Performance of CCHP with ice storage under climate change: a case study in Shenzhen

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Abstract
District energy system (DES) has the advantage of economies of scale and high system efficiency when providing heating and cooling to multiple buildings. However, the impacts of climate change on the district energy systems are rarely evaluated. In this research, district energy system is modeled and analyzed under three climate scenarios and the performance of the combined cooling, heating, and power (CCHP) systems are simulated and compared. Lifetime annualized heating and cooling per area cost (HC) is used to compare the economic performance of the district system. It is found that the annual cooling load in RCP4.5 and RCP8.5 increases by 6% and 9.68%. The HC of the CCHP is from 72.36 Yuan/m² to 95.24 Yuan/m². Compared with the conventional system, the optimal CCHP system charges 32.5% to 41% less on the building end users if the lifetime profit rate is to be maintained between 5% to 20%.

Highlights
- Analytical model for studying the economic performance of district energy systems is developed
- The economic performance of district energy systems is studied and compared under different climate change scenarios
- The size of the ice storage system has a breakpoint where the best economic performance occurs
- Optimal CCHP system charges 32.5% to 41% less on the building end users when the lifetime profit rate is between 5% to 20%.

Introduction
As an important technology to optimize energy configuration, CCHP system can make rational use of limited resources, and reduce the damage to the environment with a good reliability of energy supply. With its advantages of small investment, short response time, low carbon emission, low energy transmission loss and high energy utilization rate up to 80%~90%, CCHP system has become an important branch of distributed energy supply system (Ahlamne and Saari, 2004; d’Accadia et al., 2003). A key factor for the goal of reduce energy consumption and GHG emissions is the correct sizing of the CCHP system. Many researchers have developed programming models for the optimization of system configuration to reach a lowest energy consumption (Bahari et al., 2016; Fragaki, Andersen, and Toke, 2008; Ren, Gao, and Ruan, 2008; Ruan et al., 2016; Sameti and Haghghat, 2019). However, energy demand to determine the size of the system is mainly based on weather data of a typical meteorological year (TMY), which does not take into account the effect of climate change. “Feedback hypothesis” suggests that energy use would contribute climate change and in turn climate change would give a feedback on energy consumption(Akhmat et al., 2014). Climate change has a significant impact on energy consumption, no matter cooling or heating load (Cox et al., 2015; Dirks et al., 2015; Kaufmann et al., 2013; Perez-Andreu et al., 2018; Rosenthal, Gruenspecht, and Moran, 1995; Wang and Chen, 2014). A global warming of 1 °C would reduce projected U.S. energy expenditures in 2010 by $5.5 billion (Rosenthal, Gruenspecht, and Moran, 1995). One reason may be that as climate warms, energy consumed to provide hot water was reduced (Kaufmann et al., 2013). Different global circulation models have been used to analyze heating and cooling load, such as HadCM3, CNRM-CMS and MPI-ESMLR (Perez-Andreu et al., 2018; Wang and Chen, 2014), and also for evaluating climate change impact on various building systems (Shen and Lior, 2016; Wan et al., 2012), onsite renewable energy systems (Abdullah, Agalgaonkar, and Muttaqi, 2014; de Lucena et al., 2009), and building retrofitting (Gaterell and McEvoy, 2005; Shen et al., 2019). However, few studies have been done to investigate the effect of climate change on district energy system, let alone CCHP system. Therefore, this paper presents a method to understand the climate change impacts on district energy system in hourly granularity by integrating dynamic building energy simulation, downscaling morphing method for global climate model (GCM) results, and district energy system modeling.

