A MINLP multi-objective optimization model for operational planning of a case study CCHP system in urban China

Xuyue Zheng[a], Guoce Wu[a], Yuwei Qiu[a], Xiangyan Zhan[a], Nilay Shah[b], Ning Li[a],

Yingru Zhao[a,]*

[a] *College of Energy, Xiamen University, Xiamen 361005, China*
[b] *Department of Chemical Engineering, Imperial College London, London SW7 2AZ, UK*

Abstract

Urban energy systems comprise various supply side technologies, by which heating, cooling and electricity energy are produced, converted and consumed in a given urban area. The number of alternative arrangements of technologies introduces many degrees of freedom, particularly where large numbers of buildings and networks are in play. The problem being modeled in the present study is to determine the best combination of technologies to meet the energy demand of district buildings subject to practical constraints. This district planning aims to establish a smart micro-grid for the application of renewable and clean energy. A range of technologies including gas turbine, absorption chiller, electrical chiller, condensing boiler, ground source heat pump, PV, electrochemical storage, heat storage, ice storage air-conditioning system etc., have been considered as alternative supply side technologies. A MINLP model is developed to solve the multi-objective optimization problem.

Results are described by four scenarios, namely baseline scenario, low energy bill scenario, low CO_2 emissions scenario and integrated scenario, showing that a significant reduction is achievable in net present value, primary energy saving and CO_2 emissions by the installation of roof-top PV, ground source heat pump, natural gas-based CCHP and storage systems.

Keywords: urban energy system, CCHP system, optimization model, operation strategy, sensitivity analysis.

* Corresponding author. Tel.: +86 592 5952781; Fax: +86 592 2188053.
E-mail address: yrzhao@xmu.edu.cn (Y. Zhao).

1. Introduction

Nowadays the depletion of fossil fuels and the issues associated with environmental crisis have attracted extensive attention worldwide, raising the fluctuation in energy prices and threatening the balance between energy demand and supply [1]. The need to cut down on the usage of fossil fuels accompanied by the necessity to realize the global GHG reduction targets allows for no delay [2,3]. In this context, the combined cooling, heating and power (CCHP) technology, with the advantage of substantial reliability, environmental friendliness [4], sizable energy efficiency, shortened fuel transport distance as well as the relatively lower investment, has a highly visible presence in the energy production and supply industry [5,6].

CCHP system, which is normally used for distributed energy production, can be integrated with various primary energy resources consist of natural gas, wind, solar, biomass, geothermal energy and other renewable energy resources [7]. The application of CCHP refers to various forms and approaches, such as base load equilibration, emergency stand-by power sources, peak shaving and valley filling for bulk power systems, airports, university campus, residential and industrial parks, etc. A wide range of technologies could be employed for CCHP system compared with the traditional energy generation system, therefore it is considered as the most promising technology which is able to achieve an energy conversion efficiency by up to 90%.

Despite of all the above significant advantages, the optimal design and operation of a CCHP system is not an easy task [8]. The selection of technology combination, the determination of capacity magnitude, as well as the optimization of operation strategies to meet the various energy demands implies a great amount of effort. Considering the complexity and difficulty in such a process, there is a lot of interest in the systematic analysis and performance evaluation of CCHP systems [9,10]. Chicco et al. [11] made an assessment and review on the studies of CCHP system from diverse aspects including technologies modeling, methods solution, reliability, emissions, stability, uncertainty, demand response and multi-objective optimization etc., showing that a number of design and modelling works have made certain progress.

From the holistic perspective, CCHP problems can be divided into two categories, i.e., the short-term optimization with operational planning of system in a short period like one year or so, or the long-term optimization with the formulation of plant design problems over the whole plant life cycle. For example, Bischi et al. [12] presented a detailed optimization model of CCHP system for the planning of its short time operation with an objective to minimize the total operating and maintenance costs. For long-term problems, Jabari et al. [13] proposed a novel energy and exergy based methodology for the optimum design of an air heat pump-based CCHP system. In Ref. [14], economic indicators such as net present value (NPV) and present payback period (PBP) were used to perform long-term economic analysis that also takes plant cost into consideration.

End-use complexity as well as load uncertainty require suppliers to take full account of the various building load profiles and the fluctuations in production of technologies [15]. Therefore, several attempts have been made to develop the optimal/near-optimal operation strategies for CCHP, dealing with the coordination between production and consumption [9,16]. Ameri et al. [17] developed a mixed integer linear programming (MILP) model to determine the optimal strategies that minimize the overall energy cost for the CCHP system. Farahnak et al. [18] presented an optimization algorithm to identify the best operation condition of the PGU and to minimize energy cost. Yang et al. [19] provided a detailed optimization model to determine the operating schedule that minimizes consumer’s cost of purchasing electricity and natural gas plus the cost of GHG emission or maximizes the revenue of selling electricity back to the grid, with considering various electricity and gas prices and heating/cooling demands during different time periods. Apart from the economic criterion, the energetic, environmental and political factors have been also adopted in previous research, introducing different perspectives for system evaluation. By using an optimal energy dispatch algorithm, Cho et al.[9] optimized the operation of CCHP systems for different climate conditions, with considering the operational cost, primary energy consumption, and carbon dioxide emissions. Carvalho et al.[20] introduced a mixed integer linear programming (MILP) model for the optimal synthesis of a CCHP system subject to the minimization of its environmental burden associated with the production of equipments and consumption of resources.

As stated by Evins in Ref. [21], around half of the aforementioned studies addressed the single objective problems in which formulation is straightforward and allows for detailed exploration, while the other 40% of works applied the Pareto multi-objective optimization which is becoming more and more popular these years. Many researchers prefer to develop a multi-objective model integrated with various criteria, in which several objectives are combined into a single one by weighted method [2,22] or overall assessment [23-25]. For example, Mallikarjun et al. [26] proposed a two-stage multi-objective strategic technology-policy framework for the determination of optimal energy technology allocation, which simultaneously considered economic, technical, and environmental objectives. Somma et al. [28] performed a multi-objective optimization for the designing of a small-scale distributed DESs system, taking into consideration the exergetic and cost assessments. In Ref. [27], a multi-objective optimization considering the minimization of total annual costs and CO_2 emissions has been carried out, with an internal cycle for performance assessment and an external cycle for the determination of equipment size by using evolutionary algorithms.

Furthermore, the parametric sensitivity analysis is also an important approach to identify the influence of changes in parameters on the optimization results [29-32]. Ref. [33] presented a sensitivity analysis on the optimal performance of BCHP system in terms of technical, economic and environmental parameters. Pantaleo et al. [34] addressed the effects of energy demand typologies (i.e., urban energy density, heat consumption patterns, buildings energy efficiency levels, baseline energy costs and available infrastructures) and specific constraints on the transport logistics, air emission levels and space availability of urban areas, based on sensitivity analysis.

In summary, there have been a considerable number of models developed to optimize the performance of CCHP systems. However, in most of these studies the long-term strategic planning and the short-term operational planning were discussed separately, and few of them referred to the high-dimensional, highly integrated multi-energy sources, not to mention to determine the combined design, energy dispatching optimization, coordinated dispatching and hourly operation control of the integrated network [35]. Moreover, very limited research has focused on the multi-objective optimization of CCHP systems incorporating storage with simultaneous sensitivity analysis of energy price in order to reveal the tradeoff between key system parameters. Furthermore, the challenging hourly demand forecast, as the key to the medium- and long-term planning of integrated systems, is not widely taken into account. In addition, most research use the averaged monthly or annual load to calculate indicators of the system over the entire planning horizon, ignoring the interaction between fluctuations in yearly energy demand and the initial combination of technologies and the investment on newly installed technologies or equipment replacement. However, this will greatly affect the operational strategy of the system. In fact, considering the yearly fluctuation in energy demand will significantly increase the number of variables and hence complexity of the model, but make more practical senses at the same time.

In this context, a comprehensive mixed integer nonlinear programming (MINLP) modeling framework is developed to determine the optimal combination and operational strategies of various technologies to meet the energy requirements under different circumstances. A range of commercially available technologies in China, such as combined heat and power (CHP) plant, auxiliary condensing boiler, electric chiller (EC), absorption chiller (ABS), heating & cooling and electrical storage units, ice storage air conditioner (ISAC), roof photovoltaic (PV) system, ground source heat pump (GSHP) etc., are all taken into consideration as alternative supply side technologies to be installed to cover the energy demand sufficiently. A mix of technologies that will best meet the energy requirements during the period of year 2016 to year 2026 is suggested. The initial scenario for year 2016, i.e., nothing changes, is taken as reference for comparison. Specifically, there are 960 time intervals (10 years ×4 seasons ×24 daily hour periods) in the case to ensure accuracy.

The rest of the paper is organized as follows. Section 2 describes the mathematical formulations of the proposed model. Section 3 outlines and explains the reference scenario and other four scenarios, namely baseline, low carbon emissions, low energy bill and multi-objective scenarios, followed by sensitivity analysis. Section 4 highlights the main conclusions of this study.

2. Model description

A MINLP (mixed-integer nonlinear programming) model is formulated in GAMS (General Algebraic Modeling System), which is a modelling environment with high performance in mathematical programming and optimization and is tailored for complex, large scale modeling applications. GAMS allows to build large MINLP models that can be found guaranteed globally optimal solutions with continuous and/or discrete variables, and the Lindo optimizer is used with GAMS to seek for the optimal arrangement of aforementioned technologies [36-39]. In the present case study, the overall model includes 141769 equations, 484081 constraints and 194896 variables. The calculation time required to solve the problem is more than 5 hours with an i5 CPU 2.6 GHz and 8GB RAM.

The objective function of the model is to minimize total cost from the initial year, discounting all future costs that consist of annual investment in new technologies, annual maintaining and operating expenses as well as benefits to their present value. The main decision variables of the model refer to type, size and operating strategy of the technologies, as described in Section 2.1.

Unlike previous studies where the real time variations of energy demand were normally ignored, the effect of hourly demand fluctuation is considered in the present model.

The model proposed in the present study will help to address the following question: For a given urban area consists of office, hotel, commercial and residential buildings, with its available renewable resources, buildings and their related load profiles, which combination of energy conversion technologies will be best suited to meeting its energy demand, and how these technologies should be integrated and operated?

2.1 Objective function

Economic performance is a key criterion for evaluating the CCHP system. The overall objective of the present model is to minimize the total costs of the CCHP system over a time horizon to satisfy the fluctuant energy demand, which are usually the most relevant criterion for decision making. Given the complexity of practical operation, the capacity of supply side technologies is hard to determine. As is well known, larger capacity implies greater initial capital cost and O&M (operation and maintenance) cost. However, CCHP takes no remarkable superiority when the capacity is too small, since insufficient energy is supplied by external system such as the grid. Therefore, the present study aims to maximize economic benefits of CCHP system to satisfy the hourly energy demand over a time horizon. As for economic analysis, all future costs and benefits in the objective function are converted into their net present value (NPV). Note that NPV is identified as the economic criterion best suited for optimization and the objective function is examined for a multi-year period, given by:

$$NPV = \min\left[\sum_{y}\frac{CC_y + OM_y - RE_y}{(1+r)^y}\right] \tag{1}$$

There are three cost constraints in Eq. (1), i.e., capital cost *CC*, operation & maintenance cost *OM* and revenue *RE* from selling extra electricity to the Grid, all of which are dependent upon the number of operating schedules for supply side technologies. *r* represents the discount rate, and subscript *y* represents the year. The constraints of capital cost are briefly expressed as follows:

$$CC_y = \sum_{i}\sum_{t} Nit_{i,t,y}\cdot Ct_t + \sum_{e} Nis_{e,y}\cdot Cs_e \tag{2}$$

The yearly capital cost for each energy generation technologies *t* and storage components *e* can be obtained from Eq.(2), where *Nit* and *Nis* are the number of newly invested energy generation technologies and storage units, respectively, calculated separately in order to clearly depict the contribution of different sources in achieving the optimization goal for energy production and storage from different units. Note that both *Nit* and *Nis* are assumed to change yearly, *Ct* and *Cs* are related to the cost of each unit, and subscript *e* includes electrochemical storage, thermal storage tank and ISAC. *i* represents the set of spatial nodes.

$$
\begin{aligned}
OM_y = &\sum_i \sum_{tg} \sum_s \sum_h Ein^{gas}_{i,tg,y,s,h} \cdot Pgas + \sum_s \sum_h ELim_{y,s,h} \cdot Ptou_h \\
&+ \sum_e Ns_{e,y} \cdot \beta_e + \sum_i \sum_t Nt_{i,t,y} \cdot \beta_t
\end{aligned}
\tag{3}
$$

The operation & maintenance cost *OM* comprises three parts:

(1) Operating cost, i.e., fuel cost, which only accounts for the consumption of natural gas Ein^{gas} that consumed by CHP or condensing boiler, both subset to *tg*. The electricity Ein^{elec} consumed by GSHP, absorption/electric chiller or other electricity driving technologies *te* is attributed to electricity consumption in Eq. (5). The subscripts *s* and *h* represent the temporal sets of seasons and hours respectively.

