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Pragmatic design solution to decarbonize building industry through a low temperature district network☆

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ABSTRACT

The European Union's aim to decarbonize the building stock by 2050 requires significant reductions in the energy use for space heating and cooling. One such solution to decarbonization could be energy sharing between buildings. This paper presents the potential for energy saving and subsequent reduction in carbon emission with a low temperature district network in an energy community based in Malmö, Sweden. In this study, environmental impact of energy consumption has been performed, together with a Modelica based simulation which incorporates the detailed dynamic modelling of the digital twin of energy system stationed at this community. The modelled network is of a novel design that features geothermal boreholes as the primary energy source for the community's thermal demands and allows sharing of excess energy between the buildings connected to the network. The study shows that sharing energy between the buildings improves the overall seasonal performance of the substation from 5.2 to 6.2 and reduces the net purchase of energy by approximately 14.1 % in comparison to the standalone systems. Furthermore, benefits were identified in the form of load sharing between borefields accounting to approximately 50 MWh of thermal energy exchange between the substation's borefield leading to a longer operational lifespan of borefields. The result also showed that emissions from the studied network are only 7 % of the emissions associated with the existing district heating network available in the region, thereby emphasizing the substantial environmental benefits and great potential to reduce emissions related to urban heating and cooling in general.

1. Introduction

1.1. Context

Heating and cooling requirements of buildings accounted to approximately 50 % of the total energy use in the European Union (EU) leading to 36 % of the Green House Gas (GHG) emissions in 2022 [1,2]. In order to achieve the target, set by the EU's *"fit for 55"*, and the *"European Green Deal"* policies which aims to cut the emissions by 55 % compared to the 1990 s level, efficient distribution, and integration of renewable energy sources to the district heating and cooling network is envisioned [1,2]. The decarbonization pathways however is not straight forward and often has complex interdependencies between the energy sources and the distribution system such as those seen on the district heating and cooling networks.

From its inception in 1870 s [3], District Heating and Cooling systems (DHCs) has evolved to the current fifth generation district heating and cooling systems (5GDHCs) which along with low distribution losses, features the integration of renewable and low temperature energy sources including geothermal, solar thermal, and low exergy process heat [[4]. Low temperature and "otherwise waste" heat can in this system be extracted and redirected for heating and cooling needs of buildings. This makes 5GDHCs one of the promising solutions to meet the proposed EU goal to decarbonize the building heating and cooling sector [5].

The surge to decarbonize the DHCs in Europe began with the use of heat pumps coupled with low temperature district network (LTDN) [6] with a reportedly 38.9 % increase in the use of heat pumps in 2022 compared to the year 2021 [7]. Heat pump systems that extract heat from the environment (air, water or ground) came out as a viable option where ground coupled heat pump systems were found to provide ample opportunities to improve thermal efficiency due to its low temperature variation and high heat capacity of the ground [[8]. Owing to the high heat capacity of the ground, Shallow Geothermal System (SGS) gained popularity as ground could act not only as an energy source but also as an energy balancing unit for the network [9]. This was promoted further when the European commission officially adopted the Net Zero Industry Act (NZIA) in 2024 which in addition to prioritizing domestic

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manufacturing of clean energy technologies, recognized "geothermal" as a strategic net zero technology [10].

As SGS can operate as an energy balancing unit, the role of SGS can be extended to act as an "energy sharing" component of the LTDN for the connected buildings in the network. This paves the way for individual buildings connected to the LTDN to act as prosumers of heat and behave as part of a holistic energy community [4,8]. In such configuration, as an energy community, individual building in the network can take in or give out heat from/to the network thereby making it possible to share excess and "otherwise" waste heat.

1.2. Research gaps and contributions

The underlying operating principles on how energy sharing through a shallow geothermal energy source can be realized was presented in [4,11]. The study concludes with a need for a detailed study of the system to explore the actual benefit of energy sharing. Numerous case studies such as ref. [[12,13,14,15] can be found on literature that presents system configuration for a 5GDHC system. The studies describe the role and effect of different system components including pumping units, balancing units and network arrangement on the performance of the system. There is, however, a gap in practical design for optimized integration of substations in a network that features dynamic energy exchange. The studies recommend for detailed research on the underlying challenges related to synchronizing the hydraulic design and operational control of the systems required to establish a synergy between buildings that can help realize efficient energy sharing between each other.