CCHP System with Ice Storage
A CCHP system is also called a cogeneration system, which is usually made up of the following subsystems: heat engine system (HES), heat recovery system, and adsorption chiller. Moreover, since the CCHP system usually cannot fulfill the full onsite energy demand, to make the system more stable and reliable, traditional subsystems like regular chillers and boilers are also equipped with. In this paper, the CCHP system also consists of two additional energy storage system, namely an ice storage system (ISS), and a battery bank. The battery bank is charged with electricity converted from grid alternating current (AC) to make use of time-of-use (TOU) tariff during the night, and that part of the stored energy demand to determine the size of the system is mainly based on weather data of a typical meteorological year (TMY), which does not take into account the effect of climate change. "Feedback hypothesis" suggests that energy use would contribute climate change and in turn climate change would give a feedback on energy consumption(Akhmat et al., 2014). Climate change has a significant impact on energy consumption, no matter cooling or heating load (Cox et al., 2015; Dirks et al., 2015; Kaufmann et al., 2013; Perez-Andreu et al., 2018; Rosenthal, Gruenspecht, and Moran, 1995; Wang and Chen, 2014). A global warming of 1 °C would reduce projected U.S. energy expenditures in 2010 by $5.5 billion (Rosenthal, Gruenspecht, and Moran, 1995). One reason may be that as climate warms, energy consumed to provide hot water was reduced (Kaufmann et al., 2013). Different global circulation models have been used to analyze heating and cooling load, such as HadCM3, CNRM-CMS and MPI-ESMLR (Perez-Andreu et al., 2018; Wang and Chen, 2014), and also for evaluating climate change impact on various building systems (Shen and Lior, 2016; Wan et al., 2012), onsite renewable energy systems (Abdullah, Agalgaonkar, and Muttaqi, 2014; de Lucena et al., 2009), and building retrofitting (Gaterell and McEvoy, 2005; Shen et al., 2019). However, few studies have been done to investigate the effect of climate change on district energy system, let alone CCHP system. Therefore, this paper presents a method to understand the climate change impacts on district energy system in hourly granularity by integrating dynamic building energy simulation, downscaling morphing method for global climate model (GCM) results, and district energy system modeling.
electricity is mainly for meeting the direct current (DC) demands from electric vehicle, street lighting, and etc.

In this research, the hourly energy production by each subsystem of the CCHP is calculated based on the coupling to the hourly building load in the district. The building load simulation will be further introduced in chapter 3. The calculation of the subsystem energy production is shown in the following equations:

\[ l_{abs,cool} = \min \left( l_{cool} - \frac{1}{\mu_{gen}} l_{plug} - \frac{1}{\mu_{gen}} \mu_{fume} L_{abs,cool} \right) \tag{1} \]

\[ l_{rec,heat} = \min \left( l_{heat} - \frac{1}{\mu_{exch}} \mu_{fume} L_{rec,heat} \right) \tag{2} \]

\[ l_{rec,DHW} = \min \left( l_{DHW} - \frac{1}{\mu_{exch}} \mu_{fume} L_{rec,DHW} \right) \tag{3} \]

where.

\[ \mu_{gen} = \max \left( \frac{1}{l_{plug}} \right) \tag{4} \]

\[ l_{abs,cool}, l_{rec,heat}, l_{rec,DHW} \] is the cooling load met by the absorption chiller, heating load met by the recovered waste heat, and domestic hot water (DHW) heating load met by the recovered waste heat in the building, respectively.

\[ l_{plug}, L_{cool}, L_{heat}, L_{DHW} \] is the actual electricity plug, heating, cooling, and DHW load, in MW, \( \mu_{gen}, \mu_{fume}, \mu_{exch} \) is the efficiency of the generator, waste fume capturing, and plate heat exchanger, respectively. \( CO_{abs} \) is the coefficient of performance of the absorption chiller. \( r_{gen} \) is the peak hourly electricity load. Then, the hourly electricity generation by the motor and the space heating load, \( E_{gen} \), and DHW load met by the auxiliary boiler, \( l_{boiler} \), in MW, can be found by:

\[ E_{gen} = l_{abs,cool} + \frac{l_{rec,heat} + l_{rec,DHW}}{\mu_{exch}} \left( 1 - \frac{1}{\mu_{gen}} \right) \tag{5} \]

\[ l_{boiler} = l_{heat} + l_{DHW} - l_{rec,heat} - l_{rec,DHW} \tag{6} \]

As mentioned above, the ice storage capacity ratio for the IST, \( r_{IST} \), is defined to be the ratio to the daily cooling load on the cooling design day:

\[ r_{IST} = \frac{l_{dd,cool}}{l_{IST}} \tag{7} \]

where, \( l_{dd,cool} \) is the daily cooling load on the cooling design day, in MW, and the \( r_{IST} \) is the IST storage capacity, in MWh. The ice needed to be prepared during the valley price period can be determined by the following equation:

\[ \sum_{i=1}^{24} l_{i,ice,cool} = \sum_{i=1}^{7} l_{i,ice,cool} - \sum_{i=8}^{23} l_{i,ice,cool} \tag{8} \]

