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Community energy system planning: a case study on technology selection and operation optimization

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Abstract

Community energy planning has attracted wide attention in China as the implementation of China's low-carbon city policies. Meanwhile the rapid development of energy science and technology has shifted buildings and communities from energy consumers to prosumers, which lead to more difficulties in configuring the energy technology portfolio. This study es-tablishes an optimal decision-making model for community energy planning and develops an online tool called District EnErgy Planning(DEEP). Based on DEEP, the impact of energy price and equipment cost on optimization results, and the corresponding operational strategies are discussed through case study and scenario analysis. The results show that, when natural gas price exceeds 2yuan/m^3, the gas-based solutions become economically uncompetitive. The technologies are propitious when equipment prices are reduced by 50%, 50%, 80% for CHP facilities, PV panels and electric battery, respectively.

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Keywords: Community energy planning; Decision optimization; Renewable energy; Distributed energy system; Operational strategy

1. Introduction

In recent years, climate change has become one of the most pressing problems facing all countries all over the world. Inefficient use of fossil fuels is an important reason. Community energy planning(CEP) is a useful tool to improve energy efficiency and reduce building energy consumption in district scale. In China CEP is becoming increasingly a necessary part in area planning and construction of low carbon cities. However, the current decision-

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making process of the energy planning is generally lack of scientific basis. The planned scheme is usually difficult to implement and/or achieve the desired goals. The optimal analysis, as an important means to achieve efficient matching of energy supply side and demand side, is the key segment of CEP. It helps to find an efficient technology portfolio and economic operation mode for district energy system.

The energy system configuration and operational optimization issues, in fact, is a unit commitment problem, which refers to optimizing generation resources over a short time horizon to satisfy load demand at minimum operational cost while satisfying prevailing constraints[1]. There have been some discussions in the literature, but most of them are from the view of energy supply side, focusing on certain energy technologies like combined heat and power[2]. A few of them consider from the demand side to study the optimal technology portfolio to meet the energy needs, but relatively less technologies are involved[3]. It cannot meet the requirements of multi-energy complementary and low-carbon community without taking into account the distributed energy, renewable energy, energy storage, waste heat and/or absorption technologies as a whole. Most of these optimization studies have adopted a lower temporal resolution, but few of them discuss the impact of the time interval and the load handling approach on optimization results.

To make rational decisions in energy planning process, a District EnErgy Planning (DEEP) tool have been developed to provide support for the optimal selection of energy technologies and the determination of operation strategy. DEEP leverages a large-scale mixed integer linear programming method, using the minimized cost as objective to optimize the technology selection and operation strategy. The model is established based on predicted load data with full time resolution (8640 hourly data), and taking into account the combination of up to 16 kinds of energy technologies. DEEP also use carbon emission reduction objective and give carbon emission analysis by using carbon tax and carbon emission factors. Moreover, DEEP can con-sider the loss of pipe network for district energy plant. This paper validates DEEP's optimization ability through a case study. Different system configuration solutions and operation strategies are obtained and analyzed through changing the boundary conditions.

2. Mathematical models

2.1. Object and boundary

DEEP is particularly suitable for a comparative analysis for a variety of energy technologies, which can be decentralized energy technologies on the customer side or a centralized energy technology, i.e. an energy plant. By considering the competitive relationship between the centralized technologies and decentralized technologies, DEEP can decide whether an energy plant is needed. Although centralized energy plant is not the focus of DEEP, the transmission loss for DHC utility is involved by considering a simplified method regarding pipeline net-work topology and a load-related thermal loss.

DEEP provides an abundant technology candidates library. Fig. 1 is the energy flow diagram showing the most complicated energy technology portfolio considered in the model. Electricity, gas, heat from the municipal network and/or waste heat on the spot are considered as primary energy input. The energy conversion technology candidates include: conventional energy technologies such as boilers and electric chillers; renewable energy technologies like solar thermal, PV and all kinds of heat pumps; combined cooling heating and power (CCHP) and energy storage technologies like electric battery and thermal tank. The DEEP model pro-vides an optimized multi-energy complementary solution on the basis of energy demand and price information.