The aim of this study is thus to present a novel and pragmatic LTDN design solution together with a detailed control strategy to achieve effective energy sharing via a shallow geothermal system connected to an energy sharing network. The study contributes by presenting unique and scalable energy sharing control strategy for connected substations. Moreover, it provides a comprehensive description of substation design and implementation strategy, including technical specifications of components, control logic and predicted performance metrices that enables stakeholders to replicate this system in diverse contexts.

1.3. Paper Organization

This article has been organized as follows: In subsequent Section 2, the design of the energy sharing system, including the digital model used to simulate the energy system, is explained. Section 3 presents the overall results that quantifies the amount of energy sharing and its subsequent effects on the long-term performance of the connected substations. Finally, concluding remarks and future pathways for low temperature systems are discussed in section 4.

2. Methodology

Starting from process design to creating a digital twin of the studied network and finally analyzing the system performance, and impact assessment; a systematic method as shown in Fig. 1 was followed to study the low temperature network. This section describes the design and operation of the low temperature district heating and cooling network installed to serve the area Embassy of Sharing (EOS) in Malmö, Sweden. A digital twin of network components and distribution systems was built in Dymola using the Modelica modeling language. The development of the system includes the shallow geothermal borefield, uninsulated central pipe network, energy substation, and associated auxiliary components for energy exchange within the substation all of which are described in the following sections.

2.1. Case study

Fig. 2 shows the schematic layout of the substations and the LTDN network in Embassy of Sharing. The Embassy of Sharing community is an undergoing development project at Malmö, Sweden, consisting of seven buildings located in separate real estates, with unique designs, and features promoting a sustainable community [16]. The community with a heated floor area of 61,901 sq. meters houses spaces for residence, offices, recreation, and commercial purposes. Owing to the diverse use-

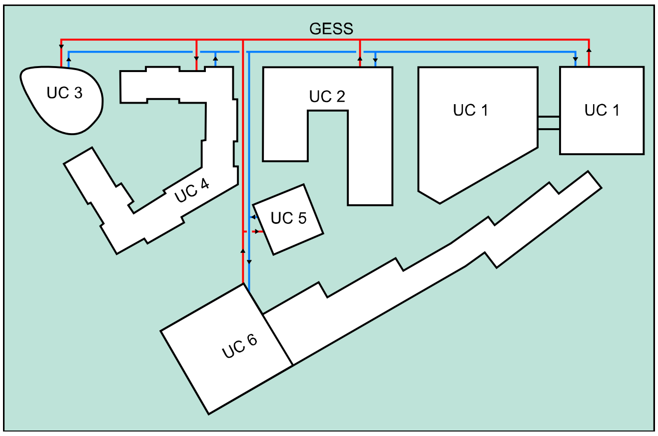

Fig. 2. Schematic layout of the Embassy of sharing community showing all the sub-stations and the GESS network.

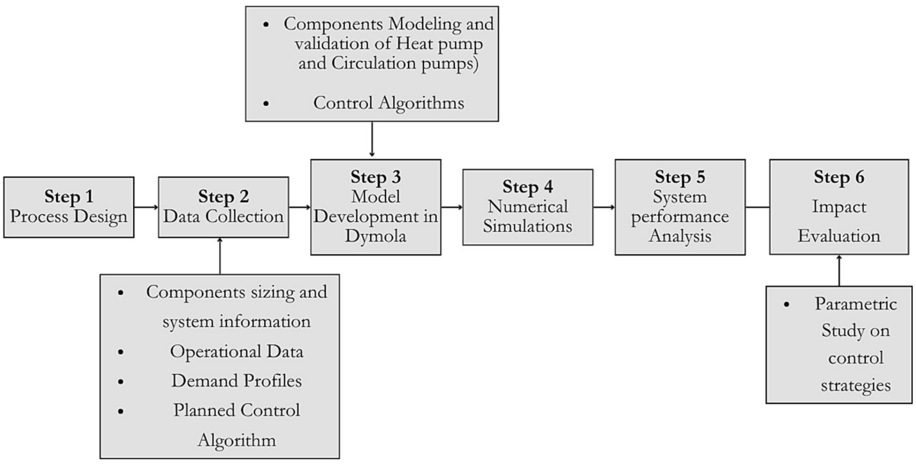

Fig. 1. Methodological flowchart depicting steps followed for modelling, simulation and analysis.

types of buildings, EOS has thermal energy needs for both heating and cooling which amounts to an estimated 2.2 GWh and 0.4 GWh of energy respectively for heating and cooling annually. To meet the thermal needs of the buildings, the community is equipped with a low temperature district heating and cooling network. The network is integrated with shallow geothermal borehole heat exchangers (BHEs) as one of the primary energy sources. Further, heat pumps are equipped at each building level to alter the fluid temperature, to meet individual building demands.