where, \( \sum_{i=2}^{23} l_{i,ice,cool} \) is the total amount of ice that needs to be prepared. \( \sum_{i=1}^{7} l_{i,ice,cool} \) is the daily cooling of the off-peak period, in MW. The hourly cooling load met by the dual chiller during the off-peak period, \( l_{ice,cool} \), and the hourly cooling load met by the regualr chiller during the valley period, \( l_{reg,cool} \), can be calculated by:

\[ l_{ice,cool} = l_{cool} - l_{abs,cool} - l_{L_{ice,cool}} \tag{9} \]

\[ l_{reg,cool} = l_{cool} - l_{abs,cool} \tag{10} \]
where, $L_{i,\text{ice,cool}}$ is the cooling load met by melting ice during the peak period, in MW.

Moreover, the electricity storage capacity ratio of the battery bank $r_{\text{batt}}$, is defined to be the ratio to the highest daily electricity load:

$$p_{\text{batt}}^\text{max} = r_{\text{batt}} \cdot \max(\sum_{i=1}^{24} I_{\text{plug},i}^d, \sum_{i=1}^{24} I_{\text{plug},i}^z, \sum_{i=1}^{24} L_{\text{plug},i}^d = 365, i)$$

(11)

where, $p_{\text{batt}}^\text{max}$ is the electricity storage capacity of the battery bank, in MWh. $\sum_{i=1}^{24} L_{\text{plug},i}^d$ is the daily summed electricity plug load on $d$th day, in MWh.

The model parameters including the equipment efficiencies and basic assumptions of the CCHP system are listed in Table 1.

<table>
<thead>
<tr>
<th>Item</th>
<th>Assumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Project Lifetime (years)</td>
<td>15</td>
</tr>
<tr>
<td>Discount Rate (%)</td>
<td>5%</td>
</tr>
<tr>
<td>Gas Generator Efficiency</td>
<td>0.45</td>
</tr>
<tr>
<td>Gas Boiler Efficiency</td>
<td>0.85</td>
</tr>
<tr>
<td>Dual Duty Chiller COP</td>
<td>5</td>
</tr>
<tr>
<td>Regular Chiller COP</td>
<td>5</td>
</tr>
<tr>
<td>Storage Battery Capacity Ratio</td>
<td>0.05</td>
</tr>
<tr>
<td>Absorption Chiller COP</td>
<td>1.2</td>
</tr>
<tr>
<td>Rectifier Efficiency</td>
<td>0.95</td>
</tr>
<tr>
<td>Commercial Charging Pile Number</td>
<td>100</td>
</tr>
<tr>
<td>Natural Gas Caloric Value (MJ/m3)</td>
<td>37.26</td>
</tr>
<tr>
<td>Plate Exchanger Efficiency</td>
<td>0.95</td>
</tr>
<tr>
<td>Fume Capturing Efficiency</td>
<td>0.9</td>
</tr>
<tr>
<td>Maximus Ice Releasing Rate</td>
<td>15%</td>
</tr>
</tbody>
</table>

### Economic model

The calculation of the annualized running cost of each utility from each subsystem is conducted in the following way:

$$C_{\text{gas,total}} = \sum_{i}^{8760}(U_{i,\text{gas,gen}} \cdot P_{\text{gas}} + U_{i,\text{gas,boiler}} \cdot P_{\text{gas}})$$

(12)

$$C_{\text{grid,cool}} = \sum_{i}^{8760}(U_{i,\text{grid,reg}} \cdot P_{\text{grid}} + U_{i,\text{grid,dua1}} \cdot P_{\text{grid}})$$

(13)

$$C_{\text{grid,total}} = \sum_{i}^{8760}(U_{i,\text{grid,plug}} \cdot P_{\text{grid}} + U_{i,\text{grid,charge}} \cdot P_{\text{grid}} - E_{i,\text{gen}} \cdot P_{\text{grid}} - E_{i,\text{batt}} \cdot P_{\text{grid}}) + C_{\text{grid,cool}}$$

(14)

$$C_{\text{hc,purchase}} = C_{\text{gas,total}} + C_{\text{grid,cool}}$$

(15)

where, $C_{\text{gas,total}}$, $C_{\text{grid,total}}$, and $C_{\text{grid,cool}}$ are the annual cost of total gas purchase, total electricity grid purchase, and grid purchase for cooling, in Yuan. $C_{\text{hc,purchase}}$ is the cost of purchased heating and cooling. $U_{i,\text{gas,gen}}$ and $U_{i,\text{gas,boiler}}$ are the gas consumed by the generators and boilers in $i$th hour.