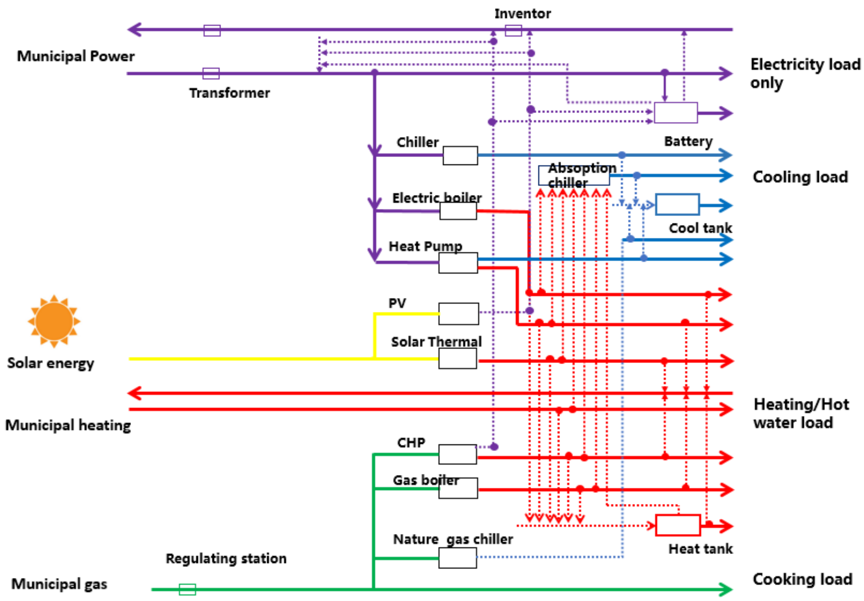

Fig. 1. Energy flow diagram of integrated system including all technologies in the model

2.2. Objective function

The optimization problem minimizes the total cost for planning and operating the district energy system. This includes investment costs, operating costs, maintenance costs, and the costs of electricity and heat exchange between the municipal grid and local energy system. A carbon tax is also concerned to account the greenhouse gas emission issues. Although there is no carbon tax policy in China presently, this item in the objective function could help achieve the minimal optimization of carbon emissions or perform multi-objective analysis. By considering a dynamic calculation method for the capital time value, we convert the investment into yearly investment cost throughout its lifetime. To get the annualized capital cost, the capital recovery factor (CRF) of each equipment is utilized.

$$f^{TOT} = [f^{INV} + f^{OP} + f^{MTN} + f_{ele}^{GRID\_PUR} + f_{heat}^{IND\_PUR} - (f_{ele}^{GRID\_SAL} + f_{heat}^{GRID\_SAL})] + f_{carbTax} \tag{1}$$

where f^{INV} is investment cost for energy conversion technologies, f^{OP} is operation cost for energy conversion systems, including natural gas fuel, electricity and heat expenses, f^{MTN} is the maintenance cost, $f_{ele}^{GRID\_PUR}$ is the electricity purchasing from the power grid used for the operation of energy conversion systems, $f_{heat}^{IND\_PUR}$ is the heat purchasing from the heat networks, $f_{ele}^{GRID\_SAL}$ is the electricity generation from local power generators sold to power grid, $f_{heat}^{GRID\_SAL}$ is the heat generation from local heat generators sold to heat networks, $f_{carbTax}$ is the carbon tax, which reflects the carbon content of the purchased electricity or natural gas used in a boiler, CHP, or natural gas-fired absorption chiller etc.