The central network consists of two pipes which serve as a Geo-Energy Sharing System (GESS) for the whole community. GESS facilitates sharing excess energy from individual substations to substations that have an energy demand. This reduces “otherwise” waste-heat and allows each building to act as a prosumer. The two pipes do not serve as a distinct supply and a distinct return. Meaning that one of the pipes can be a supply node for one of the substations and a return node for the other. Based on a forecasted building thermal load, the supply and return synchronization for two pipes is pre-determined to ensure unidirectional flow in the network and to maximize the energy sharing. The direction of flow from the pipes to each substation can be visualized in Fig. 2.

2.2. System description

There are a total of six sub-stations in the area. The GESS is connected to each sub-station (UC) via a three-way valve connection which regulates the flow between the substation, BHEs and the GESS. The substation further houses a mix of components including heat pumps, heat exchangers, storage tanks and other auxiliary components. The system design, flow scheme and components of substation 1 (UC 1) is used as a reference in the following sub-sections to describe the working modality of the overall system.

2.2.1. Sub-station design and flow scheme

Fig. 3 shows the system design of UC 1. The sub-station is equipped with 31 single U-tube BHEs, each running approximately 285 m deep. The BHEs are connected with the GESS and the building via a three-way valve SV 51, as shown in Fig. 7, which regulates whether the entire flow to the building comes from the BHEs or the GESS system. In other words, the regulation of the three-way valve decides whether the sub-station works as a standalone system or as part of an energy sharing system. The regulation of this valve and mode of operation is further described in section 2.2.5 of this article.

The building tied to UC 1 houses seven heat pump units, where each of the heat pumps has a peak heating output capacity of approximately 100 kW. The space heating distribution line of the building is directly connected to the condenser side of the heat pumps whereas a storage tank of 1500 L capacity is installed on the domestic hot water loop. It should be noted that only Heat pump 1 and Heat pump 3 in UC1 are connected to the DHW loop, whereas all seven heat pump units can deliver heat to the space heating system.

Hex 1 and Hex 2 are two heat exchangers installed on the sub-station, only activated when the building has cooling needs. Hex 2 is connected to the evaporator side of the heat pumps and exchanges the necessary cooling energy between the space cooling distribution and the brine solution with ethanol and water circulating on the source side of the sub-station. At the same time, Hex 1 exchanges, and dumps all the heat produced from the heat pumps during active cooling to the borefield thereby replenishing/recharging the borefield.

2.2.2. Heat pumps design and control

All installed heat pumps are the same type and brand; GEO IVT 280, which has two scroll compressors. In total, 14 compressors make up the seven heat pump units installed. These compressors are regulated individually depending on the amount of heat output required at the demand side of the building. The heat pumps thus can be in 15 different states, including the OFF state where all compressors are turned off. Further, the operation of heat pumps is regulated, based on the type of demand on the sub-station.

The heat pumps included in the system are modeled using a multivariate equation fit method. The variables used in the model are the outgoing temperatures on the condenser and the evaporator side. The model uses a set of heat load performance coefficient (α), and electrical power performance coefficients (β) to determine the available heat at the condenser side and electrical power used by the compressors. The model equation defining the performance is presented in Eqs. (1) and (2).

$$\dot{Q}_{ava} = \alpha_1 + \alpha_2 T_{loa,out} + \alpha_3 T_{Sou,out} \tag{1}$$

$$P = \beta_1 + \beta_2 T_{loa,out} + \beta_3 T_{Sou,out} \tag{2}$$

In Eqs. (1) and (2):

$\dot{Q}_{ava}$ is the available heat at the condenser side,
$T_{loa,out}$ is the load side entering water temperature,
$T_{Sou,out}$ is the source side entering fluid temperature,
P represents the electrical power used by the heat pump.