$U_{i,\text{grid,plug}}$, $U_{i,\text{grid,charge}}$, $U_{i,\text{grid,reg}}$, $U_{i,\text{grid,dua1}}$ are the hourly grid purchase for plug load, battery charging, regular chiller, dual duty chiller, in MWh, respectively.

$E_{i,\text{gen}}$, $E_{i,\text{batt}}$ are the hourly electricity production from the generator and the amount of electricity released from the battery bank, in MWh. $P_{\text{gas}}$ is the gas price, which is constant throughout the year, at 2.5 Yuan/m3. $P_{\text{grid}}$ is the TOU electricity purchase price in hour $i$.

The revenue of the electricity sold to the onsite commercial end users can be calculated by:

$$R_{\text{elec}} = \sum_{i}^{8760}(U_{i,\text{grid,plug}} \cdot P_{\text{grid,plug}} + U_{i,\text{elec}} \cdot P_{\text{elec}})$$

(16)

where, $S_{i,\text{elec}}$ is the TOU electricity selling price in hour $i$.

The annualized initial cost for each subsystem can be calculated in the following way:

$$IC_{\text{boiler}} = 2 \cdot p_{\text{boiler}}^\text{max} \cdot C_{\text{boiler}}$$

(17)

where, $IC_{\text{boiler}}$ is the annualized costs of boiler in Yuan, which has been averaged throughout the life period using a constant discount rate. $l$ and $r$ are the life time of the CCHP system and discount rate, respectively. $p_{\text{boiler}}^\text{max}$ denotes the capacity of boiler. $c_{\text{boiler}}$ indicates the capital cost per capacity of each subsystem. The annualized initial cost of IST, dual duty chillers, regular chillers, generators, and absorption chillers can be figured out with a similar formular with boiler. The annualized initial cost of boilers and chillers are doubled to take into account backup units for them. Moreover, a facility cost for the HVAC system and end user distribution equipment including pumps and ducts is also considered and is estimated by tripling the equipment cost of boilers, IST, dual duty chillers, regular chillers, generators, and absorption chillers:

$$IC_{\text{facility}} = 3 \cdot (IC_{\text{boiler}} + IC_{\text{IST}} + IC_{\text{dua1}} + IC_{\text{reg}} + 0.5 IC_{\text{gen}} + 0.5 IC_{\text{abs}})$$

(18)

In addition, the annualized cost of grid distribution $IC_{\text{dist}}$, can be obtained based on:

$$IC_{\text{dist}} = C_{\text{dist}} \cdot \max(U_{i,\text{grid,total}} \cdot P_{\text{grid}} + U_{i,\text{grid,total}} \cdot P_{\text{grid}}) / 0.85$$

(19)

where, $C_{\text{dist}}$ is the unit cost of grid distribution in Yuan/kVA.

Hence, the annualized total cost of the equipment can be obtained:

$$IC_{\text{total}} = IC_{\text{boiler}} + IC_{\text{IST}} + IC_{\text{dua1}} + IC_{\text{reg}} + IC_{\text{gen}} + IC_{\text{abs}} + IC_{\text{batt}} + IC_{\text{dist}} + IC_{\text{facility}}$$

(20)

To reflect the economic performance of the CDES and CCHP, an annual heating and cooling cost per square meter, $HC$, in Yuan/m2, is chosen to show the lifetime overall economic performance of the district energy system. $HC$ indicates the lifecycle fee that the clients in the commercial buildings have to pay for their heating and cooling under certain lifecycle profit rate $y$, which can be calculated as:

$$HC = IC_{\text{total}} / (1+y) + C_{\text{grid,cool}} \cdot \sum_{i}^{8760}(U_{i,\text{grid,plug}} \cdot P_{\text{grid,plug}} + U_{i,\text{elec}} \cdot P_{\text{elec}}) + C_{\text{hc,purchase}}$$

(21)
where, \( A \) is the total building floor area of the project, in m2. What equation 27 calculates is how much heating and cooling fee the end users of the buildings have to pay for per floor area to make the project profitable (with a rate of \( y \)) in the lifetime of \( l \). In this research, the lifetime of the project is assumed to be 15 years.