2.3. Energy balance

The system needs to fulfill electricity, heating and cooling energy requirements, which not only consist of terminal area loads for customs, but also include the energy demand by the energy conversion technologies. In Eq. (2), terminal electricity loads, as well as the electricity consumed by chillers, heat pump and electrical boilers can be met by CHP facilities, PV panels, batteries, and being purchased from power grid. In Eq. (3), terminal heating load for customs can be satisfied by CHP units, heat pump, electrical boiler, natural gas boiler, natural gas chiller, solar thermal system, heat tank or purchased from municipal heat network or industry waste heat while meeting the heating demand for absorption chiller as well as pipeline heat loss. In Eq. (4), cooling loads and pipeline loss can be satisfied by heat pump, or all sorts of chillers. The pipeline loss is accounted using a load following method, which means the loss calculation is based on the thermal energy delivered by the pipeline network. Therefore, the loss will vary in time as the thermal load varies during the year. It is assumed that the heating loss in pipelines is proportional to the heating load distributed through the network.

- Electricity balance:

$$E_{m,d,h}^{ele_{only}} + E_{m,d,h}^{GRID_{SAL}} + (E_{m,d,h}^{ELE_{chill}} + E_{m,d,h}^{HP} + E_{m,d,h}^{ELE_{boil}}) + E_{m,d,h}^{BAT_{sto}} = E_{m,d,h}^{GRID\_PUR} + E_{m,d,h}^{PV} + E_{m,d,h}^{CHP} + E_{m,d,h}^{BAT_{from}}, \forall m,d,h \tag{2}$$

- Heating balance:

$$H_{m,d,h}^{BLDG_{heat}} + H_{m,d,h}^{HST_{STO}} + H_{m,d,h}^{PIPE_{loss}} + H_{m,d,h}^{ABS_{chill}} = H_{m,d,h}^{INDS_{PUR}} + H_{m,d,h}^{HP} + H_{m,d,h}^{ELE_{boil}} + H_{m,d,h}^{NGboil} + H_{m,d,h}^{CHP} + H_{m,d,h}^{NG_{chill}} + H_{m,d,h}^{ST} + H_{m,d,h}^{HST_{from}}, \ \forall m,d,h \tag{3}$$

- Cooling balance:

$$Q_{m,d,h}^{BLDG_{cool}} + Q_{m,d,h}^{PIPE_{loss}} = Q_{m,d,h}^{HP} + Q_{m,d,h}^{ELE_{chill}} + Q_{m,d,h}^{ABSchill} + Q_{m,d,h}^{NG_{chill}}, \ \forall m,d,h \tag{4}$$

2.4. Technology formulation

The technologies are dedicatedly formulated in DEEP model. There are two categories of technology candidates in DEEP. Candidates among the first category are considered as continuous technology, of which capacity is a continuous variable, such as solar PV, electric boiler, etc. Candidates among the other category are considered as either discrete technology (such as CHP) or no capacity limit (such as power grid, heating purchasing from industry waste heat). In the DEEP model, four types of CHP facilities are formulated in order to more accurately reflect the current situation of the real products and facilitate type selection. In this way, we can also distinguish centralized energy plant from decentralized technology by introducing different system COPs considering the district loss and part-load state. At the planning stage, CHP decision variables include the number of installations and their individual capacities.

Besides the planning constraints, CHP facilities also have to follow the operating requirements, such as heat-to-electricity relations, startup and shutdown cost, part-load operating characteristics and Ramp-up/down constraints. The detailed formulations regarding the mathematical model for CHP and other technologies would not be described here due to the length limitation, some information can be found in the literature [1].

3. Case study

To verify DEEP's capabilities and investigate to what degree the influencing factors impact on technology selection, a simulation analysis is conducted on a demonstration project in a building cluster in Shenzhen. We have pre-fixed terminal load data for four types of buildings in three typical cities in different climate zones. These data, including year-round electricity, heating and cooling hourly loads, are obtained through energy consumption simulation software. Although the prediction error of terminal load and meteorological data on optimization have been discussed in the literature [1], concluding there is certain influence on the optimization results, it is considered that the refined boundary conditions are not necessary for energy planning in our study.

The total investment cost of equipment consists of a variable cost proportional to the equipment capacity and a fixed cost. By setting a fixed cost of 5000~15000 yuan, too small installation capacities can be avoided. The maintenance cost of the equipment is set according to the total cost [4] or the system output. The current energy prices in Shenzhen are employed, with the natural gas price of 3.5 yuan/m^3 and the average electricity price of 0.8yuan/kWh. Also, the time-of-use (TOU) electricity tariff was set accordingly.

