexibly control the heat-to-power ratio of the whole UDH system. (b) The prime movers of the heating associations run at full load throughout the heating season.

As shown in Figure 3, the exergy efficiency of DES+24-h HPH is lower than that of DES-SF by approximately 0.81%. The on-demand HPH can reduce heating capacity and electricity consumption of HPH when end users need suspend heating. Thus, DES+on-demand HPH can reach the highest average exergy efficiency among the various UDH systems proposed for USTB.

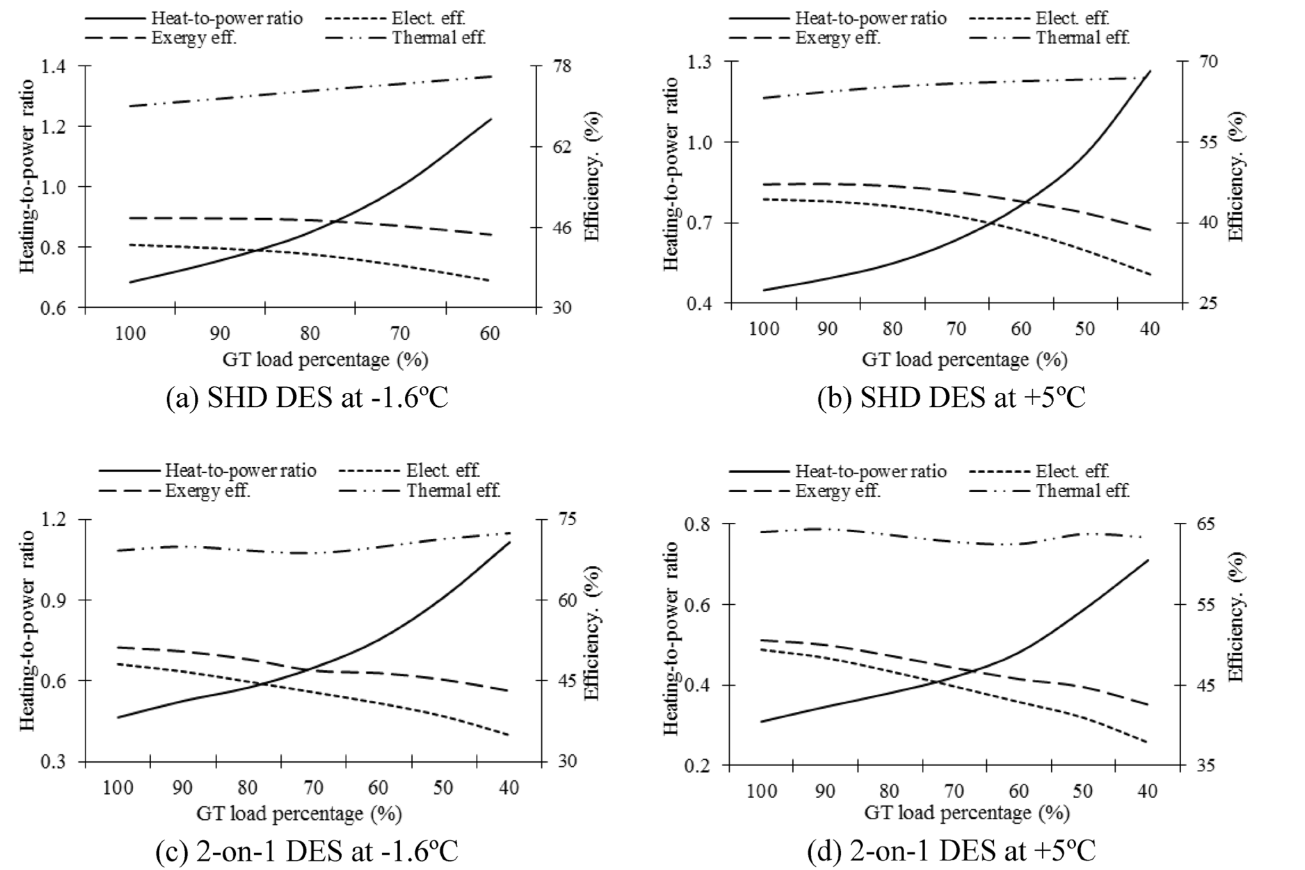
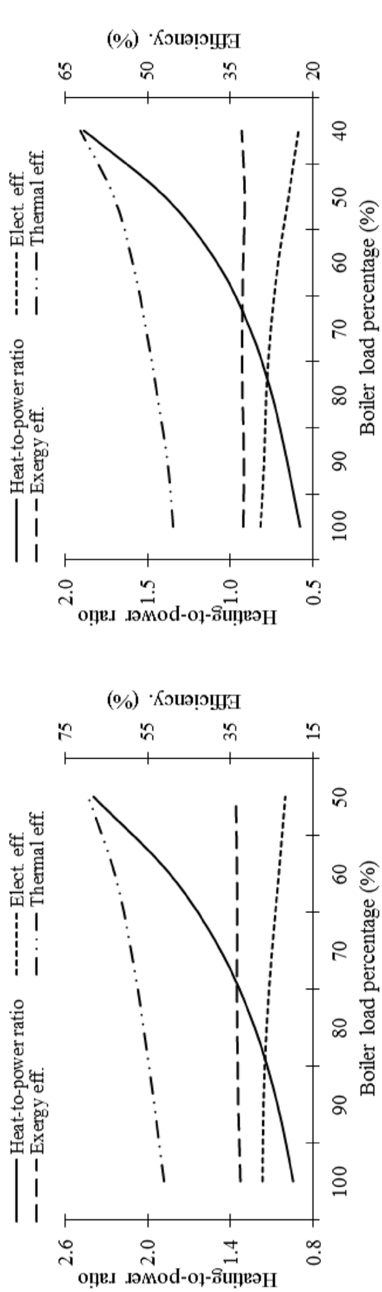