**Case Study**

**District of interest**

The case study in this research is going to be one of the most influential and large-scale urban renewal projects in the near future in Shenzhen. To make the whole urban renewal project closer to the frontier of district energy system, technology and management, the property developer attempts to integrate CCHP system to the district to make it one of the role models in the city on distributed district energy system. There are mainly four building types to be planned and constructed in the urban renewal area of the project – residential, office, mall, and hotel. The distributed district energy system in this case study will supply energy to the office, mall, and hotel. For the residential buildings, the residents will purchase directly from the grid. The floor areas of each type are listed in Table 2.

**Table 2 Floor area of each building type**

<table>
<thead>
<tr>
<th>Subtype</th>
<th>Floor area</th>
<th>Major type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Research and Development</td>
<td>4.60</td>
<td>Office</td>
</tr>
<tr>
<td>Office</td>
<td>71.14</td>
<td>Office</td>
</tr>
<tr>
<td>Hotel</td>
<td>20.56</td>
<td>Hotel</td>
</tr>
<tr>
<td>Mall</td>
<td>31.06</td>
<td>Mall</td>
</tr>
<tr>
<td>Underground commercial</td>
<td>16.00</td>
<td>Mall</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>144.46</strong></td>
<td></td>
</tr>
</tbody>
</table>

**Building simulation**

Since the urban renewal project is going to take place in the near future, there is no on hand metered historical building energy use data. The reference building models of the latest International Energy Conservation Code (IECC) 2015 is used for the building energy simulation in this case study (IECC, 2012). EnergyPlus is used for detailed building energy simulation in this research to provide energy demand profiles for the district energy system. EnergyPlus is a “whitebox” building performance simulation tool. It is a console-based program, developed and managed by DOE and the National Renewable Energy Laboratory, designed to create models of energy use in buildings (Crawley et al., 2001). The model specifics on thermophysical properties of the three major building types in this case study that are crucial inputs to EnergyPlus modeling are shown in Table 3.

**Table 3 Thermophysical properties of the modeled prototypical buildings of different building types**

<table>
<thead>
<tr>
<th>Type</th>
<th>Office</th>
<th>Hotel</th>
<th>Mall</th>
</tr>
</thead>
<tbody>
<tr>
<td>Infiltration (ACH)</td>
<td>0.10</td>
<td>0.2</td>
<td>0.33</td>
</tr>
<tr>
<td>Ventilation (L/s/m2)</td>
<td>0.52</td>
<td>0.5</td>
<td>1.50</td>
</tr>
</tbody>
</table>

**Assessment of Climate Change Impact**

Due to restricted computational cost, the results of the GCM need to be downscaled from its course grid to more local application. Moreover, most of the downloadable online resources of GCM outputs only contain monthly mean results extracted from the actual model results, while precision in predicting climate change impacts on building energy systems including peak load shifts and changes are necessitated by applying hourly resolution weather data. Users not only needs to downscale the outputs spatially, but also temporally. Belcher et al. put forward a morphing method (Belcher, Hacker, and Powell, 2005), which applied time series method to transform the monthly outputs from GCM together with a “baseline” hourly weather data – usually typical meteorological year (TMY), to a new set of hourly weather data that reflects both monthly change of the GCM and at the mean times retains the statistical characteristics of the local climate. The method is quick and easy to apply, and effective in integrating predictions from GCM under different future emission scenarios. The detailed processing of morphing method in transforming the TMY weather data will be not expatiated in this paper. It can be found in (Shen, 2017).

We used morphing method to transform the TMY weather data to the that in period of year 2050-2060 as predicted by the IPSL GCM under the two climate change scenario RCP4.5 and RCP8.5, and attempted to find out how climate change is going to influence the building loads and then to the optimal sizing of the CCHP system as well as its economic performance.

**Results and Discussion**

**Building simulation**

*Heating and cooling load under TMY scenario*

As different building shares different thermal properties, occupant and equipment schedule, equipment intensity, etc., the hourly heating, cooling, electricity load for each building are different, leading to disparate energy use profile. There are eight buildings in total being simulated by EnergyPlus, categorized into three major building types. We conglomered the simulation results for buildings of same type and analyzed the load and energy use characters for each building type under TMY scenario.
Heating and cooling load under future climate scenarios

The building simulation is also conducted using the downscaled hourly weather data from IPSL GCM under RCP4.5 and RCP8.5. The climate change does not affect DHW heating load as DHW heating is more independent from the outdoor air temperature compared with other three load types. For cooling load, all three building types have increased cooling load during winter and swing season. The annual district cooling load under two future climate scenarios have increased compared with TMY scenario. Though heating load has more irregular trend, the annual heating load in future climate also rises. It is also interesting to find that the future electricity use has a clear increasing trend compared with TMY scenario for all three building types. Since the plug load in the building does not change however the outdoor environment is, the growth in electricity use can be imputed to the increased HVAC related energy use, for example, pump and fan energy use due to the increment in future heating and cooling load.