4. Results and discussion

4.1. Effect of energy price

The influence of price ratio on the optimization is investigated through changing the natural gas prices while keeping the electricity tariff profile unchanged. Since including storage technologies often make the optimization very time consuming and unpredictable, the test is firstly performed without storage technology candidates. In these cases, DEEP does not consider thermal and electric storages as an option. In contrast, if storages are included, DEEP have the option to select them as economics dictate. The results are shown in Fig. 2.

It is observed that a natural gas price around 2~2.5yuan/m^3 become a critical value that determines whether the gas-based energy system or electricity-based energy system prevails in the final solution. As natural gas becomes more costly, DEEP favors more electric chiller and solar thermals against CHP. The transition occurs at about 2 yuan/ m^3, which is also lower than the usual actual market price of 3.5 yuan/ m^3. The options of thermal storages are able to marginally bring down prices, but as natural gas price increases above 2 yuan/m^3, the benefit is diminishing since the optimal technology mix includes less natural gas powered plants and more solar thermals and electric chillers. Electric batteries are never selected due to expensive ownership. As natural gas price increases, the capacity of thermal storage is diminishing while the electric chiller and solar thermal increases in size and the total expenses rise, indicating that the time-of-use power price no longer play the dominated role so that energy storage is not economical. When price is higher than 2 yuan/m^3, CHPs become economically unfavorable.