(2) The second part of Eq. (3) is the cost of electricity bought from the Grid, which represents the amount of electricity imported from Grid *ELim* at time h. Note that the gas price *Pgas* is taken as constant, while the time-of-use pricing of electricity *Ptou* is considered for hourly specifically, as listed in Table 1. The electricity can, of course, be bought from the Grid.

(3) The yearly maintenance cost [40] is calculated by multiplying the total number of supply side technologies *Nt* and storage components *Ns* with the maintenance factor *β*.

$$
RE_y = \sum_s \sum_h ELex_{y,s,h} \cdot Pfi \tag{4}
$$

The last term in the objective function, *RE*, is the revenue from selling extra electricity *ELex* to the Grid, where *Pfi* is the feed-in tariff of electricity. This is, of course, a negative cost, presented to be an income to the system.

2.2 Energy demand constraints

The energy demand constraints are divided into three parts based on the types of energy requirement, i.e., electricity, heating and cooling. Eqs. (5) and (6) represent the constraints of electricity balance:

$$\sum_i Eout^{elec}_{i,'PV',y,s,h} + Eout^{elec}_{'CHP',y,s,h} + Sd_{'ES',y,s,h} = Sc_{'ES',y,s,h} + Sc_{'ISAC',y,s,h} + \sum_i Ein^{elec}_{i,te,\mathrm{y,s,h}} + Enet^{elec}_{y,s,h} \tag{5}$$

$$Enet_{y,s,h} + ELim_{y,s,h} = \sum_i Ed_{i,y,s,h} + ELex_{y,s,h} \tag{6}$$

where *Enet* represents the total net electricity generated by energy systems and supplied to the district electrical network. *Sc* denotes the electricity charged into the electrical storage unit *es* (mainly electrochemical battery in this research), while *Sd* is the electricity discharged by the electrical storage units. Note that the marked subscript *'ES'* is an element of set *e*. In this study, except for the subscripts indicated by quotation marks referring in particular to an element, such as '*PV'*, '*CHP'* and *'ES'* in Eq. (5), all the others are sets which include various elements. The subscript *te* of *Ein* in Eq. (5) represents the parasitic power consumption. The electricity demand *Ed* and extra electricity *ELex* exported to the Grid is calculated as sum of the net electrical energy generated by energy system and the amount of insufficient electricity imported from the Grid *Eim*. It is noteworthy that the electricity imported from and exported to the Grid cannot occur simultaneously, so the electricity imported from the Gird is stored in the electrical storage components:

$$ELex_{y,s,h} \cdot ELim_{y,s,h} = 0 \tag{7}$$

$$Eim_{y,s,h} \cdot Sd_{'eb',y,s,h} = 0 \tag{8}$$

This is to avoid an unreasonable situation that all electricity is imported from the Grid when its price is on the valley period. It is also to avoid that all the power generated is sold to the Grid or purchasing all electricity from the Grid and store into the storage units.

For yearly energy demand over the whole planning horizon, planners should take into consideration the impact of 'real-world' factors (e.g., population expansion, newly constructed buildings etc.) on the energy demand of the given urban area. Eq. (9) take the electricity demand as an example, which can be extended to the heating and cooling demands:

$$Ed_{i,y,s,h} = Ed_{i,y-1,s,h} * (1+\alpha_y) \tag{9}$$

where α is the growth rate. The subscript y denoted α can change yearly, which can be a forecast value or a stochastic value changing within a reasonable range. The impact of energy demand growth on the investment of newly technologies or technologies replacement will be discussed in section 2.3.

In terms of the other two energy balances, the sum of heating and cooling output *Eout* from supply side technologies must be equal to the sum of demand side and specific energy requirement (such as heat required by *ABS*), while energy may be stored (*Sd*), discharged (*Sd*) by thermal storage system *TES* (main storage tank in this case), or neither:

$$\begin{aligned} & Eout^{heating}_{'Boiler',y,s,h} + Eout^{heating}_{'CHP',y,s,h} + Eout^{heating}_{'GSHP',y,s,h} + Sc_{'TES',y,s,h} = \\ & \sum_i Hd_{i,y,s,h} + Hd_{'ABS',y,s,h} + Sd_{'TES',y,s,h} \end{aligned} \tag{10}$$

$$\begin{aligned} & \sum_i Eout^{cooling}_{i,'GSHP',y,s,h} + Eout^{cooling}_{'ABS',y,s,h} + Eout^{cooling}_{'ISAC',y,s,h} + Eout^{cooling}_{'EC',y,s,h} + \\ & Sc_{'TES',y,s,h} = \sum_i Cd_{i,y,s,h} + Sd_{'TES',y,s,h} \end{aligned} \tag{11}$$

In order to provide a more realistic model for heating, cooling and electricity storage, the energy input to and output from the storage units cannot occur simultaneously:

$$Sc_{e,y,s,h} \times Sd_{e,y,s,h} = 0 \tag{12}$$

Similarly, only one type of energy is allowed to be stored in the storage tank in the same season, i.e., heating energy for heating seasons and cooling energy for cooling seasons.

2.3 Technology constraints

The capacity of technologies is limited by the absolute number of installed and in-use technologies. In fact, in the planning stage, the number of devices and the capacity of initially planned facilities normally cannot cope with the practical demand due to the increase in regional population and construction area. Therefore, *Nt* is an integer variable defined as the number of newly invested and replaced technologies. *Rt* is defined as the technology replacement parameter to reflect the effect of multiple exchanges of technology, whose value is either -1or1. Noted that the set *t'* is an alias of *t*. For example, a new absorption chiller (ABS) investment would replace an existing electric chiller (EC), thus $RT_{'ABS','EC'}$=-1, while replace EC with a ABS implies $RT_{'EC','ABS'}$=1. This simple use of a replacement parameter enables a better balance of the model. Therefore, the technology balance formulates a solid approach for modelling the capacity changes to each technology of the CCHP system, ensuring that the replaced technology will not be miscalculated in the model.

$$Nt_{i,t,y} = Nt_{i,t,y-1} + \sum_{t'} Nit_{i,t',y} \cdot Rt_{i,t',t} \quad (13)$$

The output energy is calculated by multiplying the operation capacity *CAP* with the duration of time period *D*, as well as the input energy *IE* and the efficiency of technologies η, as given in Eqs. (14) and (15):

$$Eout_{i,tg,\mathrm{y,s,h}} = CAP_{i,tg,\mathrm{y,s,h}} \times D_{s,h} = Ein^{gas}_{i,tg,\mathrm{y,s,h}} \times \eta_{tg} \quad (14)$$

$$Eout_{i,te,\mathrm{y,s,h}} = CAP_{i,te,\mathrm{y,s,h}} \times D_{s,h} = Ein^{elec}_{i,te,\mathrm{y,s,h}} \times \eta_{te} \quad (15)$$

Note that heating, cooling and electricity are different types of output energy, but one technology may have two different types of output energy with different efficiencies, e.g., CHP, as given in Eqs. (16) and (17):

$$Eout^{heating}_{i,'CHP',\mathrm{y,s,h}} = CAP_{i,'CHP',\mathrm{y,s,h}} \times D_{s,h} = Ein^{gas}_{i,'CHP',\mathrm{y,s,h}} \times \eta^{heating}_{'CHP'} \quad (16)$$

$$Eout^{elec}_{i,'CHP',\mathrm{y,s,h}} = CAP_{i,'CHP',\mathrm{y,s,h}} \times D_{s,h} = Ein^{gas}_{i,'CHP',\mathrm{y,s,h}} \times \eta^{elec}_{'CHP'} \quad (17)$$

2.4 Constraints on renewable technologies

There are two renewable technologies modelled in the present model, i.e., roof-PV and GSHP (ground source heat pump). The technical application of roof-PV is limited by two key parameters.

Firstly, electricity generated by roof-PV is inversely proportional to the solar irradiance δ_{pv}, as given by the following equation:

$$Eout^{elec}_{i,'PV',y,s,h} = \eta_{'PV',s,h} \times \delta_{s,h} \times Nt_{i,'PV',y} \times \varepsilon_{'PV'} \tag{18}$$

where *Eout* is the power output of PV, η is the efficiency taken as a constant equal to 14.2%, ε_{pv} is the average size of a PV panel, and δ_{pv} is the solar irradiance at a specific time whose value can be obtained from local solar radiation database.

Secondly, the installation number of roof-PV is constrained by the available roof space $A_{i,pv}$ in spatial area i:

$$Nt_{i,'PV',y} \times \varepsilon_{'PV'} \leq A_{i,'PV'} \tag{19}$$

Similarly, the installation of GSHP is also limited by its available space:

$$Nt_{i,'GSHP',y} \times \varepsilon_{'GSHP'} \leq A_{i,'GSHP'} \tag{20}$$

where *Nt* represents the number of technologies in year y, ε is the corresponding average area per installation, and *A* is the available geographic area of spatial node *i*.

In addition, GSHP has other constraints on its coefficient of performance (COP), which is the efficiency between the energy input and output of a single GSHP unit, calculated according to an empirical relationship on the time-varied temperature difference between soil and GSHP outlet (ΔT).

$$COP_{s,h} = 0.00073\Delta T^2_{s,h} - 0.15\Delta T_{s,h} + 8.77 \tag{21}$$

$$Eout_{i,'GSHP',y,s,h} = Ein^{elec}_{i,'GSHP',y,s,h} \times COP_{s,h} \tag{22}$$

For GSHP, only one energy, either heating or cooling, can be produced at a time.

2.5 Constraints on storage technologies

Heat storage tank and electrical storage units are considered to increase the operational flexibility and energy efficiency of the CCHP system. Where storage exists, it is defined as existing in one of the following three states: i) state of being stored; ii) state of being produced; iii) state of being consumed. These three states are thought suitable for a simplified and reasonable modeling of CCHP system.

$$Sa_{e,y,s,h} = Sa_{e,y,s,h-1} + Sc_{e,y,s,h} - Sc_{e,y,s,h} - Sl_{e,y,s,h} \tag{23}$$

$Sa_{s,h}$ and $Sa_{s,h-1}$ represent the amount of energy stored in current and previous hourly time period, respectively. *Sc* and *Sd* denote the thermal energy being stored or consumed in time period *h*, respectively. *Sl* represents the storage losses, the calculation of which is based on the definition of an hourly heat loss coefficient. The detailed constraints of storage units are modeled as follows:

$$Sl_{et,y,s,h} = Sa_{et,y,s,h-1} \times \eta_{et,h} \tag{24}$$

$$Sa_{et,y,s,h} \le Ns_{et,y} \times CAP_{et}^{\max} \tag{25}$$

$$Sc_{et,y,s,h} \le Ns_{et,y} \times CAP_{et}^{\max} - Sa_{et,y,s,h-1} \tag{26}$$

$$Sd_{et,y,s,h} \le Sa_{et,y,s,h-1} \tag{27}$$

$$Ns_{et,y} = Ns_{et,y-1} + Nis_{et',et,y} \cdot Rt_{et',et} \tag{28}$$

where set *et* includes two storage technologies, i.e., thermal storage system and electrical storage, and obviously, *et* is also a subset of *e*. Storage losses *Sl* are calculated by the amount of stored energy at last time period *h-1* and hourly storage loss coefficient η. The amount of stored energy cannot be larger than its maximum capacity $CAP^{\max}$, and the energy input *Sc* in the current period must be less than the additional storage space. Similarly, the storage output *Sd* in the current period should be lower than the amount of stored energy during the last time period. The final constraints equation represents that the total storage capacity is limited by the absolute number of installed units, which can also be changed yearly.

