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Modelica-based simulations of decentralised substations to support decarbonisation of district heating and cooling

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Abstract

District heating and cooling are considered effective solutions to decarbonise the energy use in the building sector. The latest generation of district heating and cooling also increases the potential of integrating heat pumps and chillers in each building substation. The benefits of such integration are the reduction of network temperature and distribution losses; the recovery of waste heat through a bidirectional network; and the decentralised production of heating and cooling. Sizing the network depends mainly on the heat flows between connected buildings. The substation performance and technical installations determine these heat flows. We present in this paper Modelica-based simulations of two design cases for substations. The first design case involves installed heat pump, chiller, and circulation pumps. Alternatively, the second design enables the heat pump to provide direct cooling through a heat exchanger. The models for these installations were developed using the Modelica language to perform continuous-time simulations. The performance in each design case was evaluated in terms of seasonal coefficient of performance and total electric energy use. An analysis on a cluster of 11 buildings suggests that the addition of the direct cooling heat exchanger can save up to 10% of the total annual electric energy use. Additional savings can be achieved by optimising the building supply temperatures and the district network temperature.

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Keywords: Heat pumps; Waste heat recovery; 5GDHC; Modelica

1. Introduction

The new goals in the Swedish Climate Policy Framework adopted in 2017 aim at reaching zero net emissions of greenhouse gases by 2045 [1]. The country has also a promising target to achieve 100% renewable electricity production by 2040 [2]. To attain these goals, innovative solutions in different sectors are necessary. Heating and cooling of residential and commercial buildings account for almost 40% of the total final energy use in Europe and in Sweden [3]. This figure shows that there is a possibility to improve the energy-efficiency within the building

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sector. Waste heat recovery, security of supply, efficient heat distribution, and competitive price strategies are some of the current questions researchers attempt to address to improve energy-efficiency.

District heating and cooling (DHC) are considered effective solutions to decarbonise the building sector and can help reaching national and international energy-efficiency targets [4]. The systems are a common way for heating and cooling buildings in urban areas with an implementation rate exceeding 50% in Sweden, Denmark, Finland, Russia, and northern China [5]. Regardless of their popularity, conventional DHC systems have two main drawbacks. First, the centralised heat production results in higher distribution losses through the pipe network. Second, separate pipes are required for the supply of simultaneous heating and cooling. A possible solution to these problems is the integration of heat pumps and chillers in each building substation. The term *substation* refers to the link between the building side and the district network. A typical substation in a fifth-generation district heating and cooling (5GDHC) system mainly consists of a heat pump, chiller, circulation pumps, and heat exchanger for direct cooling. The outcomes of decentralised substations are the significant reduction in network temperature, and the simultaneous supply of heating and cooling through the same pipes.

1.1. Design and modelling of 5GDHC systems

A typical 5GDHC system leverages the synergies between connected buildings with different thermal demands. Hence, the heat carrier in the pipe can flow in either direction depending on the type of thermal demand at a given point in time. The system mainly comprises of the following three subsystems: (1) substations with installed heat pumps and chillers to modulate the temperature to the building desired supply levels, (2) low temperature bidirectional network with uninsulated pipes, and (3) balancing unit for energy storage and heat production. Previous work that investigated this generation can be seen in the comprehensive review by Buffa et al. [6]. For system design, Wirtz et al. [7] presented a mathematical model based on linear programming for the design of bidirectional networks. Another study by Abugabbara and Lindhe [8] demonstrated an analytical solution to balance energy flows between connected buildings and to size 5GDHC networks. An important aspect that is lacking in these studies is the ability to evaluate the system performance dynamically and for different design cases. In equation-based object-oriented modelling, large complex systems are composed by assembling smaller stand-alone subsystem models. These subsystem models can be easily reconfigured to simulate the system under different design cases.

The Modelica language offers high flexibility and reusability of component models across several domains. District heating and cooling systems involve components from thermo-fluid and control domains. A recent review by Abugabbara et al. [9] motivated the choice of Modelica for modelling and simulation of complex physical systems such as the 5GDHC systems. The free open-source Modelica *Buildings* Library [10] contains validated models for building and community energy systems. We use these models to construct larger models for decentralised substations. An investigation of different design cases and their impact on the system performance was carried out and the main findings are presented in this paper.