At every simulation step, the coefficient of performance (COP) for the heat pumps is calculated using Eq. (3) and heat extracted on the evaporator ($\dot{Q}_{eva}$) is calculated using Eq. (4).

$$COP = \frac{\dot{Q}_{ava}}{P} \tag{3}$$

$$\dot{Q}_{eva} = \dot{Q}_{ava} - P \tag{4}$$

As mentioned earlier, there are a total of 14 compressors, and each can be independently regulated. In the model as shown in Fig. 4, two Proportional-Integral (PI) controllers have been defined namely “HeaCounter” and “CooCounter”. The output of these controllers ranges from 0 to 1. HeaCounter takes as an input the space heating supply temperature and regulates against the heating supply setpoint temperature. The heating setpoint temperature is obtained dynamically using an outdoor temperature compensated curve. Similarly, CooCounter takes as an input the space cooling supply temperature and regulates against the cooling setpoint temperature. At every simulation step, only the maximum value between two PI controller signals is sent further to a stage counter. The stage counter equally divides the PI controller’s output into 15 stages and assigns an appropriate compressor stage. The PI controller’s output is equally divided into 15 stages to replicate the 15 different states of the compressors. In this case, stage 1 represents all compressors are turned off and stage 15 represents all compressors of 7 heat pumps are turned on.

In addition to the distinct heating circuit and a cooling circuit, the substation also has a DHW distribution circuit, where the necessary DHW load is met by HP1 and HP3. The output signal that turns the number of compressors ON or OFF for HP1 and HP3 is thus also dependent on the load on the domestic hot water (DHW) circuit of the substation. As shown in the substation flow scheme in Fig. 3, the substation is equipped with a 1500 L DHW storage tank which in addition to supplying the necessary heat for DHW use, also acts as a hydraulic separation between the heat pumps and the DHW demand circuit.

The control logic to control the heat pump operation based on the DHW requirement is depicted in Fig. 4. The main logic conscripted in the control is to maintain a constant DHW supply temperature at 55 °C, and to ensure that the lowest return temperature does not fall below 50 °C in the overall DHW distribution system according to legal standards. The input signal “dhwTank” represents the instantaneous fluid temperature in the storage tank. Four different hysteresis control blocks each with a lower and upper limit for tank temperature are defined as presented on Table 1. Each hysteresis block shown in the bottom part of Fig. 4 is responsible for regulating one compressor each on HP1 and HP3.