Regarding the ice storage air conditioner ISAC, its three storage states are similar to that defined in Eq. (23), but unlike the first two states the electrical energy will be converted into cooling energy when electricity is at valley price or extra electricity exists, as given in Eqs.(30) and (31). The other constraints are similar to those of Eqs. (25)- (28):

$$Sa_{'ISAC',y,s,h} = Sa_{'ISAC',y,s,h-1} + Sc_{'ISAC',y,s,h} - Sd_{'ISAC',y,s,h} - Sl_{'ISAC',y,s,h} \tag{29}$$

$$Sc_{'ISAC',y,s,h} = Ein_{'ISAC',y,s,h} \cdot \eta^{in}_{'ISAC'} \tag{30}$$

$$Eout^{cooling}_{'ISAC',y,s,h} = Sd_{'ISAC',y,s,h} \cdot \eta^{out}_{'ISAC'} \tag{31}$$

where Eq. (30) denotes the ISAC converting excess electricity into cooling energy, so does the case of valley electricity price.

2.6 Constraints on CO_2 emissions

Carbon dioxide emissions of the CCHP system are mainly due to its natural gas consumption and electricity imported from the Grid. Therefore, the CO_2 emissions are calculated as sum of these direct and indirect emissions:

$$EM = \sum_{i}\sum_{tg}\sum_{s}\sum_{h} Ein^{gas}_{i,tg,\mathrm{y,s,h}} \times \theta_{gas} + \sum_{s}\sum_{h} Eim_{y,s,h} \times \theta_{elec} \tag{32}$$

where *EM* represents the total CO_2 emissions in year y, θ_{gas} and θ_{elec} represent the CO_2 emissions per unit consumption of gas and the electricity imported from the Grid.

2.7 ***Constraints on energy bill***

In addition to the environmental impact, the annual energy bill is also a key criterion in the selection of proper energy technologies and reasonable operation strategies. This is deemed an important insight for decision maker, particularly reflecting the correct operation strategy from a financial perspective after the CCHP system is put into operation. The annual energy bill *EB* can be calculated as the sum of prices of input energy, mainly focusing on natural gas and electricity imported from the Grid.

$$EB_y = \sum_i \sum_{tg} \sum_s \sum_h Ein_{i,tg,y,s,h}^{gas} \times Pgas + \sum_s \sum_h Eim_{y,s,h} \times Ptou_h \tag{33}$$

3. Case study

3.1 Energy demand profiles and scenarios

In order to better understand and describe the flexibility of the combination and operational strategy for the proposed CCHP system, a test case is investigated for an innovation pilot zone locate in Shanghai, China. The given urban area consists of four parts, namely office, hotel, commercial and residential buildings, with 142264m^2, 98105m^2, 11368m^2 and 65000m^2 of building areas, respectively. The electricity, space heating and cooling requirements are all considered in this test case, which are investigated in Figs.1 and 2. The case study is analyzed for the period of year 2016-2026. The year 2015 is taken as initial year, pre-planning for calibrating boundary conditions of the model, i.e., all energy demands are supplied by conventional energy systems. As the given area has a variety of buildings with different functions, the energy requirements can be divided into high and low levels due to their operation characteristics. The demands of hotel are relatively stable because it will operate 24 hours a day, while the loads of offices and commercial buildings are divided into high and low levels according to their different operation characteristics. For residential buildings, the peak load is rather high, but the average load is relatively low.

The proposed MINLP model is employed on the test case to provide strategic insights for its optimal planning and operation. Each kind of investment and operating combination of technologies is indexed by energy types, technological and temporal sets. The types of energy include electricity, space heating and cooling. The technologies consist of condensing boiler, electric chiller, roof-PV, GSHP, storage unit, natural gas CHP and absorption chiller. Fig. 3 illustrates the layout and energy flows of the CCHP system. The left side is the designed CCHP system and the right side is the conventional energy supply system. Three kinds of energy demand, namely, direct electricity consumption for lighting and electrical equipments, space heating and space cooling are represented by the color of black, red and blue, respectively. It should be noted that while the list of technology is by no means of exhaustive, it is thought suitably representative of the generic commercial options currently available for the district-scale energy supply in China. The temporal sets can be divided to three time intervals, year *y*, season *s* and hour *h*.

Based on the constraints described in Section 2, the optimal combination of technologies and operational strategies to achieve the given objective are provided by the model. Four scenarios are analyzed for comparison, differentiated by the constraints and parameters as listed below:

1. Baseline scenario, wherein all technologies are allowed to be invested, and no specific constraints are embedded to the model;
2. Low carbon emissions (LCE) scenario, in which the annual CO_2 emissions of the given area are constrained to be 50% below that of the year 2015;
3. Low energy bill (LEB) scenario, in which the annual energy bill is constrained to be 40% decrease compared to the traditional way;
4. Multi-objective (MO) scenario, wherein an integrated evaluation model is proposed to assess the comprehensive benefits of CCHP system compared to the baseline, LEB and LCE scenarios.

3.2 Results

3.2.1 Baseline scenario

The optimization results for the baseline scenario, as shown in the first and second column of Table 2 and Fig. 4, indicate that the annual electricity demand imported from the Grid decreases from 100% to 28.4%, and the rest is covered by 9MW natural gas fueled CHP and 2MW roof-PVs, which account for 61.6% and 9.9% of the total electricity demand respectively. This significant change is due to the adoption of CCHP system, which results in the annual gas consumption increasing from 84.5TJ to 379.2TJ. However, the CHP system and roof-PV do not cover all of the necessary electricity demand at particular time intervals, which is mainly because a time-of-use pricing is considered for electricity specifically, so the Grid is chosen as main electricity source when the price of electricity is at valley period (mostly night and noon) during which energy requirements are relatively low and only a small amount of electricity is supplied by CHP. On the other hand, the power demand is relatively large when the price of electricity is more expensive at flat period, especially in peak period, CHP is operated with a large load factor to generate as much electricity as possible to satisfy the demand of this given district, whereas electricity is rarely imported from the Grid, as illustrated in Fig. 7. None electrochemical storage unit is selected in this scenario due to its high capital cost. The results of the baseline scenario are compared with the results from other scenarios in Table 2.

Regarding space cooling, the optimal configuration for the baseline scenario indicates replacing 80% existing electric chillers of the traditional energy system with absorption chillers and GSHPs. The optimal configuration and operation of supply technologies for a typical summer day are illustrated in Fig. 5a. According to the cooling demand curve, the electric chillers and GSHPs generate 25.7% and 8.9% of daily required cooling respectively, while the absorption chillers have a daily supplied proportion significantly higher, up to 57.5%. The time interval of high operating partload for electric chillers and GSHPs mostly occurs in daytime when there is large energy demand, which is similar to the CHP. The storage tank and ISAC are employed as back-up cooling sources, particularly during the period of 13 pm-15 pm when the highest outdoor temperature increases the total cooling demand.

For space heating, 13MW of capacity for the initial existing condensing boilers is replaced by CHPs to meet 75.7% of the daily heating demand in a typical winter day. The condensing boiler and GSHP are used as auxiliary heaters to cover 7.0% and 8.8% of the heating load in a day, respectively. The remaining 8.5% of energy requirement are satisfied by heat storage tank, which has the largest volume and highest proportion in heating supply of all scenarios. As illustrated in Fig. 6a, the heat storage tank begins to charge around 6 am in the morning and discharge around 7am-8am. This is partly due to the relatively low outdoor temperature. Moreover, the office and commercial buildings start to operate around 8am, this will increase the heating demand and therefore, the storage tank starts running around 8am will not only be able to effectively reduce the installed capacity of heating technology, but also be able to achieve the purpose of peak shaving. In addition, during the periods of peak demand (2 pm to 21 pm) and when the electricity price is in flat and peak periods, the excess heating energy generated by CHP can be simultaneously stored in the heat storage tank, which can basically cover the heating demand of the valley-period 22:00-24:00, thus all electricity can be imported from the Grid during this period to obtain the best economic benefits.

3.2.2 LCE scenario

In order to assess how the optimal mix and operation of technologies would change when restrictions are set on the reduction amount of CO_2 emissions, the low carbon scenario is investigated with a target of 50% CO_2 reduction. Compared with the initial emissions in year 2015, the biggest difference is in the significant decrease of electricity consumption, which in turn results in a significant reduction on the electricity imported from the Grid and electricity consumed by technologies (90% and 78.9% decrease respectively). Compared to the baseline scenario, the decrease of 60.9% and 53.5% are illustrated in Table 2 and Fig. 4, which further shows that the electricity imported from the Grid mostly occurs in the valley period. It can be deduced that although there is a constraint of reducing 50% in CO_2 emissions, the objective is to minimize the total cost, while purchasing electricity from the Gird at a relatively low price can reduce the operating cost. However, the NPV still has an obvious increase compared with baseline scenario, from 450.64 to 465.7. Overall, the results imply that if the objective is set to minimize the CO_2 emissions, the amount of electricity imported from the Gird will be zero, causing a larger increase in NPV.

For cooling demand, compared with the baseline scenario, as shown in Fig. 5b, the proportions of cooling supplied by electric chillers and GSHPs both have slight decrease, only 9.46% and 5% respectively. On the contrary, the cooling supplied by absorption chillers is 78% of the total, almost 30% higher than that of the baseline scenario. There is a substantial increase in the operation time of absorption chiller, which will be running 24 hours in a typical summer day. Unlike the baseline scenario, the absorption chiller shut down during the periods of 1am-7am and 22pm-24pm. While in this scenario, all the demand during these two time periods are covered by absorption chillers when the price of electricity is at valley period, suggesting that certain economic sacrifices should be made in the cost to meet the emissions target. The storage tank will store energy in the off-peak period, then will act as an auxiliary cooling source in peak period. The percentages of daily cooling supplied by storage tank and ice storage air conditioner are 2.82% and 6.5%, respectively.

For heating demand, the percentages of heating supplied by condensing boiler, CHP, GSHP and storage tank are 14.83%, 75.8%, 7.1% and 2.3%, respectively. The most obvious change is that the proportion of condensing boiler is twice as much as that of baseline scenario, as illustrated in Fig. 6b. The results imply that the condensing boiler can effectively decrease the CO_2 emissions but achieve no economic benefits due to its single function in heating supply. Another difference compared with the baseline scenario is in the heating supply combination between 22pm and 24pm, when all the heating requirements are covered by CHP, while storage tank in this scenario only discharges in the morning peak load period.

3.2.3 LEB scenario

In this optimization mode, the minimization of NPV is still taken as the optimization objective, and the constraint of annual EB to be reduced by 40% is also taken into consideration. Comparing to other scenarios, EB does not have enormous decrease, but the usage in electric storage has a significant increase. It can be deduced that 48 million RMB of EB is the limiting value under the optimal NPV in other scenarios, while more electric storage systems must be used in light of the constraint to reduce 40% of EB. Although the capital cost is relatively high and would lead to a significant increase in NPV. This implies that the electrical storage has a great contribution to the reduction of EB, in other words, the electrical storage can make economic use of energy. As shown in Table 2 and Fig.4, approximately 10% of electricity is supplied by electrical storage units, which is also the highest amongst all scenarios.

Different from the baseline scenario and LCE scenario, as indicated in Fig. 5c, the cooling load is mainly covered by the electric chillers and absorption chillers, and the insufficient cooling energy is supplied by GSHPs. The average proportions of cooling energy from electric chiller, absorption chiller and GSHP are 37.9%, 52.7% and 9.4%. Yet it should be noticed that there is no *ISAC* investment recommended in this scenario, and no storage tank used in summer day. It is found that under the constraints of high EB reduction scenario, generating energy just enough was more suitable than the overproduction strategy which will generate superfluous energy and then store excess energy in the storage units for later use.