**Figure 2. Curves of heat-to-power ratio and efficiencies of UDH systems vs. GT/boiler load percentage at different ambient temperatures**




(e) natural gas-based CHP at -1.6°C

(f) natural gas-based CHP at +5°C

**Figure 2 (*Cont'd*). Curves of heat-to-power ratio and efficiencies of UDH systems vs. GT/boiler load percentage at different ambient temperatures**

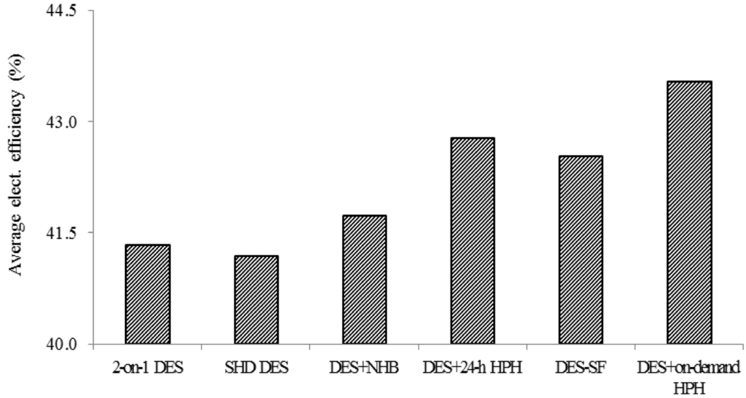
**Table 5a. Analysis results of different UDH systems at the ambient of -1.6°C**