The components comp1, and comp2 shown in Fig. 4 control the

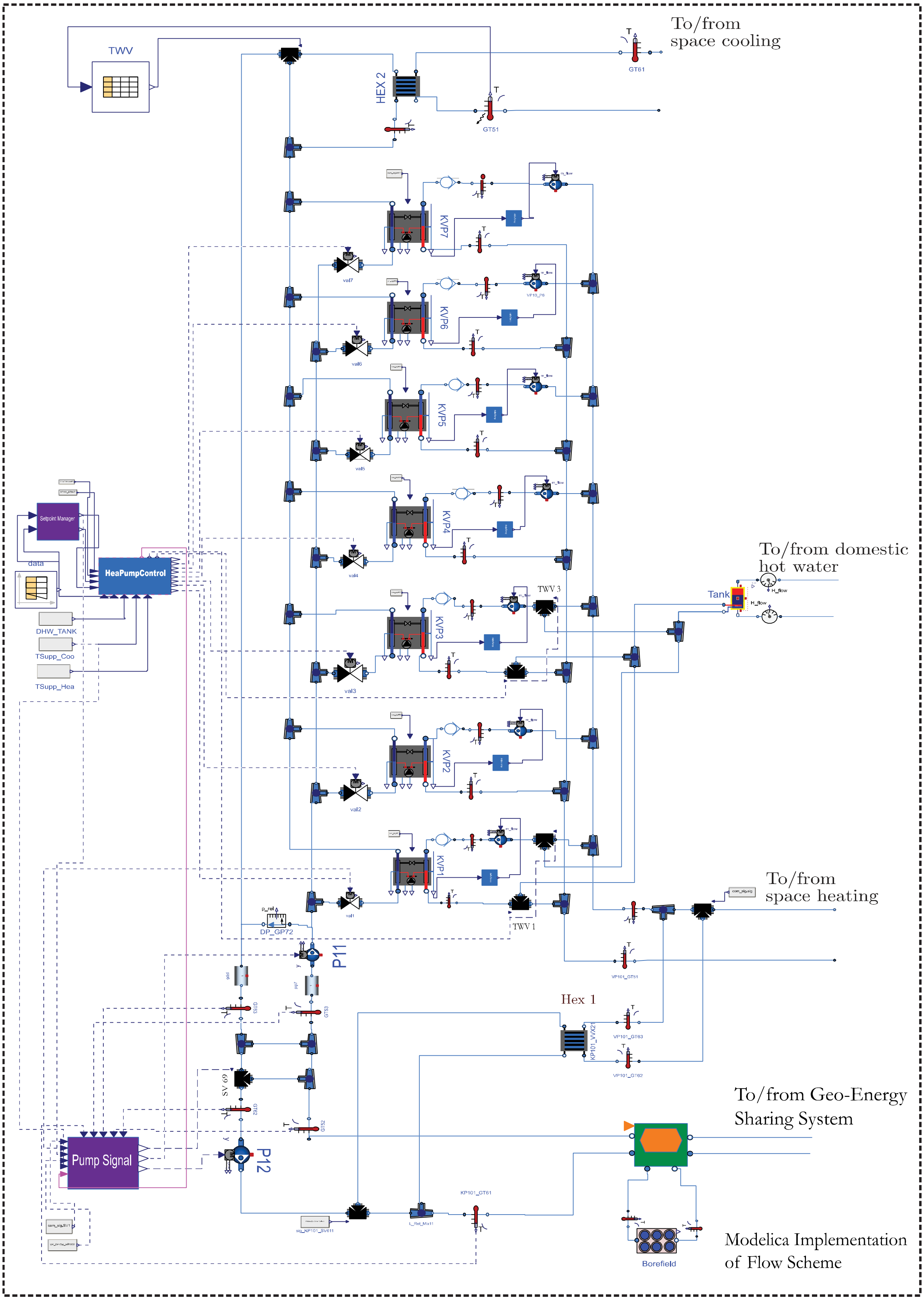

Fig. 3. Digital twin of Substation 1 in Modelica.