Regarding the optimal solution for heating supply, compared with Fig. 6a, it can be easily seen from Fig. 6c that the storage tank does not run in morning peak period and afternoon flat period, but still operate during 19pm–24pm. Due to less use of storage tank, there is an expected decrease of heating supplied by storage tank, which in turn resulting in less than half of that in the baseline scenario. Similarly, compared with the baseline scenario, the heating load is mostly covered by CHP, and the insufficient heating requirement will be supplemented by GSHPs and condensing boilers. The average proportions of heating energy in a typical winter day from CHP, GSHP, condensing boiler and storage tank are 78.6%, 9.7%, 7.6 and 4.1%, respectively.

3.2.4 Multi-objective scenario

In addition to CO_2 emission and energy consumption, NPV and operating cost are also key factors to consider in the practical planning and running of urban energy systems. Considering multiple objectives are typically required, and these objectives are sometimes conflict with each other, thus analyzing only one optimal solution with mono objective function is not sufficient. Therefore, an integrated model is developed from a multi-objective optimization perspective to assess the comprehensive indexes of the project under study. However, as the economic feasibility, environmental impact and annual EB have different dimensions, it is difficult to compare their values between different dimensions. Therefore, Eq. (34) is introduced to define three coefficients Z_1, Z_2 and Z_3, which come from the result of using entropy weight method, to compare three sub-objectives under the same dimension. The coefficient is $Z_{1,2,3}$= [0.323, 0.344, 0.333], which means that the three sub-objectives are with the same desirability. And the multi-objective function can be expressed as follows:

$$IEV = \min\{Z_1 \cdot NPV + Z_2 \cdot LCE + Z_3 \cdot LEB\} \quad (34)$$

Based on the above calculation and compared with other scenarios, the operation results of joint optimization is found to better meet the requirements of all scenarios. Compared to the baseline and LCE scenarios, the system invests in larger capacity of electrical storage and electrical chillers to minimize LEB value, but the system will reduce the amount of electricity imported from the Grid to minimize LCE value. Therefore, in the multi-objective scenario, the electricity purchased from the Gird is lower than that of the NPV and LCE scenarios, but more natural gas consumption is predicted than that of the other two scenarios, as indicated in Fig. 4 and Table 2. Note that the condensing boiler has the largest capacity in this scenario compared to other scenarios, which is shown to be a very effective technology for the joint optimization. Regarding the operation strategy of storage units, as can be seen from Fig. 8, the biggest difference lies in the operation strategy during flat period, which incorporates the features of the previous three scenarios. In terms of the specific storage technology, i) ISAC has the same capacity in this scenario compared with the baseline scenario, but its operation time is obviously different from while similar with that in the LCE scenario; ii) the operation strategy of storage tank is different with the other three scenarios; iii) the running mode of electrical storage units in this scenario is similar with that of the LEB scenario, only different in the quantity of energy.

Fig. 5d displays the hourly cooling supply combination for the multi-objective scenario, showing that the proportion of typical summer daily cooling supply by absorption chillers is almost the same as that in LCE, i.e., 76.6% versus 76.2%. The cooling supplied by electrical chillers is slightly higher than that in LCE, i.e., 10.8% versus 9.5%, but lower than that in NPV and LEB, of which the proportion can reach 25.8% and 37.9%, respectively. The cooling supplied by GSHPs is the lowest in all scenarios, accounting for only 4.5%. The cooling supplied by storage tank and ISAC are 4.0% and 4.5% of the total, which is almost unanimous with the baseline scenario, but lower than that of LCE and LEB. To sum up, the proportion curve of cooling supply in a typical summer day is similar with that of the LCE scenario but with slight difference in operation mode, which means that for the supply of cooling in summer, LCE has the greatest impact on multi-objectives. And because of the comprehensive consideration of factors in NPV and LEB, there are some differences in the mode of operation.

Different from the cooling supply, the heating supply curve integrated the characteristics of all three scenarios, as illustrated in Fig. 6d. It is seen that the heating supply combination before 2pm is similar with that of the baseline and LEB scenarios, but the latter part of heating supply combination is similar to that of LCE. The proportions of heating supply from condensing boiler, CHP, GSHP and storage tank in a typical day are 14.1%, 78.4%, 7.4% and 1.1%, respectively, which also has taken into account all the optimization modes.

4. Sensitivity analysis

4.1 Sensitivity analysis of electricity price

The energy price is another key factor that influences the planning and operation strategy of CCHP system. Thus, sensitivity analysis of primary energy prices is presented in this section. By comparing with the baseline scenario, Fig. 7 and Table.3 are given to illustrate how the important indexes change with different electricity prices.

As shown in Fig. 9, curves of NPV and EB are basically the same with no obvious increases, i.e., only increase 4.45% and 5.15% when the price increases 40%, which indicates that energy dependence on the external power system after optimization is relatively low. When electricity price increases from 40% to 100% of the current value, all indexes will barely change, so does the output ratio of all technologies, suggesting that external energy is out of consideration, as shown in Table 3. As mentioned in the baseline scenario, most of the electricity purchasing occurs when the price of electricity is at valley period or the demand of electricity is high, which implies that the scenario has been economically optimized. It should be noted that when the price of electricity is increased by 40%, there is an obvious increase in natural gas demand, leading to a cutting down on the electricity purchased from the Grid, i.e., 33.51TJ versus 2.54TJ, as shown in Table 3. This is because the system will no longer buy electricity from the Grid even if the price is at valley period.

The power consumption of equipments also shows a significant downward trend. As indicated in Table 3, the output ratio between GSHP and EC in heating and cooling supply has a gradual decline. Particularly, the output ratio will become 0 when the electricity price is increased by 50%, and thus there is no need to introduce GSHPs, while EC still provides a small proportion of cooling as its consumed electricity is mainly provided by CCHP systems. One might expect that the increased electricity price would incentivize investment in condensing boilers and storage units to compensate for the reduction of GSHP and EC, but in fact the heat supplied by condensing boilers will gradually decrease, and when the price increases to 25% the condensing boiler will be eliminated. On the other hand, the heating and cooling output ratio of the storage tank is also gradually reduced, while the investment in electrical storage and ISAC has no obvious change compared with the baseline scenario. This is because under the baseline scenario, when the price is in valley period, the heating and cooling load can be covered by back-up heating/cooling sources, and the required electricity can be imported from the Grid. Whereas when the price increases, CHP is supposed to increase the output energy even when the electricity price is off-peak, so as to achieve the maximum economic benefits. Moreover, the generated heating simultaneously reduces the role of other cooling and heating sources. When the electricity price increases 40% or more, both the annual energy output of CHP and ABS will almost increase by 50% compared with the baseline scenario. In addition, the extensive use of natural gas also reduces emissions by up to 17.88%.

4.2 Sensitivity analysis of gas price

As indicated in Table 4 and Fig. 10, CCHP system is more sensitive to the change of gas price than the change of electricity price. With the increase of gas prices, except for the significant decrease in gas requirement, all the other indexes of the CCHP system are obviously increased, among which electricity consumed by technologies is the most affected, with an increase of nearly 80% when the gas price increases by 50% (compared with baseline scenario), and even rises up to 202% as gas price increases from 50% to 90%. However, NPV, primary energy consumption, CO_2 emissions and EB will be increased by 32.19%, 34.88%, 61.36% and 52.89%, respectively, when gas price increases up to 90%. On the other hand, as indicated in Table 4, it is obvious that with the increase in gas prices, electricity generated by CHP will gradually decrease, while electricity purchased from the Grid will increase gradually.

It is interesting to find that with the sensitivity analysis of electricity, when there is a 25% increase in gas price, the electrical storage units will be no longer used, while when the electricity price increases by 30%, the use of electrical storage will reach its peak amount with an annual output of 10.63TJ. As the price continues to increase, it will reduce the use of electrical storage, mainly due to two reasons. Firstly, as the price increases by 30%, there is still more than 60% electricity demand of the given area covered by CHP. While the gas price increases by 50%, less than 1/3 of electricity will be supplied by CHP. In particular, electrical storage units are not chosen when gas price increases by 90%. Given the constraint conditions in the proposed model, electricity stored in the electrical storage units cannot be charged from the Grid. As a result, there will be no installed capacity of CHP, and only a minor amount of electricity will be supplied by PV system, while most of the electricity demand is covered by the Grid, when gas price increases 90%. Secondly, the optimal objective of this sensitivity analysis is to minimize NPV, and in the case of increasing gas prices, the high capital cost of electrical storage further restricts its usage, which illustrates that there is an optimal mode for the use of electrical storage.

In terms of heating supply, when the gas price is doubled, the load covered by condensing boiler shows a great increase compared with that of the baseline scenario, boosting from 4.57TJ to 55.28TJ. It is worth noting that when gas price increases from 90% to 100%, all indexes remain almost unchanged with the absence of CHP system due to the high gas price. Hence, natural gas is only consumed by condensing boiler, which is the main heat provider, to meet the thermal demand. This result highlights the importance of GSHP in energy supply with the rising gas prices. However, due to restrictions of available construction space, the extra thermal energy provided by GSHP accounts for only 1/3 of that from the condensing boiler , i.e., 17.5TJ versus 55.28TJ, when gas price is twice of the current value. As price continues to rise, the effect of gas price on the technologies combination is negligible. When gas price increases from 90% to 100%, the output of condensing boiler remains the same, i.e., 55.28TJ, as listed in Table 4, which implies that efficient condensing boiler is a better choice than CHP under the condition of higher gas prices.

Regarding the supply of cooling, as expected, the main cooling provider will shift from ABS to EC and ISAC as gas prices increase, meaning that EC and ISAC will contribute more in cooling supply while ABS will be phased out. The optimized results suggest that when gas price increases by 50%, the cooling provided by EC will obtain its maximum and then slightly drop as gas prices continue to rise. Meanwhile, the cooling from ABS is gradually reduced while ISAC has the opposite upward trend. The total capacity of CHP gradually reduces as the gas price increases, resulting in lower amount of electricity available from the system, whereas grid electricity becomes much more convenient than CHP to meet the electricity demand. As for ISAC, when electricity price is at valley period grid electricity can be transformed into cooling energy and stored to meet the cooling demand of high electricity price period and achieve peak load shaving, which also in turn illustrates that there exists an optimal mode for the combination of EC and ISAC.

5. Conclusions

This study aims to present an approach to solve the design and operation problems for urban CCHP systems. A robust MINLP model has been developed, which rigorously optimized the configuration, sizing and operation of the system from supply side perspectives, accounting for the time-dependent demand profiles as well as the equipment sizing and part load operations for various technologies. This proposed methodology and model, subjecting to a number of constraints that are indexed by technological, spatial and temporal sets in the analysis. To evaluate the results of applying the presented approach and demonstrate the accessibility and feasibility of this program to decision makers, the model has been applied successfully to the planning of a real-world innovation pilot zone in urban China. A range of scenarios have been analyzed, based on which the answer to the question of how the various technology mixture can meet the requirements of local energy services under different circumstances is given. The conventional energy supply system is taken as the reference system for analysis from economic, energy and environmental perspectives. According to the analysis, a few conclusions have been summarized as follows:

Firstly, for single objective optimization mode, dynamic balances have been finally achieved by the interdependent and mutual restraints of all three scenarios. The baseline scenario will preferentially guarantee the thermal energy supply of heating and cooling, while electricity will be averagely supplied by multiple sources, and the optimal total cost will require the CCHP system to make some compromise on CO_2 emissions and annual energy cost. Compared with the baseline scenario, reduced CO_2 emissions will result in higher capital cost and annual energy cost, mainly reflected by the minimization of electricity purchasing, which is principally due to the fact that electricity should be generated by CHP rather than imported from the Grid when electricity price is in valley period. The amount of heating and cooling will be supplied more by absorption chiller and condensing boiler on the other hand. Moreover, lower annual energy cost will lead to the highest capital cost and most electricity imported from the Grid. In addition, among the four scenarios, only in this scenario can the electrochemical storage have more applications because of the varied building types and subsequent load fluctuations. Consequently, only a rigid constraint, i.e., a reduction of 40% in annual EB, could be met by selecting the costly electrochemical storage which can better equalize the peak load. Learning from the results of this scenario, it is noticed that lower annual energy cost does not necessarily result in significant reduction in primary energy saving. The reason is that the CCHP system intends to import more electricity from the Grid in valley period to cut the EB, yet more electricity imported from the Grid will also lead to higher GHG emissions.