1.2. Paper objective

The objective of the paper is to evaluate the performance of substation installations in different design cases. The paper attempts to study the performance of two substations with different design cases. Fig. 1 presents the schematic diagram of the two considered substations. In substation A, the heat pump evaporator inlet is connected to the chiller condenser outlet to recover waste heat. Similarly, the heat pump evaporator outlet serves as a cold source to the chiller condenser inlet. Depending on the proportion between heating and cooling demands, heat is either extracted or injected from/to the bidirectional network. Substation B includes all previous installations in addition to a heat exchanger used for direct cooling. The heat exchanger reduces the electric power in the chiller's compressor. However, it decreases the potential to recover waste heat by the heat pump.

Heat pumps transfer thermal energy from a low temperature source to a higher temperature sink. The heat pump Coefficient of Performance (COP) increases to infinity when the temperature difference between sink and source approaches zero. Waste heat from the chiller raise the temperature at the heat pump source, hence, increasing the heat pump COP. Conversely, the direct cooling heat exchanger reduces the electric energy use for space cooling while also reducing the amount of recovered waste heat. We present in this paper the interactions between heat pumps, chillers, and the direct cooling heat exchanger on a cluster of 11 buildings in Lund, Sweden. The analysis was performed using Modelica continuous-time simulations where temperatures at each simulation time point were computed.

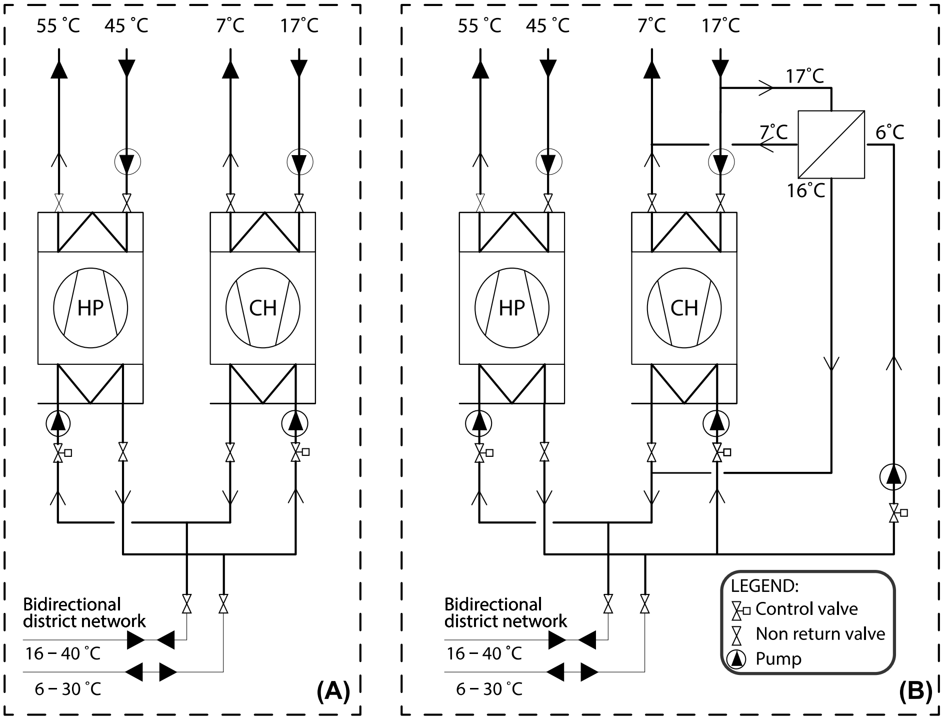

Fig. 1. Schematic diagram of a substation model with installed heat pump and chiller (A) and a substation with additional heat exchanger for direct cooling (B). Design value are presented according to the case study input parameters shown in Table 1.

2. Method

This section presents the approach for modelling the substations including heat pumps, chillers, circulation pumps, and direct cooling heat exchanger. The demand profiles in the case study together with the set of used input parameters are then presented. The performance indicators used for evaluating the substation performance are then described. The section ends with a description of the study assumptions and limitations.