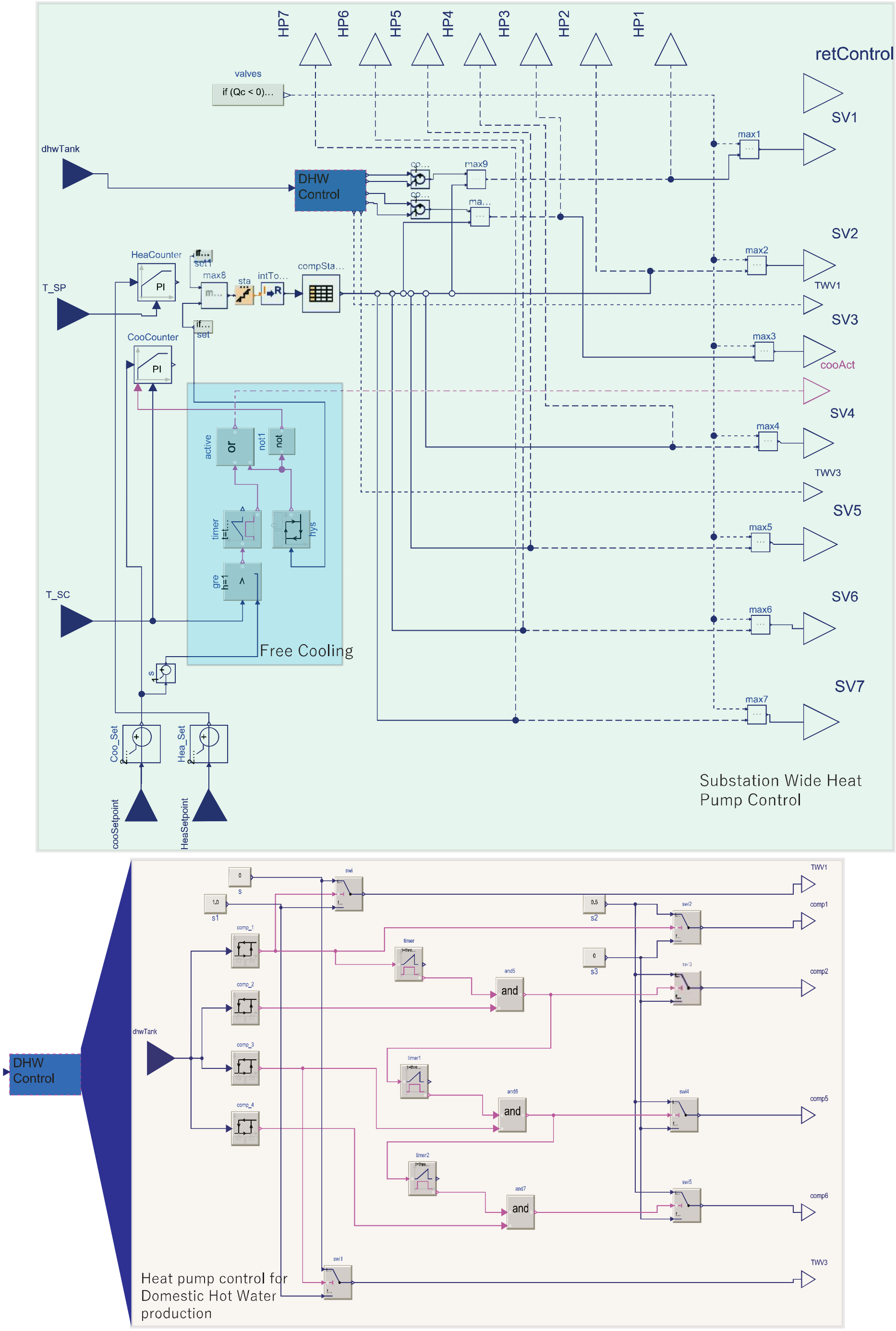

Fig. 4. Heat pump control mechanism at the substation level.

Table 1
Heat pump compressors operation stages based on DHW tank temperature.

Input signal	Hysteresis block	Lower limit	Upper limit	Wait time to send output signal	ON Signal	Off signal	Output (ON/OFF)
dhwTank	Comp1	53 °C	59 °C	No wait time	<53 °C	>59 °C	0.5/0
	Comp2	51 °C	57 °C	120 s after comp1 is ON	<51 °C	>57 °C	0.5/0
	Comp5	49 °C	55 °C	120 s after comp2 is ON	<49 °C	>55 °C	0.5/0
	Comp6	47 °C	53 °C	120 s after comp3 is ON	<47 °C	>53 °C	0.5/0

compressors of HP1 and comp5, and comp6 controls the compressors of HP3. A delay of 2 min between the start of each compressor is added to consider the system thermal dynamics.

At each simulation step, the compressor signals for HP1 and HP3 originating from the DHW control logic and the space heating/space cooling circuit logic is evaluated. The maximum of the two outputs is sent out to the heat pumps such that DHW is always prioritized. The DHW priority is achieved by regulating the three-way valves TWV1 and TWV3 which directs the flow between the space heating circuit and the DHW circuit.

2.2.3. Circulation pumps

It is worth noting that the overall network is not equipped with a central pumping unit. Instead, each substation has its own decentralized circulation pumps. The substation presented in Fig. 3 is equipped with two circulation pumps, namely P11 and P12. The circulation pump P11 is an ***IL 80/140–7.5/2*** Wilo pump and P12 is an ***IL 80/160—11/2*** Wilo circulation pump. In the Modelica model, both pumps are modeled using *"Buildings.Fluid.Movers.SpeedControlled_y"* which is a pre-defined component in the "*Modelica Buildings library*". The pump curve which defines the relation between the volumetric flow and head for the pump is obtained from the manufacturer catalogue and is input manually in the model.

The detailed control logic to operate P11 and P12 is presented in Fig. 5. The circulation pump P11 pumps the brine on the evaporator side of the heat pumps and is basically controlled using a PI controller "conPID1" that regulates the pump's speed to maintain a constant differential pressure between the supply and return of all heat pumps. Furthermore, P11 has an additional control algorithm that is activated during the free cooling mode when all the heat pumps are turned off. During the free cooling mode, P11 is regulated using a PI controller "conPID" which takes as an input the cooling supply temperature and the cooling setpoint.

The pump P12 is a slave pump that pumps the working fluid through the heat exchanger HEX1, borefield and the GESS system. Control of P12 is particularly crucial and interesting as it can reshape the energy exchange between the substation, borefield and the GESS. When the substation is in heating mode or a free cooling mode meaning that not in active cooling mode then the P12 pumps follows the pumpP11 to maintain the same differential temperature between leg 1 and leg 2 of the brine circuit. The PI controller "conPID3" regulates P12 during this phase.