| Heating means | Natural gas-based CHP | SHD DES | 2-on-1 DES | DES+ NHB | DES+ 24-h HPH | DES-SF | DES+ on-demand HPH |
|---|---|---|---|---|---|---|---|
| Boiler/GT load percentage (%) | 75 | 97 | 64 | 100 | 100 | 100 | 100 |
| Thermal input (MW) | 118.8 | 136.2 | 139.8 | 96.7 | 91.2 | 97.4 | 91.2 |
| Power output (MW) | 30.5 | 57.7 | 58.2 | 40.3 | 39.1 | 41.4 | 39.6 |
| Thermal output-steam (MW) | 36.6 | 30.6 | 29.3 | 27.9 | 27.9 | 33.8 | 27.9 |
| Thermal output-hot water (MW) | | 6 | 7.3 | 8.6 | 4.1 | 2.8 | 4.1 |
| Thermal output-HPH (MW) | | | | | 4.5 | | 2.4 |
| Heat-to-power ratio | 1.2 | 0.6 | 0.6 | 0.9 | 0.9 | 0.9 | 0.9 |
| Electricity efficiency (%) | 25.7 | 42.4 | 41.6 | 41.7 | 42.8 | 42.5 | 43.5 |
| Thermal efficiency | 56.5 | 69.3 | 67.8 | 79.5 | 83.0 | 80.1 | 81.3 |
| | | | | | | | |
| Fuel exergy input (MW) | 125.2 | 143.5 | 147.6 | 102.1 | 96.3 | 102.9 | 96.3 |
| Exergy output-steam (MW) | 11.5 | 9.6 | 9.2 | 8.8 | 8.8 | 10.7 | 8.8 |
| Exergy output-hot water (MW) | | 0.5 | 0.7 | 1.6 | 0.3 | 0.3 | 0.3 |
| Exergy output-HPH (MW) | | | | | 0.5 | | 0.3 |
| Exergy efficiency (%) | 33.6 | 47.3 | 46.1 | 49.7 | 50.6 | 50.9 | 51 |

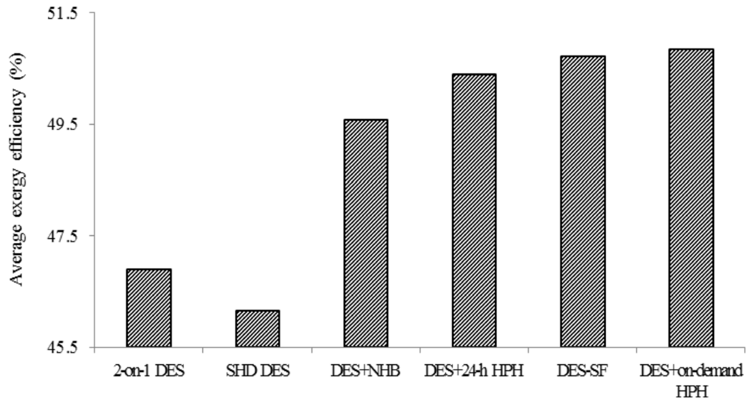
**Table 5b. Analysis results of different UDH systems at the ambient of +5°C**

| Heating means | Natural gas-based CHP | SHD DES | 2-on-1 DES | DES+ NHB | DES+ 24-h HPH | DES-SF | DES+ on-demand HPH |
|---|---|---|---|---|---|---|---|
| Boiler/GT load percentage (%) | 50 | 64 | 41 | 96 | 96 | 96 | 96 |
| Thermal input (MW) | 79.2 | 96.1 | 101.8 | 85.2 | 85.2 | 85.2 | 85.2 |
| Power output (MW) | 19.3 | 38.1 | 38.8 | 38.6 | 38.6 | 38.5 | 38.6 |
| Thermal output-steam (MW) | 24.4 | 19 | 18.4 | 20.4 | 20.4 | 21.3 | 20.4 |
| Thermal output-hot water (MW) | | 5.3 | 5.9 | 3.8 | 3.8 | 3 | 3.8 |
| Thermal output-HPH (MW) | | | | | 0 | | 0 |
| Heat-to-power ratio | 1.3 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 |
| Electricity efficiency (%) | 24.4 | 39.6 | 38.2 | 45.3 | 45.3 | 45.2 | 45.3 |
| Thermal efficiency | 55.2 | 64.9 | 62.0 | 73.8 | 73.8 | 73.7 | 73.8 |
| | | | | | | | |
| Fuel exergy input (MW) | 83.5 | 101.2 | 107.4 | 90 | 90 | 90 | 90 |
| Exergy output- steam (MW) | 7.7 | 6.0 | 5.8 | 6.4 | 6.4 | 6.7 | 6.4 |
| Exergy output-hot water (MW) | | 1.7 | 2.2 | 1 | 1 | 0.8 | 1 |
| Exergy output-HPH (MW) | | | | | 0 | | 0 |
| Exergy efficiency (%) | 32.4 | 45.2 | 43.6 | 51.2 | 51.2 | 51.1 | 51.2 |