Secondly, for multi-objective optimization mode, the entropy weight method has been applied to evaluate the comprehensive benefits of CCHP system via economic, CO_2 emissions and EB criteria. The scenario considered all the same energy demand and economic context, but with different constraints specifically. The analyses showed that the joint optimization could better balance the results of the other three scenarios, yet with different daily operation curves. Meanwhile, the results indicated that the environmental impact is the most important indicator for the joint optimization case, the annual EB comes second, and the NPV has the least impact on the benefits of integrated scenario.

Thirdly, in addition to the combination design and operation strategy of the CCHP system, the energy price is also directly associated with energy policy that can lead to important consequences in certain legal contexts as the one considered here. First of all, with the increase in electricity prices, NPV and EB did not change significantly, indicating that after optimization the CCHP system is less dependent on external energy, only purchasing electricity from the Grid for specific time when the price is in valley period. On the other hand, with the price growth more usage of natural gas-driven devices and less usage of cooling and heating storage tank have been predicted, which in turn caused a reduction in energy consumption and emissions. When the current electricity price is increased by 40%, few electricity will be imported from the Grid. Instead, the regional energy demand is shown to be mostly covered by the CCHP system. Secondly, the optimized CCHP system is more sensitive to the changes in gas prices than electricity in terms of NPV, EB and even emissions. Moreover, for higher gas prices, efficient condensing boiler will become more convenient than CHP to meet the heating demand, while GSHP, ISAC and EC have been predicted to take more prominent roles to compensate for the reduction of CHP. The investigation also shows that when electricity produced by CHP is reduced under high gas prices, ISAC is more convenient than EC for economic objective, while the electrical storage will be mostly applied when the gas price increases to 40% and then begins to decrease. Therefore, compared to the natural gas-driven technologies, the technologies using lower price fuels such as coal-fired power plant and coal-fired boiler etc. will directly affect the invest combination and operation strategy of CCHP.

In conclusion, the proposed method is considered to be applicable for a wide variety of urban energy systems and related systems for electricity, heating and cooling supply. The employment of optimization models for improved decision-making at the preliminary stages of design allows a better insight into the synergies between different sources of energy. The weakness of the present research lies in that the efficiencies of supply side technologies are assumed to be constant. Besides, the optimization on technology siting and pipeline connections of the district is not covered in this paper. The enrichment of database for technologies as well as the improved analysis for energy flows between nodes would be major tasks for the future research. Moreover, further issues about the practical feasibility of such optimization procedures need to be addressed. A more in-depth analysis of technology siting and energy transmission trade-offs should be performed as well to improve the understanding of the interactions between different technologies and the links between each nodes of the district.

Acknowledgments

The work is supported by the National Natural Science Foundation of China for support under grant No. 51206137. The authors are also grateful to the Fundamental Research Fund for the Central Universities with grant No. 20720150111.

Nomenclature

Subscripts and superscripts

Sets

e	storage components
et	thermal storage system and electrochemical battery, subset to *e*
h	hours
i	spatial node of geographical area
s	seasons
t	energy generation technologies
te	electricity driving technologies, subset to *t*
tg	natural gas driving technologies, subset to *t*
y	year
t'	alias of *t*
et'	alias of *e*

Elements

ABS	absorption chiller
Boiler	condensing boiler
CHP	combine heat and power
ES	electrical storage (electrochemical battery)
EC	electrical chiller
ISAC	ice storage air conditioner
PV	photovoltaic
TES	thermal storage system (storage tank)
GSHP	ground source heat pump
Grid	national grid

Parameters

A	avaliable area for the installation of PV and GSHP
CAP^{max}	max capacity
Cd	cooling demand
Cs	captial cost for each storage component
Ct	captial cost for each technologies
D	time duration
Ed	electricity demand
Hd	heating demand
Pfi	price of feed-in tariff
Pgas	price of natural gas
Ptou	time-of-use electricity price
r	discount rate

α	growth rate
β	maintenance factor
δ	solar irradiance
ε	average size
η	efficiency
θ	emission rate
Rt	technology replacement parameter

Variables

CAP	operating capacity
CC	captial cost
COP	coefficient of performance
EB	energy bill
Ein	energy input
ELex	electricity export to grid
ELim	electricity imported from grid
EM	CO_2 emission
Enet	net electricity generated by energy system
Eout	energy output
Nis	number of new invest storage component
Nit	number of new invest technologies
NPV	net present value
Ns	number of storage component
Nt	number of technologies
OM	operating and maintenance cost
RE	revenue
Sa	amount of energy stored in energy system
Sc	energy charge into storage component
Sd	energy discharge by storage component
Sl	storage losses
Z	weight factor

References

[1] Zheng CY, Wu JY, Zhai XQ. A novel operation strategy for CCHP systems based on minimum distance. Applied Energy. 2014;128(128):325–35.

[2] Li L, Mu H, Li N, Li M. Economic and environmental optimization for distributed energy resource systems coupled with district energy networks. Energy. 2016;109:947-60.

[3] Rodríguez LR, Lissén JMS, Ramos JS, Jara EÁR, Domínguez SÁ, Yan J. Analysis of the economic feasibility and reduction of a building's energy consumption and emissions when integrating hybrid solar thermal/PV/micro-CHP systems. Applied Energy. 2016;165:828-38.

[4] Ascione F, Canelli M, Masi RFD, Sasso M, Vanoli GP. Combined cooling, heating and power for small urban districts: AnItalian case-study. Applied Thermal Engineering. 2014;71(2):705-13.

[5] Cho H, Luck R, Eksioglu SD, Chamra LM. Cost-optimized real-time operation of CHP systems. Energy and Buildings. 2009;41(4):445-51.

[6] Braslavsky JH, Wall JR, Reedman LJ. Optimal distributed energy resources and the cost of reduced greenhouse gas emissions in a large retail shopping centre. Applied Energy. 2015;155:120-30.

[7] Tian Z, Niu J, Lu Y, He S, Tian X, Yan J. The improvement of a simulation model for a distributed CCHP system and its influence on optimal operation cost and strategy. Applied Energy. 2016;165(5):430-44.

[8] Li M, Mu H, Li N, Ma B. Optimal design and operation strategy for integrated evaluation of CCHP (combined cooling heating and power) system. Energy. 2016;99:202-20.

[9] Cho H, Mago PJ, Luck R, Chamra LM. Evaluation of CCHP systems performance based on operational cost, primary energy consumption, and carbon dioxide emission by utilizing an optimal operation scheme. Applied Energy. 2009;86(12):2540-9.

[10] Cho H, Smith AD, Mago P. Combined cooling, heating and power: A review of performance improvement and optimization. Applied Energy. 2014;136:168-85.

[11] Chicco G, Mancarella P. Distributed multi-generation: A comprehensive view. Renewable and Sustainable Energy Reviews. 2009;13(3):535-51.

[12] Bischi A, Taccari L, Martelli E, Amaldi E, Manzolini G, Silva P, Campanari S, Macchi E. A detailed MILP optimization model for combined cooling, heat and power system operation planning. Energy. 2014;74:12-26.

[13] Jabari F, Nojavan S, Ivatloo BM, Sharifian MBB. Optimal short-term scheduling of a novel tri-generation system in the presence of demand response programs and battery storage system. Energy Conversion & Management. 2016;122:95-108.

[14] Arcuri P, Florio G, Fragiacomo P. A mixed integer programming model for optimal design of trigeneration in a hospital complex. Energy. 2007;32(8):1430-47.

[15] Ju L, Tan Z, Li H, Tan Q, Yu X, Song X. Multi-objective operation optimization and evaluation model for CCHP and renewable energy based hybrid energy system driven by distributed energy resources in China. Energy. 2016;111:322-40.

[16] Hu M, Cho H. A probability constrained multi-objective optimization model for CCHP system operation decision support. Applied Energy. 2014;116:230-42.

[17] Ameri M, Besharati Z. Optimal design and operation of district heating and cooling networks with CCHP systems in a residential complex. Energy & Buildings. 2015;110:135-48.

[18] Farahnak M, Farzaneh-Gord M, Deymi-Dashtebayaz M, Dashti F. Optimal sizing of power

generation unit capacity in ICE-driven CCHP systems for various residential building sizes. Applied Energy. 2015;158:203-19.
[19] Yang H, Xiong T, Qiu J, Qiu D, Dong ZY. Optimal operation of DES/CCHP based regional multi-energy prosumer with demand response. Applied Energy. 2015;167:353-65.
[20] Carvalho M, Serra LM, Lozano MA. Optimal synthesis of trigeneration systems subject to environmental constraints. Energy. 2011;36(6):3779-90.
[21] Evins R. A review of computational optimisation methods applied to sustainable building design. Renewable and Sustainable Energy Reviews. 2013;22:230-45.
[22] Wang E. Benchmarking whole-building energy performance with multi-criteria technique for order preference by similarity to ideal solution using a selective objective-weighting approach. Applied Energy. 2015;146:92-103.
[23] Jing Y-Y, Bai H, Wang J-J. Multi-objective optimization design and operation strategy analysis of BCHP system based on life cycle assessment. Energy. 2012;37(1):405-16.
[24] Tulus V, Boer D, Cabeza LF, Jiménez L, Guillén-Gosálbez G. Enhanced thermal energy supply via central solar heating plants with seasonal storage: A multi-objective optimization approach. Applied Energy. 2016;181:549-61.
[25] Xiao L, Shao W, Wang C, Zhang K, Lu H. Research and application of a hybrid model based on multi-objective optimization for electrical load forecasting. Applied Energy. 2016;180:213-33.
[26] Mallikarjun S, Lewis HF. Energy technology allocation for distributed energy resources: A strategic technology-policy framework. Energy. 2014;72:783-99.
[27] Kang L, Liu Y. Multi-objective optimization on a heat exchanger network retrofit with a heat pump and analysis of CO2 emissions control. Applied Energy. 2015;154:696-708.
[28] Di Somma M, Yan B, Bianco N, Graditi G, Luh PB, Mongibello L, Naso V. Multi-objective design optimization of distributed energy systems through cost and exergy assessments. Applied Energy. 2017.
[29] Yan J, Zhao T, Kang J. Sensitivity analysis of technology and supply change for CO2 emission intensity of energy-intensive industries based on input–output model. Applied Energy. 2016;171:456-67.
[30] Ahn J, Cho S, Chung DH. Analysis of energy and control efficiencies of fuzzy logic and artificial neural network technologies in the heating energy supply system responding to the changes of user demands. Applied Energy. 2017;190:222-31.
[31] Bhatt A, Sharma MP, Saini RP. Feasibility and sensitivity analysis of an off-grid micro hydro–photovoltaic–biomass and biogas–diesel–battery hybrid energy system for a remote area in Uttarakhand state, India. Renewable and Sustainable Energy Reviews. 2016;61:53-69.
[32] Martins TAdL, Adolphe L, Bastos LEG, Martins MAdL. Sensitivity analysis of urban morphology factors regarding solar energy potential of buildings in a Brazilian tropical context. Solar Energy. 2016;137:11-24.
[33] Wang J, Zhai Z, Jing Y, Zhang X, Zhang C. Sensitivity analysis of optimal model on building cooling heating and power system. Applied Energy. 2011;88(12):5143-52.
[34] Pantaleo AM, Giarola S, Bauen A, Shah N. Integration of biomass into urban energy systems for heat and power. Part II: Sensitivity assessment of main techno-economic factors. Energy Conversion and Management. 2014;83:362-76.
[35] Anatone M, Panone V. A Model for the Optimal Management of a CCHP Plant. Energy Procedia. 2015;81:399-411.
[36] Almansoori A, Betancourt-Torcat A. Design optimization model for the integration of renewable

and nuclear energy in the United Arab Emirates' power system. Applied Energy. 2015;148:234-51.
[37] Andrei N. Nonlinear Optimization Applications Using the GAMS Technology[J]. 2013, 81.
[38] Mertz T, Serra S, Henon A, Reneaume J-M. A MINLP optimization of the configuration and the design of a district heating network: Academic study cases. Energy. 2016;117:450-64.
[39] Boukouvala F, Misener R, Floudas CA. Global optimization advances in Mixed-Integer Nonlinear Programming, MINLP, and Constrained Derivative-Free Optimization, CDFO. European Journal of Operational Research. 2016;252(3):701-27.
[40] Jennings M, Fisk D, Shah N. Modelling and optimization of retrofitting residential energy systems at the urban scale. Energy. 2014;64:220-33.