2.1. Models for substations

Heat pumps and chillers were modelled as a Carnot refrigerant cycle. Adjusting the COP based on the Carnot efficiency avoids favouring any particular product [11]. The COP for a heat pump and a chiller is defined as

$$COP_{HP} = \eta_{Carnot} \frac{T_{condenser}}{T_{condenser} - T_{evaporator}} \qquad COP_{CH} = \eta_{Carnot} \frac{T_{evaporator}}{T_{condenser} - T_{evaporator}} \tag{1}$$

Since the physical behaviour of chillers is almost identical to heat pumps, we will only present models for heat pumps. At each simulation time point, mass flow rates at the condenser and evaporator are computed as

$$\dot{m}_{condenser} = \frac{\dot{Q}_h}{c_p \Delta T_{condenser}} \qquad \dot{m}_{evaporator} = \frac{\dot{Q}_h - W_{compressor}}{c_p \Delta T_{evaporator}} \tag{2}$$

where $\dot{Q}_h$ is the building heat demand in Watts, c_p is the water specific heat capacity in J/kg·K, $\Delta T_{condenser}$ and $\Delta T_{evaporator}$ are the temperature difference between condenser and evaporator inlet and outlet, and $W_{compressor}$ is the heat pump electric power which is equivalent to

$$W_{compressor} = \frac{\dot{Q}_h}{COP_{HP}} \tag{3}$$

On the heat pump evaporator side, the circulation pump extracts water in the amount of $\dot{m}_{evaporator}$. The circulation pump electric power is derived as

$$W_{cirPump} = \frac{\dot{V}_{evaporator}\Delta p}{\eta_h \eta_m} \tag{4}$$

where $\dot{V}_{evaporator}$ is the volume flow rate in m^3/s, Δp is the pump pressure rise in Pa, η_h and η_m are the hydraulic and motor efficiencies of the circulation pump.

Lastly, the Carnot cycle models for heat pumps and chillers were used to construct models for substations. Fig. 2 depicts the case of a substation with only heat demands and installed heat pump. Modelling systems in Modelica is realised by instantiating components and connecting them visually in a Lego-like approach. Connector lines interface component variables inside the model when seen from within, and from the outside when the component is externally connected. The right box in Fig. 2 provides a description of the components in substation model with only heating demand. Fluid ports 17 and 19 represent the connection to the respective district warm and cold pipes when the model is connected from the outside. The fluid transport delay in the substation is taken into account as shown in components 16 and 18. On the heat pump evaporator cold side, the circulation pump extracts water from the warm district pipe to the evaporator inlet. The cold water at the evaporator outlet then flows to the district cold pipe. On the heat pump warm side, mass flow rates at the condenser inlet are computed in components 01 to 06 based on the building demand. The condenser outlet is connected to the building sink shown in component 08. Finally, the substation total electric power and heating demand are interfaced externally through components 14 and 15 for processing results.

2.2. Case study

We analysed a cluster of 11 buildings to evaluate the substation performance in both design cases. The buildings are located in Lund, Sweden and have a total heated floor area of about 110,000 m^2. Most of the floor area is used for offices, conference rooms, and labs. Other space usage includes restaurants and a sport centre. To understand the demand requirements in the cluster, Fig. 3 shows the yearly heating and cooling demand profiles. As clearly noticed, the cluster has simultaneous demands for heating and cooling throughout the year. The simultaneous demands increase the potential to exchange energy between connected buildings. However, the actual amount of exchanged energy depends on the COP of heat pumps and chillers. The substation and network design temperatures play an important role in determining the amount of exchanged energy within the cluster.

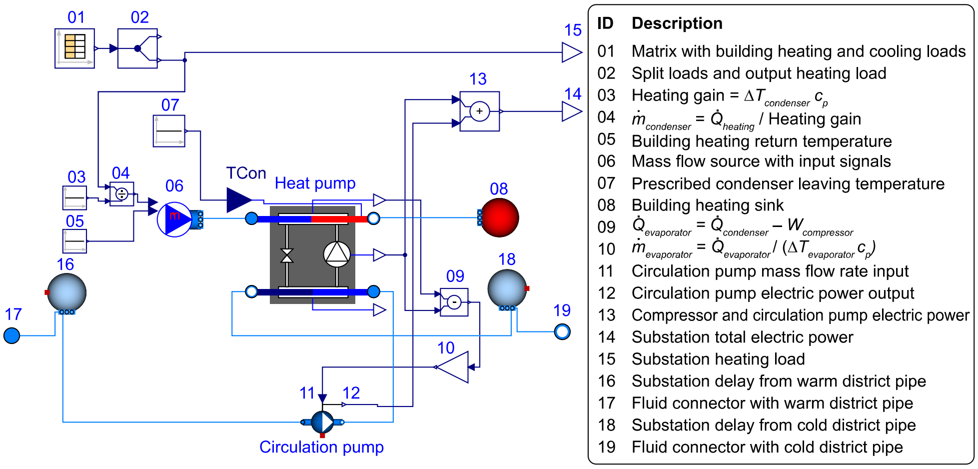

Fig. 2. Diagram view of a substation model with only heating demand. The right box describes the different components included in the model.