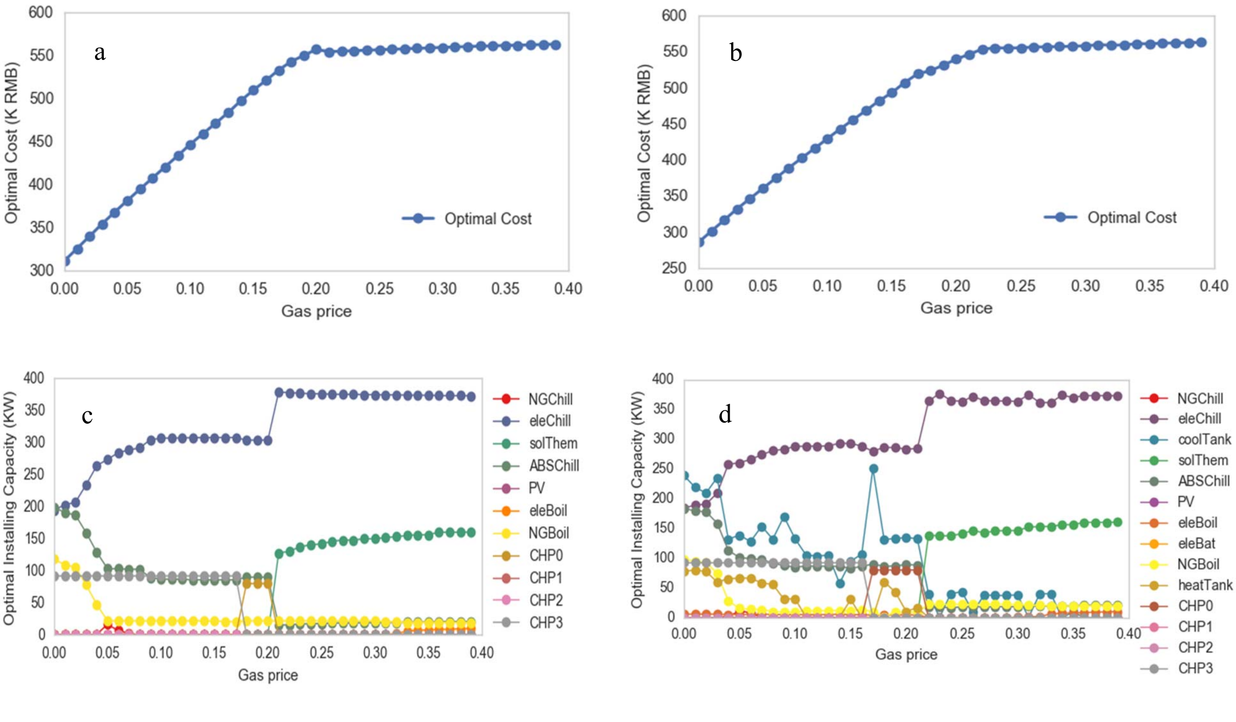

Fig. 2.Influence of energy price on optimal cost and technology selection. (a) Without Storage technologies; (b) With Storage technologies; (c) Without Storage technologies; (d) With Storage technologies

4.2. Effect of equipment price

Novel energy technologies, like CHP and photovoltaic power panel are not economically competitive at the current price level. However, with the progress of science and technology, future costs of these technologies will continually decline. The cost of PV panel, for instance, has been reduced by 50% over the past five years. Meanwhile, the government subsidizes for these technologies to promote clean energy development and carbon emission reduction. This section evaluates the effects of equipment cost on optimization. Four price levels, namely price reduction by 0, 20%, 50% and 80% are tested.

Fig. 3 shows the results of changing the investment cost of CHP facilities. When CHP price is reduced by 20%, the optimized energy portfolio has not changed. When reduced by 50%, the CHP facility becomes competitive. Further reduction of CHP cost does not lead to rise in its capacity, since CHP capacity is defined as a discrete variable and it's not economical to have another CHP. It is interesting to find that even more energy is consumed (electricity equivalent method is utilized for different energy carriers) when CHP facility is employed under the economic goal, but it does save a lot of running cost and results in less carbon emissions.

Fig. 4 is the outcomes for reducing PV and battery costs. Lowering the PV price by at least 50% is able to drive the total expense down and incentivize the installation of PV for electricity generation. Electric battery is propitious when the price is cut to 20% though the marginal benefits of including more storage is not as significant. Utilization of electric battery makes the operating costs of the integrated system decline significantly, yet increases the energy consumption and carbon emissions. Clearly, a multi-objective optimization is necessary when carbon emission is an important concern.

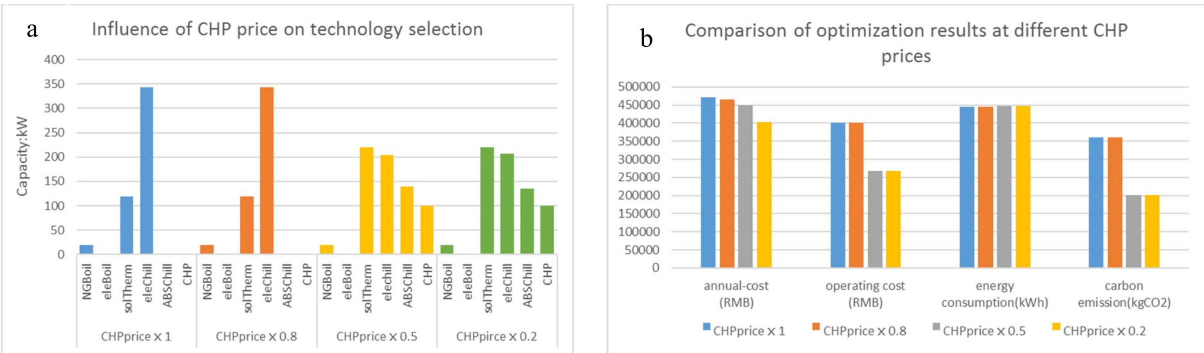

Fig. 3. Influence of CHP price on optimization results. (a) Inluence of CHP price on technology selection; (b) Comparison of optimization results at different CHP prices