Figure captions:

Fig.1 Cooling and electrical demand for a typical summer day.

Fig.2 Heating and electrical demand for a typical winter day.

Fig. 3 Flow diagram of the CCHP system.

Fig.4 Percentage of annual electrical energy generated for four scenarios.

Fig.5 Cooling energy generated by technologies for a typical summer day.

Fig.6 Heating energy generated by technologies for a typical winter day.

Fig.7 Energy generated by distributed technologies for TOU price period.

Fig.8 Energy flows in storage units for TOU price period.

Fig.9 Sensitivity analysis with different electricity prices for baseline scenario.

Fig.10 Sensitivity analysis with different gas prices for baseline scenario.

Table captions:

Table 1. Details of TOU price.

Table 2. Optimization results of the test case for different scenarios.

Table 3. Optimization results and sensitivity analysis for electricity price.

Table 4. Optimization results and sensitivity analysis for gas price.

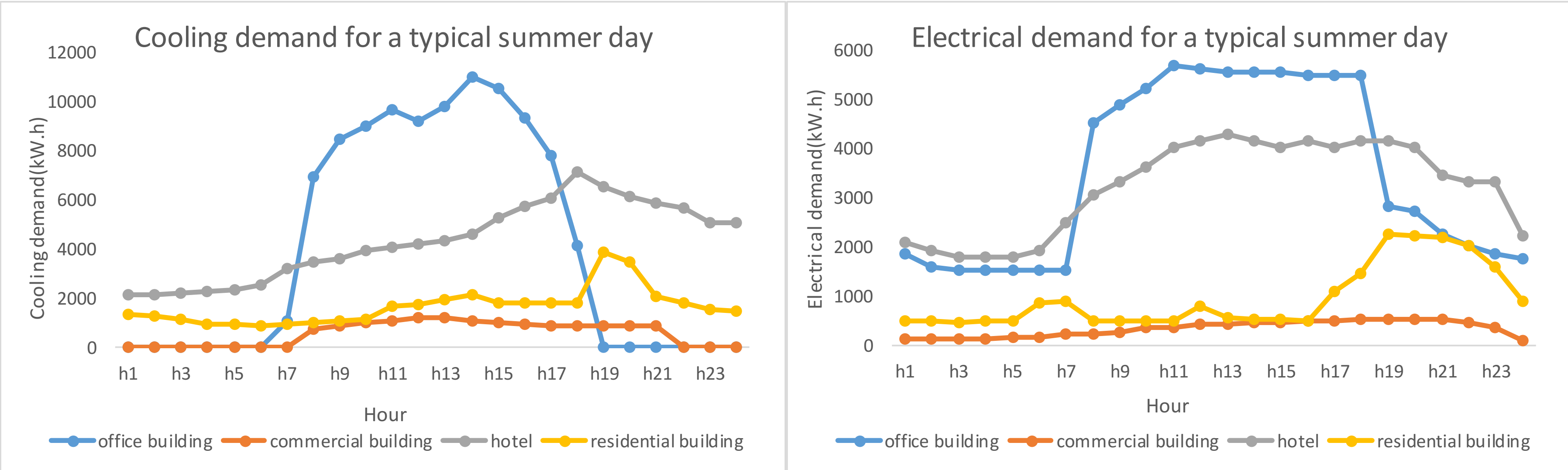

Fig.1 Cooling and electrical demand for a typical summer day

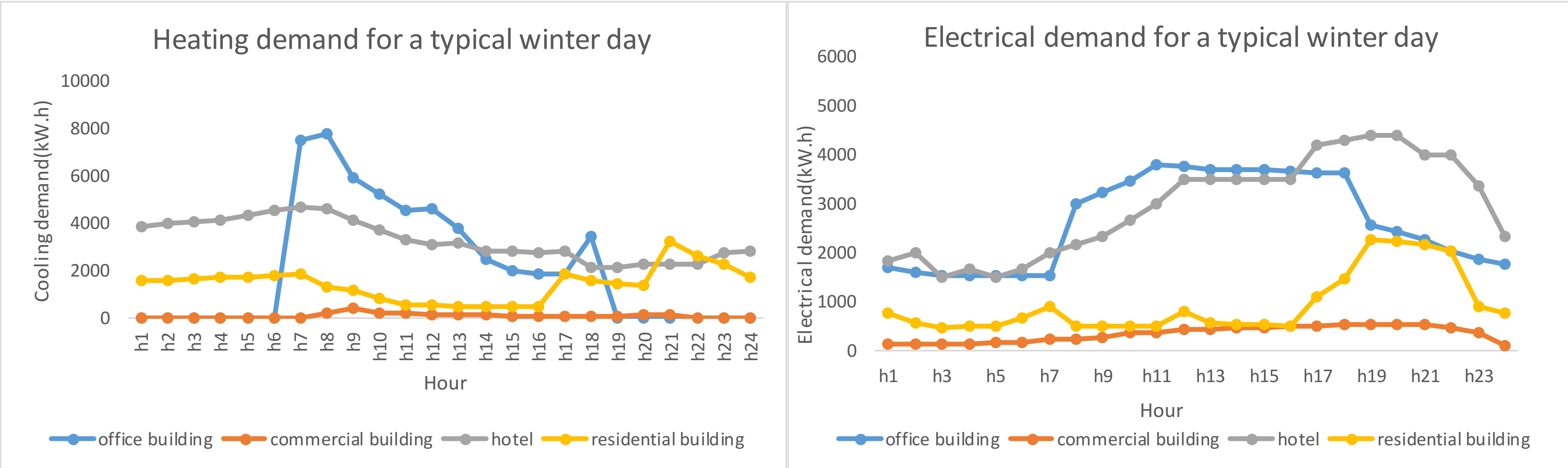

Fig.2 Heating and electrical demand for a typical winter day

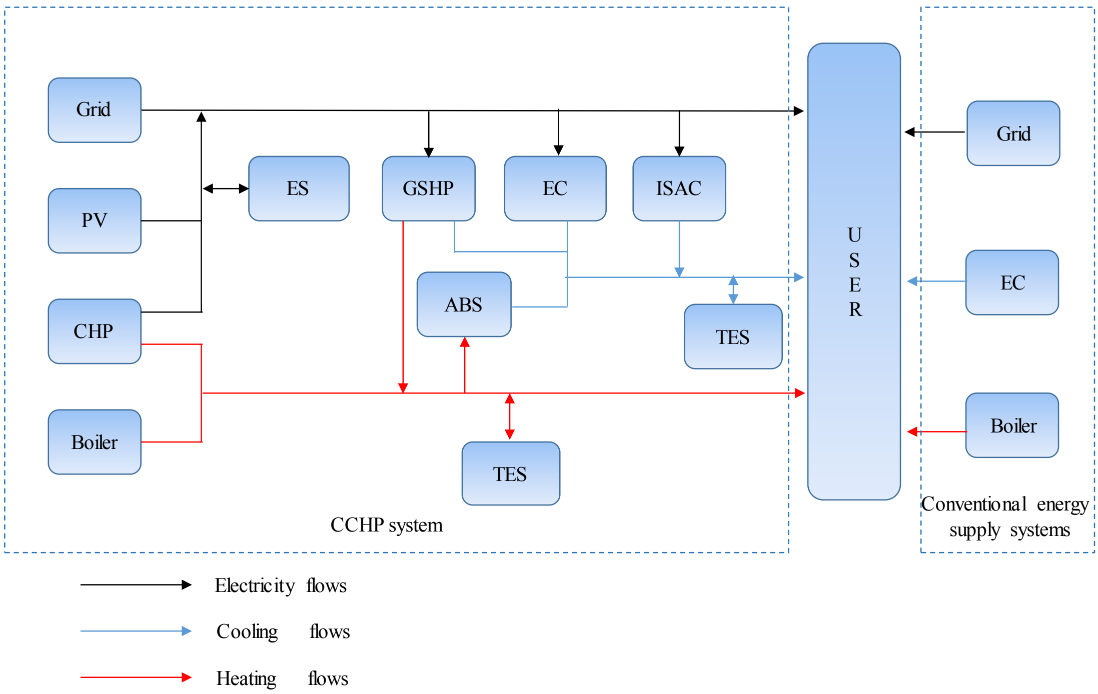

Fig. 3 Flow diagram of energy system

Grid-national grid, PV-photovoltaic, CHP-combine heat and power, Boiler-condensing boiler, ES-electrical storage, GSHP-ground source heat pump, EC-electrical chiller, ISAC-ice storage air conditioning system, ABS-absorption chiller, TES-thermal storage system