Table 1 provides an overview of the design parameters used in the simulations. On the district side, heating is injected to the network by the balancing unit when the warm pipe temperature drops below 16 °C. On the other hand, when the cold pipe temperature rises above 30 °C, the balancing unit supplies cooling to the network. The value of the parameter regarding water pressure drops over condenser and evaporator was chosen based on the

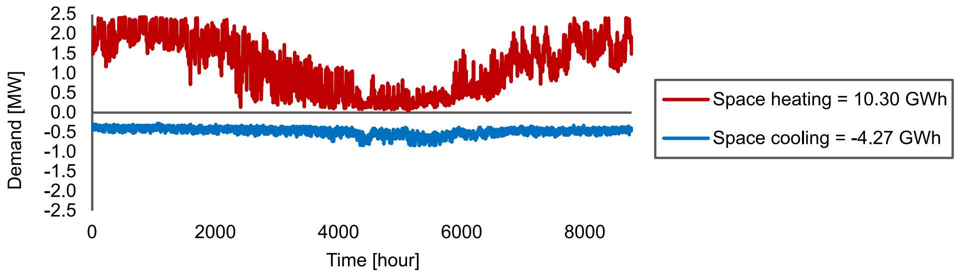

Fig. 3. Yearly heating and cooling demand profiles in the building cluster.

Table 1. Case study design input parameters.

Parameter	Value	Unit
Temperature range in warm district pipe[a]	16–40	°C
Temperature range in cold district pipe[a]	6–30	°C
Design supply temperature for space heating[a]	55	°C
Design supply temperature for space cooling[a]	7	°C
Evaporator temperature difference of the heat pump (outlet – inlet)[a]	−10	K
Condenser temperature difference of the chiller (outlet – inlet)[a]	10	K
Temperature difference between refrigerant and water outlet in condenser and evaporator	2	K
Water pressure drops over condenser and evaporator	30 000	Pa
Carnot efficiency	50	%
Pump hydraulic and motor efficiencies	70	%

[a]The reader is advised to refer to Fig. 1 to point the design values on the schematic diagram.

measurements reported in [12]. The global circulation pump efficiency was set to 0.49 for the assumed efficiencies shown in the table. Both design cases were simulated using with the same design input parameters.

2.3. Performance indicator

The case study was simulated for each of the two design cases presented in Fig. 1. For each simulation, the system performance was assessed based on the Seasonal Coefficient of Performance (SCOP). The SCOP for heating and cooling is defined as

$$SCOP_h = \frac{\sum_i \dot{Q}_{h,i}}{\sum_i W_{compressorHP,i} + W_{hCirPump,i}} \qquad SCOP_c = \frac{\sum_i \dot{Q}_{c,i}}{\sum_i W_{compressorCH,i} + W_{cCirPump,i}} \tag{5}$$

For $SCOP_h$ in Eq. (5) the $\dot{Q}_h$ denotes the total annual delivered heating energy by heat pumps, $W_{compressorHP}$ is the compressors total annual electric energy use in heat pumps, and $W_{hCirPump}$ is the total annual electric energy use in circulation pumps used for heating. The compressor electric power in heat pumps and chillers is derived from Eq. (3), whereas the electric power in circulation pumps is determined as shown in Eq. (4). It is worth noting that in a system with direct cooling, the chiller delivers thermal energy that corresponds to the difference between the cooling demand and the transferred heat in the heat exchanger.

2.4. Assumptions and limitations

When modelling the direct cooling heat exchanger, our primary interest was to utilise the available energy in the heat pump evaporator. In practice, the heat exchanger can also draw water from the district side depending on the temperature levels in the building return and the district pipes. The study did not include the temperature control between the heat exchanger and the district pipes. Therefore, direct cooling was realised when the heat pump is in operation and by assuming that the evaporator temperature satisfies the building cooling demand. Moreover, we did not model the building side of the heat exchanger. Instead, the heat transfer rate in the heat exchanger was set to be equivalent to the heat flow in the heat pump evaporator. This approach was sufficient to model the heat exchanger and was also followed by Sommer et al. when they only modelled the district side of the heat exchanger [13].