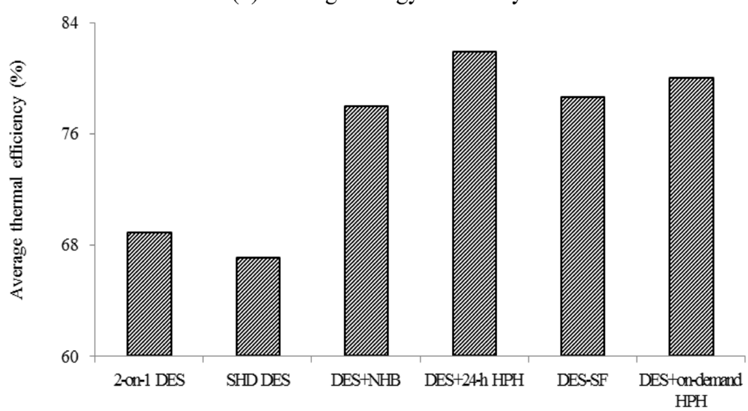
**Figure 3. Weighted average seasonal efficiencies of the UDH systems**




(a) Average electricity efficiency




(b) Average exergy efficiency




(c) Average thermal efficiency

## ECONOMIC FEASIBILITY ANALYSIS

The average spending of replacing coal-based UDH with natural gas-fired heating boilers is about 55 RMB per unit floor area [6]. Currently, the initial investment of DES+on-demand HPH is estimated to be 256 RMB per unit floor area. This value is calculated based on the total investment of DES+on-demand HPH, including a set of GT, HRSG, steam turbine, and heat pumps. The prices of the GT, HRSG, and steam turbine are 82.5, 7.75 and 9.39 million RMB, respectively. The total price of the heat pumps is about 17.24 million RMB. The average net power output of 38.8 MW can be provided by the DES+on-demand HPH. The typical investment of the predominant power-gen installation in China is 4659 RMB/kW [26]. After the deduction of the power-gen installation investment, the heating investment of DES+on-demand HPH is approximately 45 RMB per unit floor area, which is approximately 18% less than the spending of replacing coal-based UDH with natural gas-fired boilers. Therefore, it is economically feasible to promote DES+on-demand HPH to replace coal-based UDH in China.

## CONCLUSIONS

Thermal engineering software has been used to study the performance of conventional CHP and combined cycle units. The responses of the units to load percentages of prime movers at different ambient temperatures have been presented. The UDH system at USTB has been optimized for maximum average-exergy-efficiency in the heating season taking into consideration the associated constraints.

The power output and exergy efficiency of a UDH system decreases with a decrease in the load percentage of the prime mover. As an ambient temperature increases, the UDH system demands low power output by reducing the heat load fraction of the prime mover, so as to meet the minimum heat-to-power ratio required by Chinese regulation. It has been recommended to run gas turbines at full load to get good results. To run the UDH system at a high average-exergy-efficiency, it demands on-demand HPH to shave peak heating load. Therefore, China should replace coal-based UDH with DES+on-demand HPH instead of natural gas-fired heating boilers.

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**Nomenclature**

| | |
|---|---|
| 2-on-1 DES | DES including 2 sets of aero-derivative gas turbines and 1 set of steam turbine |
| CHP | combined heating and power |
| DES | distributed energy system |
| DES+HPH | a heating association of DES and heat pump heating |
| DES+NHB | a heating association of DES and natural gas-fired hot water boilers |
| DES-SF | DES with a supplementary fired HRSG |
| HPH | heat pump heating |
| HRSG | heat recovery steam generator |
| GT | gas turbine |
| SHD DES | DES including 1 set of small-scale heavy-duty gas turbine and steam turbine |
| UDH | urban district heating |

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