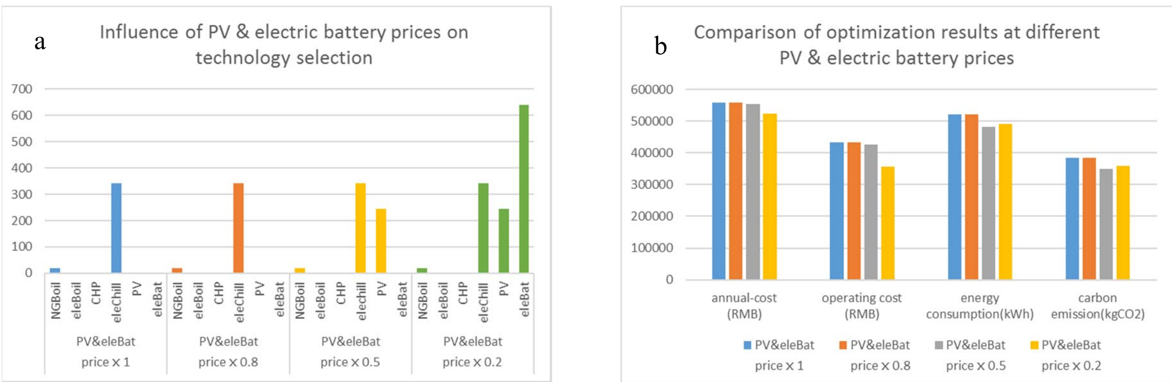

Fig. 4. Influence of PV and electric battery prices on optimization results. (a) Influence of PV and electric battery prices on technology selection;(b) Comparison of optimization results at different PV and electric battery prices

4.3. Operation strategy

As a demonstration project in the U.S.-China center in Shenzhen, a pioneer building with advanced, multi-energy-complementary and future-oriented energy system, is about to be constructed and is now under designing.

We have reduced the investment of novel energy technologies to half of the normal level, aiming at finding the optimized energy technology portfolio and operational strategies in an ideal condition. This led to a composite energy system consisting of gas-fired boiler, electric chiller, absorption chiller, solar thermal, CHP unit and electric battery. Fig. 5 to Fig. 7 represents the energy supply and demand balance state for electricity, heating and cooling load. Data below the horizontal axis denotes the energy demand, both from terminal load and energy conversion equipment, and above the axis is the energy supply from different energy technologies.

Fig. 5 illustrates the balance relationship between electricity demand and supply (data in July is taken as example). The electricity tariff is also included to better understand the system operation strategy. PV, CHP as well as grid and battery (at discharging state) constitute the power supply side, while the terminal power load, electric chiller, battery (at charging state) constitute the power consumption side. Electric battery is charged in the valley and flat periods of power price. It can be observed that, to avoid decay loss the battery is charged slowly before releasing power rather than charged immediately when entering the valley period. Battery discharges in the peak price period gradually, but the stored power cannot support the whole peak period due to limited capacity. CHP is started during the peak and flat periods when exceeding certain load rate, and grid supplement is always needed when local power equipment is insufficient. PV generates power during the daytime, and the output varies as solar irradiation fluctuates. Interestingly, PV does not have to output power when the load rate is relatively low (see the left part in Fig. 5), meaning excess power is produced and it's more economical to use the energy from CHP.

Fig. 6 shows the way in which the heating demand (January) is met. The heating demand is mainly including terminal heating load from customs and heating consumption from absorption chillers. When load rate is low (left part in the figure), solar thermal and natural gas boiler coordinate to meet the hot water demand. As load rate grows to meet the starting-up conditions (right part in the figure), CHP facilities operate and waste heat from CHP is used to produce domestic hot water. Gas boiler is always the complementary heat source when CHP and solar thermal are not economically available. Fig. 7 shows the cooling supply and demand (July) balance diagram. The cooling demand is only from terminal cooling load, and is met through electric and absorption chiller. The absorption chiller is preferred to be employed when there are excess heat resources from solar thermal and CHP unit. For the rest time, electric chiller unit is used as basic and standing by equipment.