Another assumption involved the connection points shown in Fig. 1. These points indicate fluid mixing and were modelled as mixing volumes that include the substation delay. The delay refers to the time it takes for the change in temperatures to be absorbed by the system. A time constant is used to describe this first-order lag and is defined based on engineering experience. We defined a time constant of 600 s similar to the district examples presented in the Modelica *Buildings* Library.

3. Results and discussion

This section presents the substation SCOP and electric energy use in the two design cases.

3.1. Substation SCOP

The variations in the cooling and heating SCOP throughout the year are shown Fig. 4. The left chart presents the performance for the design case without direct cooling, whereas the right chart shows the system performance when direct cooling is realised. At first glance, it can be noticed that both systems have somewhat a low heating SCOP. We have considered that heat pumps supply a constant temperature of 55 °C throughout the year. As a matter of fact, each heat pump adjusts the heating supply temperature based on the outdoor temperature and a control curve. The control curve varies from building to building and can be implemented into the model when provided. Including these curves mean that heat pumps would need to operate for lower temperature lifts compared to a constant supply temperature operation. This would result in an improved heat pump performance.

A discernible distinction between the two design cases is seen in the cooling SCOP. The addition of the direct cooling heat exchanger increased the annual cooling performance by about two and a half fold. Since heat pumps in this system were also utilised to provide cooling, chillers were running with much lower powers. In winter months where heat pumps covered most of the cooling demand, the compressor load in chillers was reduced. This can be seen by contrasting the cooling SCOP in both charts in Fig. 4. In summer months where heat pumps operate at much lower load ratios, chillers start to run to provide the required cooling. This resulted in a rapid decrease in the cooling SCOP in the system with direct cooling. In view of the fact that the building cluster has dominant heating demand throughout the year, employing direct cooling from heat pumps is regarded more favourable.

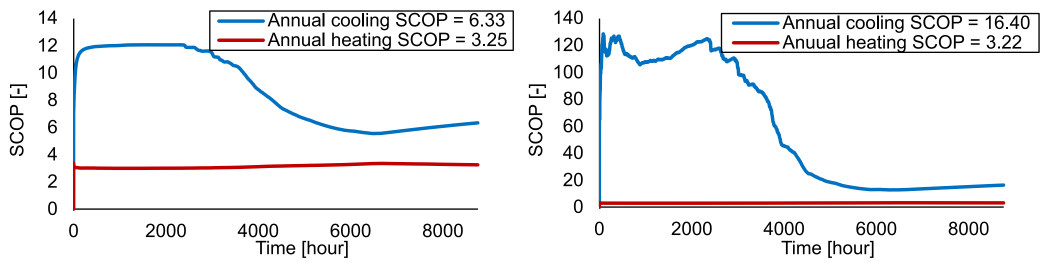

Fig. 4. Variation of heating and cooling seasonal coefficient of performance for a system with no direct cooling (left) and for a system with direct cooling (right). Note that the two charts do not have a uniform scale.

3.2. Substation electric energy use

Fig. 5 provides a better understanding of how each design case impacted the substation annual electric energy use. The top two figures A and B compare the compressor cumulative electric energy use. For heat pumps in the two design cases, the compressor electric energy use is almost identical. This accords with the presented heating SCOP in Fig. 4 since the seasonal performance was similar in the two designs. A notable difference between the two design cases is seen in chillers' electric energy use. In the first design case, chillers run continuously throughout the year to provide the required cooling demand, as shown in Fig. 5(A). When direct cooling is realised, chillers only run when heat pumps can no longer fulfil the cooling demand through the evaporator ($Q_c > Q_{evaporator}$). Overall, direct cooling covered the entire cooling demand during almost one third of the yearly operation. Moreover, it decreased