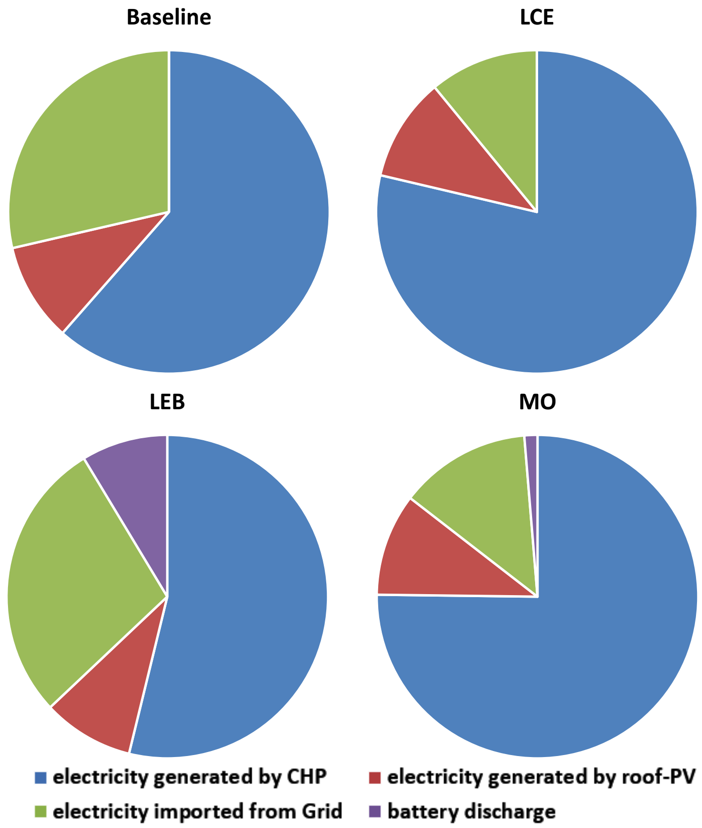

Fig.4 Percentage of annual electrical energy generated for both four scenarios

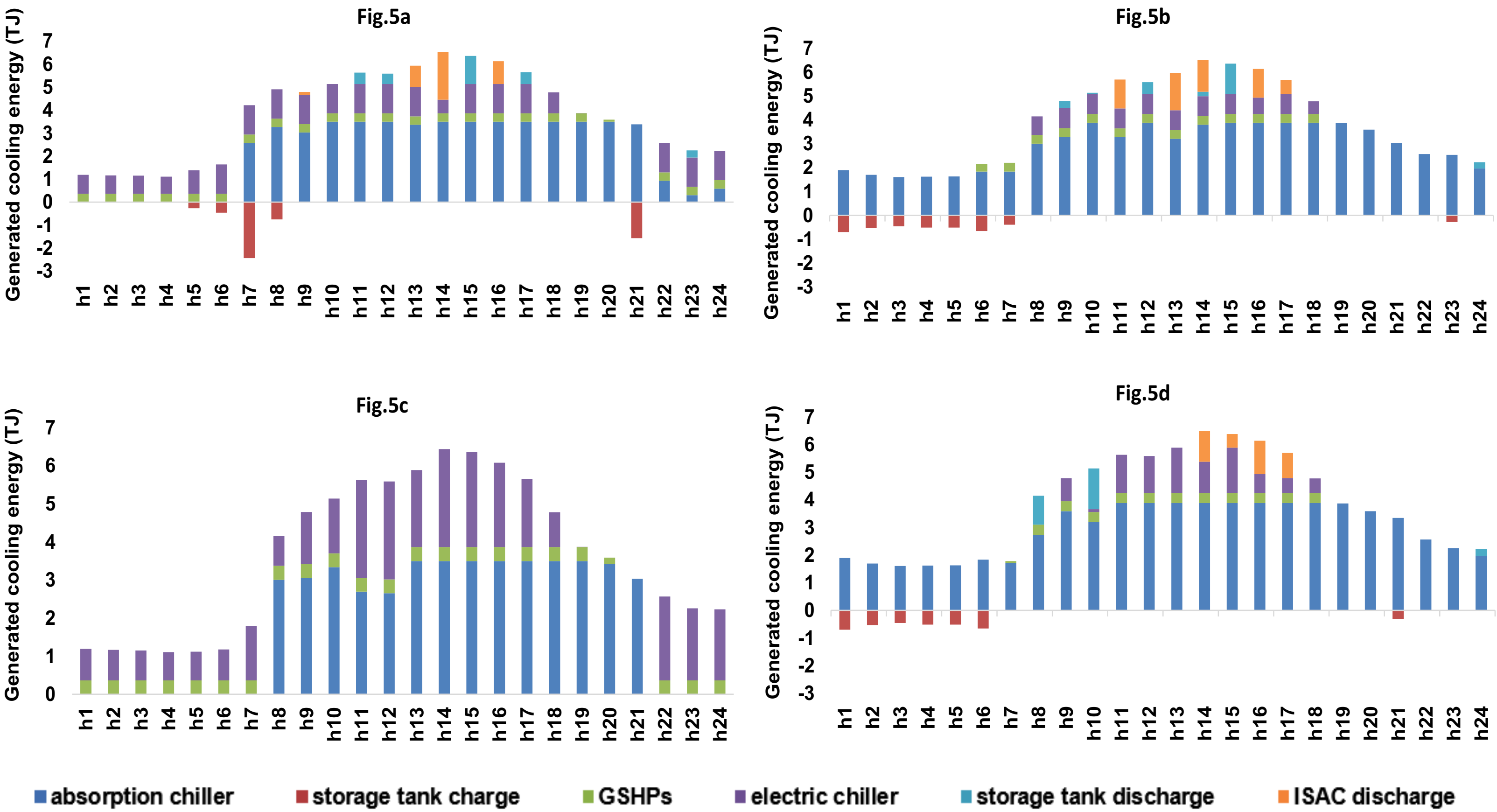

Fig.5 Cooling energy generated by technologies for a typical summer day

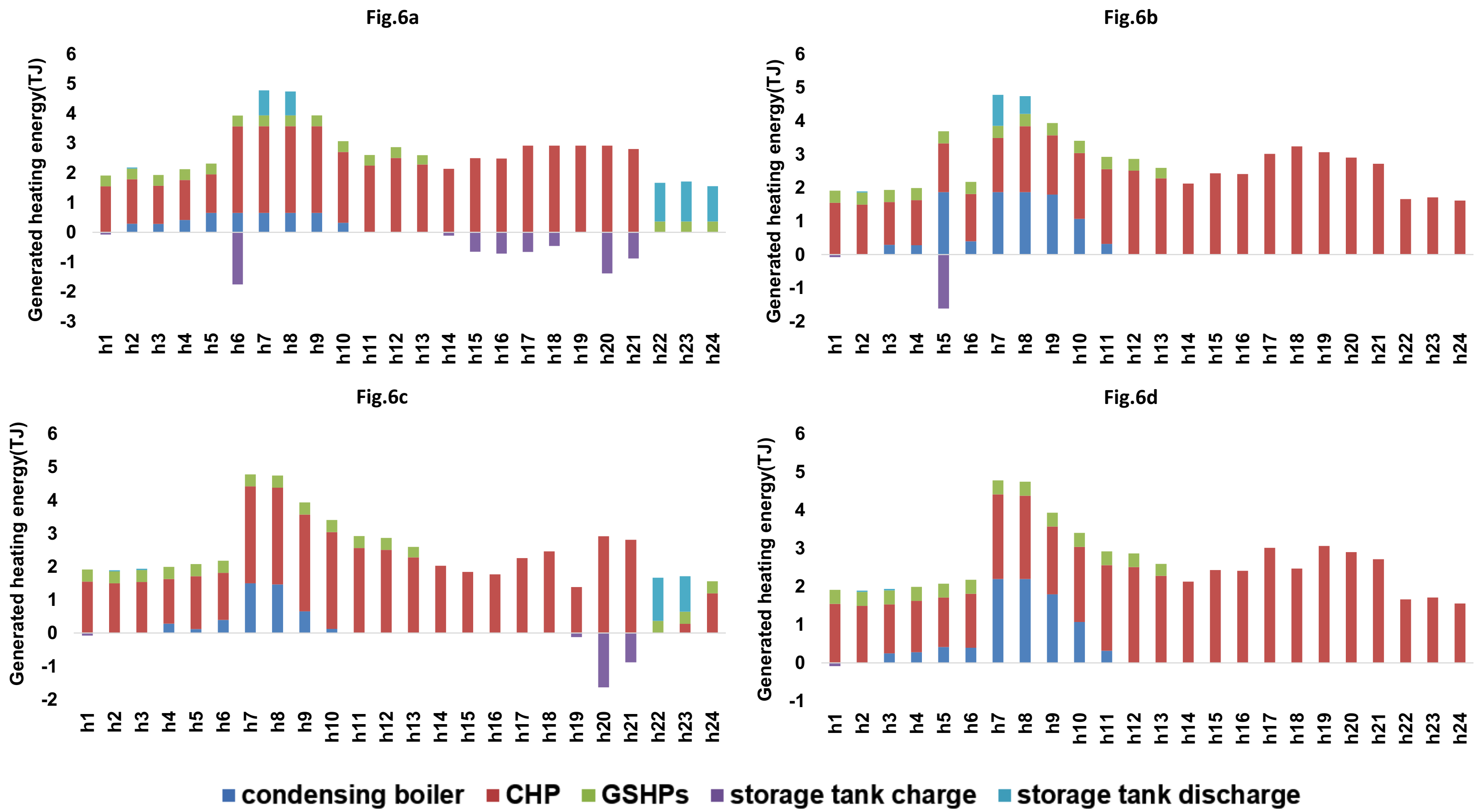

Fig.6 Heating energy generated by technologies for a typical winter day

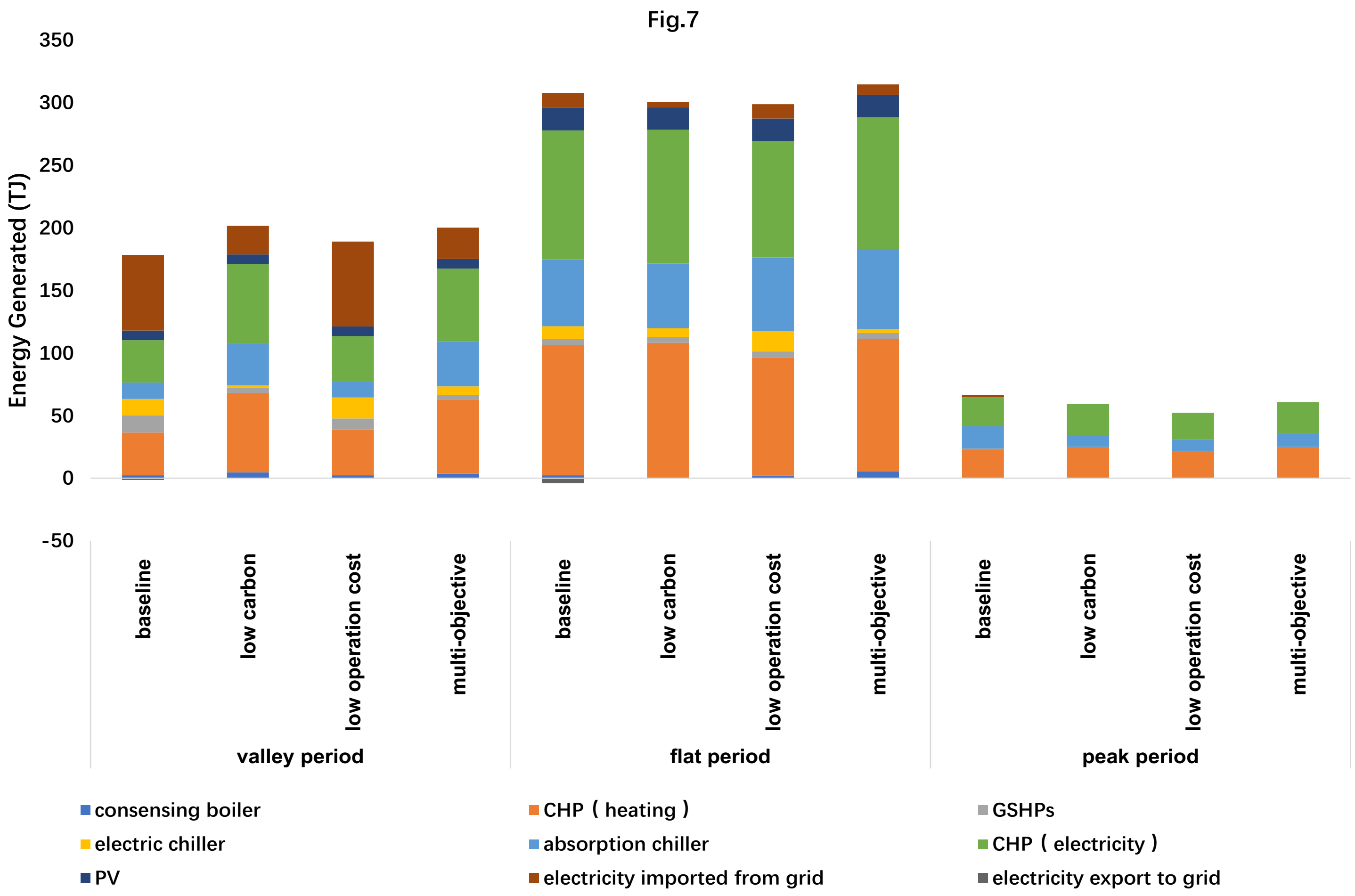

Fig.7 Energy generated by distributed technologies for TOU price period

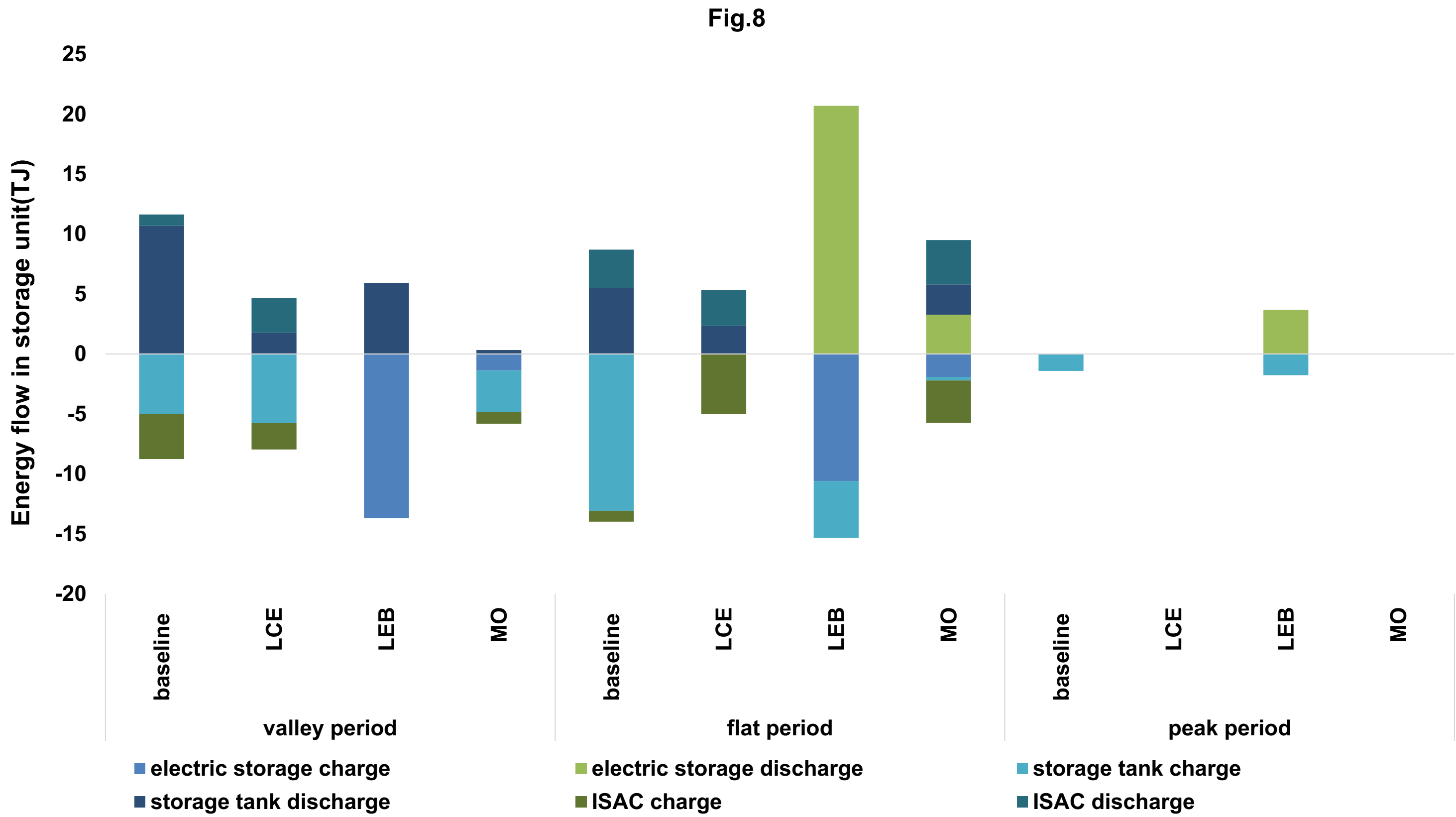

Fig.8 Energy flows in storage units for TOU price period

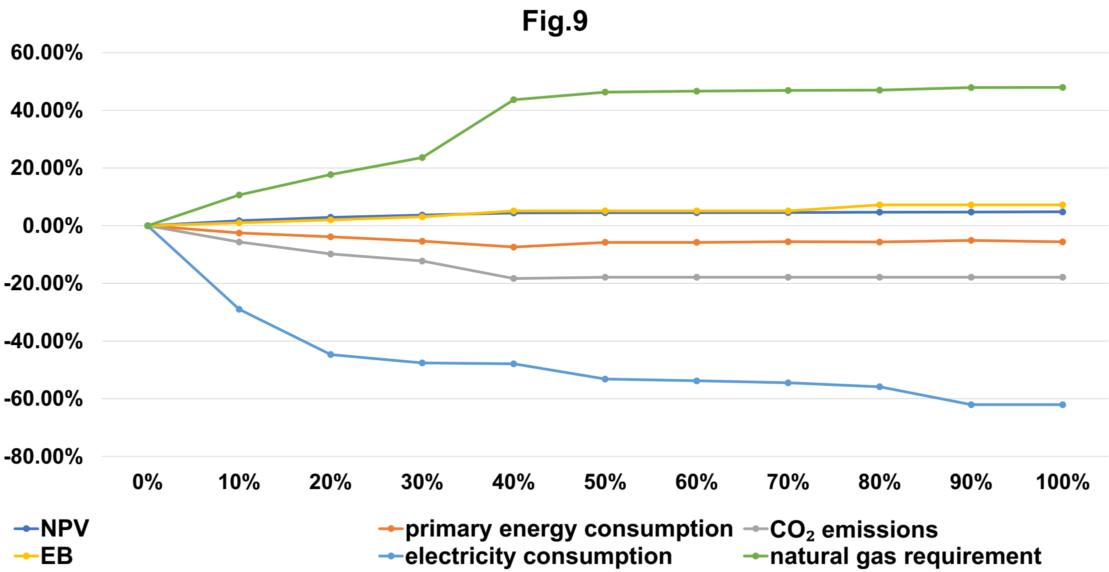

Fig.9 Sensitivity analysis with different electricity price for baseline scenario

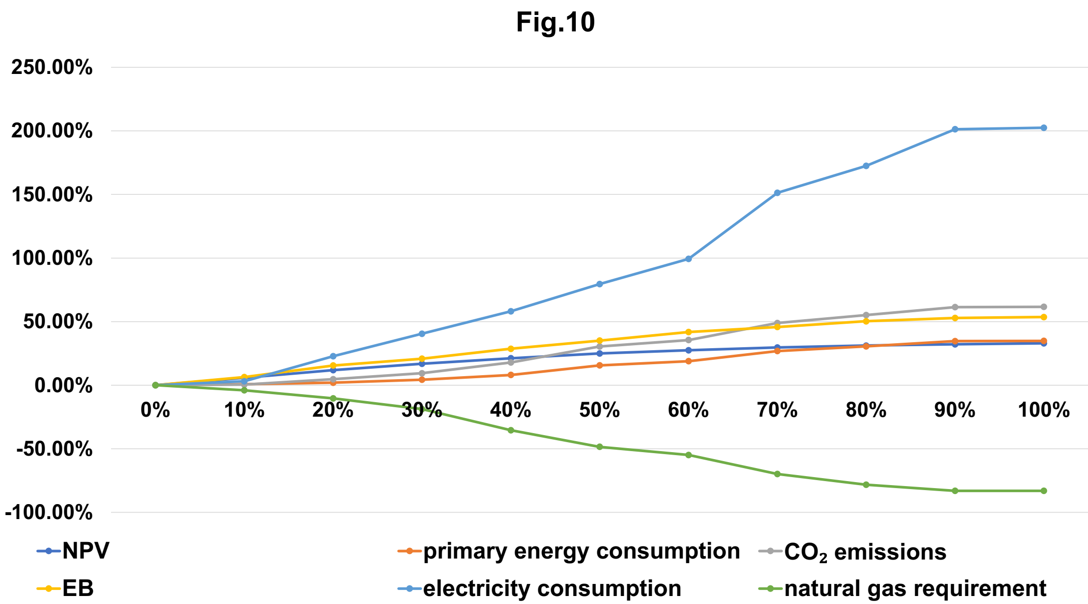

Fig.10 Sensitivity analysis with different gas price for baseline scenario

	Valley period	Flat period	Peak period
Time interval	22:00-8:00, 11:00-13:00	8:00-11:00, 13:00-19:00,21:00	19:00-21:00
Electricity price	0.571yuan/kW·h	1.074yuan/ kW·h	1.367yuan/ kW·h

Table 1. Details of TOU price.

	2015	baseline	LCE	LEB	MO
NPV(million yuan)	606.80	450.64	465.70	479.30	463.00
Annual CO_2 emission（kt）	73.00	42.50	36.00	47.30	36.50
Annual EB(million yuan)	77.45	48.50	48.90	46.50	48.00
Annual primary energy consumption（TJ）	863.00	596.00	549.00	589.00	550.80
Annual electricity imported from grid(MW·h)	75722.22	19229.17	7516.67	22061.11	9222.22
Annual electricity consumed by *te*(MW·h)	8916.67	4046.11	1880.56	3488.89	1847.22
Annual gas requirement(TJ)	84.50	379.20	469.86	366.20	456.50
Capacity of absorption chillers(MW)	-	11.00	12.00	11.00	12.00
Capacity of CHP(MW)	-	9.00	10.00	9.00	10.00
Capacity of electric chillers(MW)	20.00	4.00	2.60	8.00	5.00
Capacity of condensing boiler(MW)	15.00	2.00	5.70	4.60	7.00
Capacity of ISAC(m^3)	-	220.00	180.00	0.00	220.00
Capacity of storage tank(m^3)	-	280.00	240.00	160.00	200.00
Capacity of electric storage(MW)	-	0.00	0.00	15.00	3.00

Table 2. Optimization results of the test case for different scenarios.

electricity price	baseline	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
electricity imported from Grid	74.36	56.68	43.15	33.51	2.54	2.46	2.45	2.44	2.4	0.83	0.83
electricity generated by CHP	159.99	176.47	187.03	198.21	230.7	235.2	235.1	235.5	235.73	239.01	239.13