Performance of the CCHP system

Operation of the optimized CCHP system under TMY

For TMY scenario, the optimal system sizing in the current climate condition is reached when the gas power ratio $r_{gen}$ is 0.37 and the ice storage ratio $r_{IST}$ is 0.23, which means the capacities of gas generators and ice storage tank equal 28.12 MW and 380 MWh. The optimal annualized heating and cooling charge of the CCHP system – HC, is 81.63 Yuan/m$^2$. Under this system sizing, the capacities for the grid distributions system, absorption chillers, boilers, dual duty chiller, battery storage, and regular chillers are 67.82 MW, 37.11 MW, 21.39 MW, 67.89 MW, 47.43 MW, 43.95MW, respectively. Compared with the conventional system, the capacities of the grid distribution, boilers, and regular chillers have been reduced by 44.5%, 28.2%, and 68.4%.

To show how each system is responsible for the annual total cooling, heating, and electricity load, the monthly energy supply of cooling, heating, and the electricity in the district is plotted in Fig. 2, Fig. 3, and Fig. 4.

![Fig. 2 Monthly cooling load met by the CCHP system under TMY](image)

Fig. 2 shows that during most time of the year, the absorption chiller is capable of providing the most cooling load among all the subsystems, and the cooling released from the IST follows. During winter and transition seasons in Shenzhen, the dual chillers are hardly turned on. Most of the cooling during that period of time comes from the absorption chillers and ice, and the regular chillers work at partial load to back up the cooling demand. In summertime, the regular chillers start providing more cooling, and the dual duty chillers work at their full capacity. On an annual basis, the total cooling load supplied by the absorption chillers, IST, dual duty chillers, and regular chillers are 47.7%, 34.6%, 9.2%, and 8.5%.

![Fig. 3 Monthly heating load met by the CCHP under TMY](image)

Fig. 3 shows that on an annual basis, most of the space heating and DHW heating come from the boilers and the boilers are still the main source of heating, though CCHP reduces its sizing by about 28.2% when compared with boiler sizing under TMY scenario. In winter, more heating energy can be allocated form the CCHP as the cooling load demand is low in winter. In summer, the waste heat hardly goes to the heating of the space and DHW due to the high cooling load. The total heating load met by the subsystems of the CCHP is: 3.8% of space heating and 19.4% of DHW heating come from CCHP waste heat, and the other 76.8% is provided by the boilers.

![Fig. 4 Monthly electricity provision contributed by the CCHP under TMY](image)

The monthly electricity provision of the CCHP in the district shown in Fig. 4 demonstrates how each electricity supply system is contributing to the electricity load. It is clear to see that still, most of the electricity is purchased from the grid, and about 42.24% of the total electricity is generated onsite by the gas motors annually, while the other 35.8% and 4% come from the grid purchase and battery bank, respectively. Because of the CCHP system, the grid distribution capacity and cost of the project can be reduced by 44.5% compared with the conventional district energy system.

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Climate change impacts on optimal sizing of the CCHP performance

The simulation results in Table 4 shows that the best ice storage ratio for the CCHP system of the district is going to stay the same, while the optimal gas power ratio is going to change depending on the future scenario. For example, in RCP8.5 – the high emission scenario, the system sizing will be the same as the TMY scenario, but in RCP4.5, the gas power ratio will be raised to 0.39 to achieve the best economic performance. The annualized heating and cooling charge HC rise as the radiative force increases by 2100. Under RCP4.5 and RCP8.5, the HC is increased by 6.9% and 10.56%. The change in the HC reflects that in the future climate, even with the optimal system sizing, there will be less economic return during the operation of the district energy system. This trend cannot be altered no matter a conventional system or a CCHP system is used. It can be mainly attributed to a higher frequency of extreme weather condition occurrence in the future climate condition, which leads to more opportunities for the occurrence of peak load. Though the change rate of the HC value in the future for conventional system is lower than CCHP, the economic performance of CCHP is still more superior than the conventional system because a CCHP system is more handy in coping with more extreme weather condition and a more unpredictable climate.