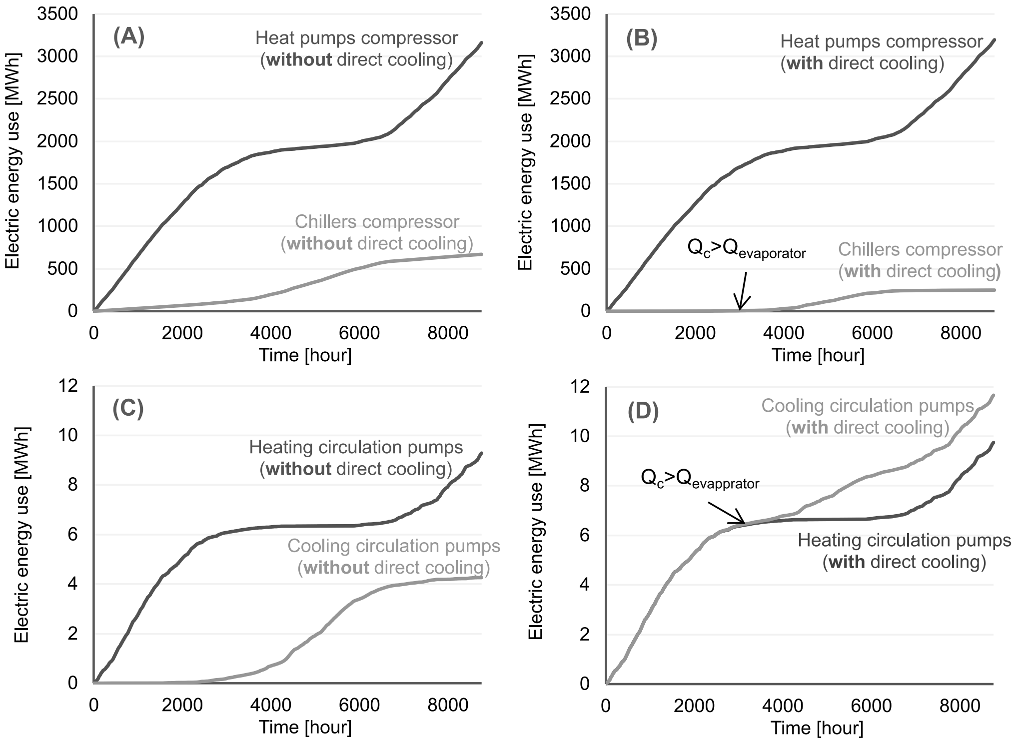

Fig. 5. Substation annual electric energy use. Figures (A) and (B) compare the electric energy use in compressors between the two design cases, while figures (C) and (D) compare the electric energy use in circulation pumps.

the operating capacity of chillers which consequently reduced the compressor annual electric energy use by about 63%.

The circulation pumps electric energy use is illustrated in Figs. 5(C) and 5(D). The two lines representing heating and cooling circulation pumps in Fig. 5(D) are superimposed on each other until a certain point. This shows that the same circulation pump is used for both heating and cooling which are provided by heat pumps. After reaching the maximum capacity of the direct cooling heat exchanger where $Q_c > Q_{evaporator}$, chillers start to operate. This is depicted in the diverging point in the grey line where other circulation pumps start to draw water to chillers. Taken together, the results suggest that the system with direct cooling yielded a reduction of 10% of the total electric energy use. The results, however, may differ from one building cluster to another depending on the simultaneity between heating and cooling demands. Previous studies aimed to investigate the simultaneous demands developed metrics such as the Diversity Index [11] and the Demand Overlap Coefficient [14]. Evaluating these metrics supports engineers to map potentially promising clusters in order to increase the efficiency of the district system.

4. Conclusions

We demonstrated in this paper Modelica-based simulations of decentralised substations with two different designs. The substations included models for heat pumps, chillers, and circulation pumps. The difference between the two designs was the utilisation of heat pumps to provide cooling from the evaporator to a direct cooling heat exchanger. We studied a cluster of 11 buildings with simultaneous heating and cooling demands to compare the two designs. The substation seasonal coefficient of performance (SCOP) and annual electric energy use were evaluated as performance indicators. The results show that the system design with direct cooling reduced the operation time of chillers by one third in addition to decreasing their operating capacity. To improve substation performance, we recommend implementing temperature controllers in both demand and supply sides. This may involve controlling the heating and cooling supply temperatures based on the outdoor weather, as well as controlling the district network temperature. The former would improve the performance of heat pumps and chillers, while the latter would increase the potential for direct cooling through the district network.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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