electricity generated by roof-PV	25.76	25.76	25.76	25.76	25.76	25.76	25.76	25.76	25.76	25.76	25.76
electricity supplied battery	0	0	0	0	0	0	0	0	0	0	0
heating supplied by CHP	84.3	89.63	93.94	100.95	115.47	120.59	120.6	120.62	120.59	120.76	120.8
heating supplied by boiler	4.57	1.87	2.03	0	0	0	0	0	0	0	0
heating supplied by GSHP	8.33	7.6	4.68	4.68	4.68	0	0	0	0	0	0
heating supplied by storage tank	8.45	9.14	6.66	2.64	3.41	2.9	3.24	3.01	2.68	2.66	2.79
cooling supplied by ABS	75.76	102.83	98.29	104.71	112.1	112.25	113.65	115.12	116.21	117.22	117.3
cooling supplied by GSHP	10.67	9.49	4.38	4.03	4.47	0	0	0	0	0	0
cooling supplied by EC	23.62	13.85	11.14	10.87	6.64	5.88	5.78	5.62	5.33	4.09	4.09
cooling supplied by storage tank	7.78	7.53	5.6	2.4	3.18	3.07	3.51	2.88	3.02	2.68	2.93
cooling supplied by ISAC	4.14	2.71	4.15	3.8	3.59	3.3	3.04	3.86	3.85	3.94	3.71

Table 3. Optimization results of sensitivity analysis for electricity price (TJ).

gas price	baseline	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
electricity imported from Grid	74.36	79.3	94.13	109.98	142.75	172.2	188.1	225.6	243.36	258.43	258.9
electricity generated by CHP	159.99	152.18	139.16	126.11	96.61	68.53	55.54	27.38	10.89	0	0
electricity generated by roof-PV	25.76	25.76	25.76	25.76	25.76	25.76	25.76	25.76	25.76	25.76	25.76
electricity supplied by battery	0	0	0	10.63	7.24	3.7	2.6	2.1	1.71	0	0
heating supplied by CHP	84.3	80.14	75.78	71.05	54.8	33	26.58	16.07	7.1	0	0
heating supplied by boiler	4.57	8.33	8.52	8.4	9.67	26.69	34.16	40.26	48.88	55.28	55.28
heating supplied by GSHP	8.33	8.33	8.33	8.9	11.54	13.1	13.46	16.51	16.79	17.5	17.5
heating supplied by storage tank	8.45	7.99	8.1	7.37	5	3.34	3.03	2.26	1.76	1.69	1.69
cooling supplied by ABS	75.76	71.71	65.11	58.45	50.01	43.42	39.73	33.88	14.67	0	0
cooling supplied by GSHP	10.67	10.68	11.31	10.65	12.4	12.04	13.21	15.98	16	16	16
cooling supplied by EC	23.62	25.24	35.83	36	39.27	40.72	39.05	38.55	38.5	38.01	37.37
cooling supplied by storage tank	7.78	7.16	6.64	6.35	5.26	4.88	4.26	5.22	4.67	5	4.66
cooling supplied by ISAC	4.14	5.86	5.68	9.35	12.99	19.39	23.31	27.36	45.94	60.9	60.9

Table 4. Optimization results of sensitivity analysis for gas price (TJ)