Table 4 The optimal system sizing under climate change scenarios

<table>
<thead>
<tr>
<th></th>
<th>TMY</th>
<th>RCP4.5</th>
<th>RCP8.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas power ratio</td>
<td>0.37</td>
<td>0.39</td>
<td>0.37</td>
</tr>
<tr>
<td>Ice storage ratio</td>
<td>0.23</td>
<td>0.23</td>
<td>0.23</td>
</tr>
<tr>
<td>HC (Yuan/m²)</td>
<td>81.63</td>
<td>87.26</td>
<td>90.25</td>
</tr>
</tbody>
</table>

The next question is: if the CCHP system adopts the optimal system sizing found under the TMY scenario, how the climate change is going to change the HC charge of that system in the future? Table 5 shows the analysis of the HC charge change in various combinations of profit rate and climate scenarios. The results indicate that the HC should also be raised to meet the lifetime profit rate goal in future climate scenarios like conventional system and the increase rate is higher than conventional system. However, it does not mean that the CCHP is less robust in confronting the climate change impact on economic performance, but more of a result of its low baseline HC charge under TMY scenario. The highest HC charge of the CCHP system (RCP8.5) in maintaining a lifetime profit rate of 20% is only around 95 Yuan/m², which is 32.7% lower than that of the conventional system. That percentage value for the profit rate of 5% is -39.5%, showing the great advantage of the CCHP system over the conventional one.

Table 5 The heating and cooling charging per square meter of the CCHP under different climate scenarios and profit rate

<table>
<thead>
<tr>
<th>Profit Rate</th>
<th>TMY (Yuan/m²)</th>
<th>RCP4.5 (Yuan/m²)</th>
<th>RCP4.5 (%)</th>
<th>RCP8.5 (Yuan/m²)</th>
<th>RCP8.5 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5%</td>
<td>72.36</td>
<td>77.52</td>
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<td>80.27</td>
<td>10.93</td>
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<tr>
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<td>77</td>
<td>82.39</td>
<td>7.00</td>
<td>85.26</td>
<td>10.73</td>
</tr>
<tr>
<td>15%</td>
<td>81.63</td>
<td>87.26</td>
<td>6.90</td>
<td>90.25</td>
<td>10.56</td>
</tr>
<tr>
<td>20%</td>
<td>86.27</td>
<td>92.14</td>
<td>6.80</td>
<td>95.24</td>
<td>10.40</td>
</tr>
</tbody>
</table>

Note: The percentage change following RCP45 and RCP85 shows the comparative change of HC values under the future climate scenario to the TMY scenario (adopting the optimal system sizing in TMY)

Conclusion

In this research, a conventional district energy supply system (CDES) and a combined cooling, heating, and power (CCHP) system are modeled and compared under three climate scenarios in Shenzhen, China – typical meteorological year (TMY), RCP4.5, and RCP8.5 scenario. Using the predicted future district energy demand profile, the simulation and optimization process is carried under the two climate change scenarios to further evaluate the system economic performance of both systems in a changing climate.

The building simulation results indicate that the peak heating load in RCP4.5 and RCP8.5 increases by 97.91% and 105.98% respectively in the period of 2050-2060 compared with TMY scenario. Meanwhile, the annual heating load in RCP4.5 and RCP8.5 also increases by 124.07% and 78.85%, and the annual cooling load in RCP4.5 and RCP8.5 has a growth rate of 6% and 9.68%. The peak electricity load in RCP8.5 scenario has a growth rate of 8%, but the increase in annual electricity load in the future is limited.

In this research, the criterion used to evaluate the economic performance of the district energy system is the annualized heating and cooling charge for building end users (HC) under certain lifetime and profit rate. The HC charge of the CCHP system is from 72.36 Yuan/m² to 95.24 Yuan/m². Compared with the conventional system, the optimal CCHP system charges 32.5% to 41% less on the building end users if the lifetime profit rate is to be maintained between 5% to 20%. The ice storage ratio is found to have a break point where the best economic performance occurs, while for gas generators, that break point for the optimal power capacity is rather hard to determine and depends on specific climate condition and economic return.

References