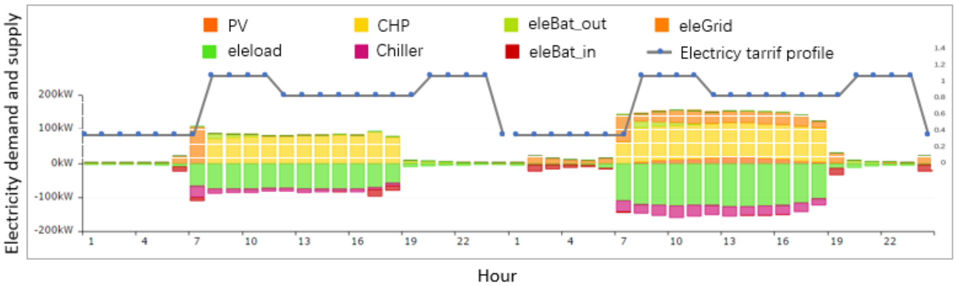

Fig. 5. Balance relationship between electricity demand and supply

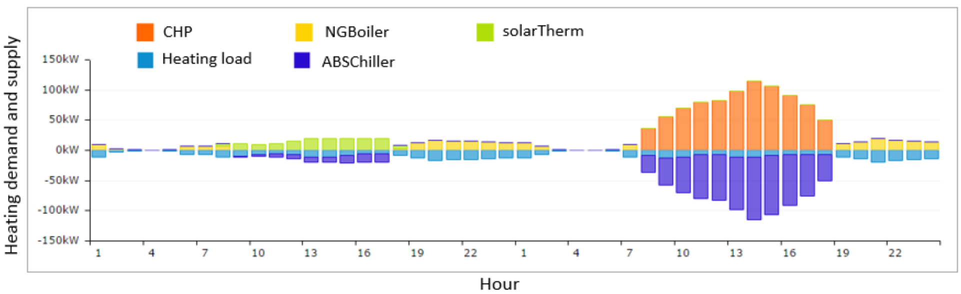

Fig. 6. Balance relationship between heating demand and supply

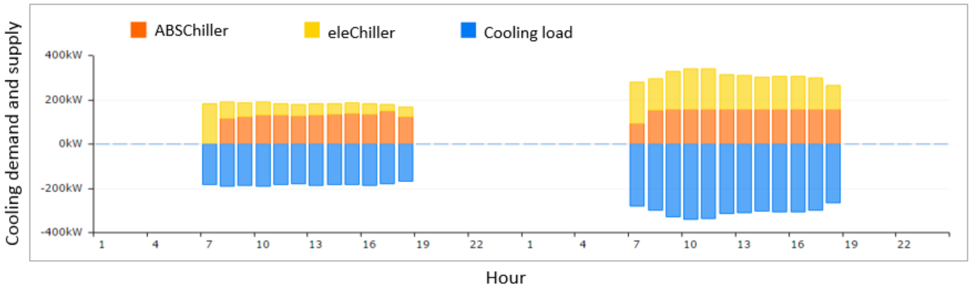

Fig. 7. Balance relationship between electricity demand and supply sides

5. Conclusions

A district energy planning tool DEEP has been developed to deal with community and/or single building energy technology selection and operation strategy problem. Several scenarios analysis are conducted to investigate the influence of energy price and equipment cost on optimization results. Moreover, the operation strategies are discussed by considering a demonstration project with equipment subsidies. The following conclusions can be drawn:

(1) DEEP, as a demand-side energy planning tool, is capable of dealing with depth analysis and comparison for multiple energy technologies in a flexible and efficient way. It pro-vides an energy cascade use and multi-energy complimentary solution to facilitate decision making for technology selection.

(2) DEEP is able to produce justifiable results with correct trends and optimized technology portfolio. Technology selection and capacity are determined by fuel prices and installation costs. The gas-based solutions are economical only when NG price drops below 2yuan/m^3. The technologies are attractive when equipment prices are reduced by 50%, 50%, 80% for CHP facilities, PV and electric battery, respectively.

(3) The operation strategies from DEEP show that, operation cost can be saved through the complementation of multiple technologies and the efficient matching between the energy demand and supply side based on the time distribution of energy prices.

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