When the substation enters active cooling mode, the temperature on sensors GT52 (supply temperature from the borefield) and GT63 (return temperature from the HEX 2) is evaluated to explore the possibility to achieve further cooling from the evaporator return temperature. If the possibility exists for such a scenario, the two circuits, above and below the SV 69, are hydraulically separated using the three-way valve SV69. When the two circuits are hydraulically separated, P12 is controlled via a PI controlled "conPID2" which ensures that a constant differential temperature over the borefield is maintained. The flow during this mode is recirculated via HEX1 to extract all the condenser heat during active cooling. The extracted heat from HEX1 is exchanged either to recharge the borefield or shared on the GESS network.

2.2.4. Borehole heat exchanger

The borefield was modeled using the component "*Buildings.Fluid.Geothermal.Borefields.OneUTube*" pre-defined in the *Modelica Buildings library*. The borefield model consists of two major parts comprising the heat transfer in the borehole and the heat transfer with the ground. The model components for the representation of borehole and the ground is shown in Fig. 6. The heat transfer in the borehole is calculated based on the thermal resistance and capacitance method presented by [17]. Each borehole is discretized vertically in the number of segments defined by the user. A temperature change depending on the amount of heat extracted from or rejected to the borehole is used to calculate the borehole wall temperature. The heat transfer between the pipes, borehole wall and the ground are modeled using a resistance capacitance network [17]. The ground heat transfer is modeled using the convolution integral between the heat flux at the borehole wall and the

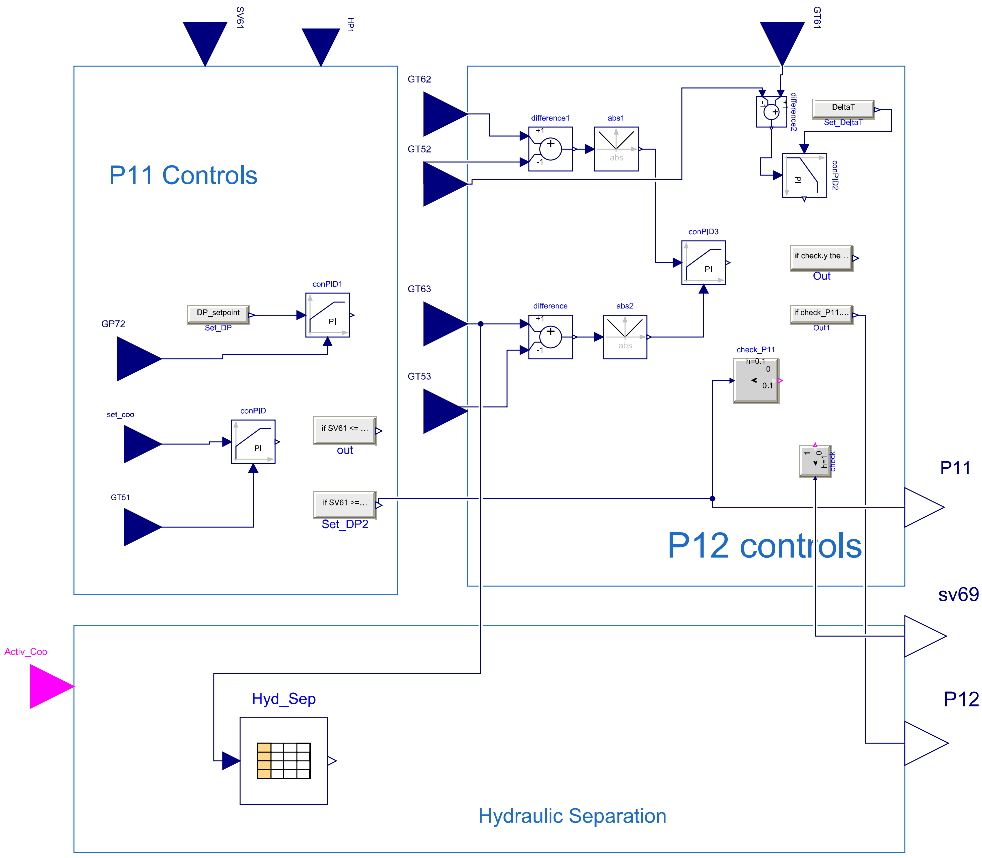

Fig. 5. Control logic to operate the circulation pumps.

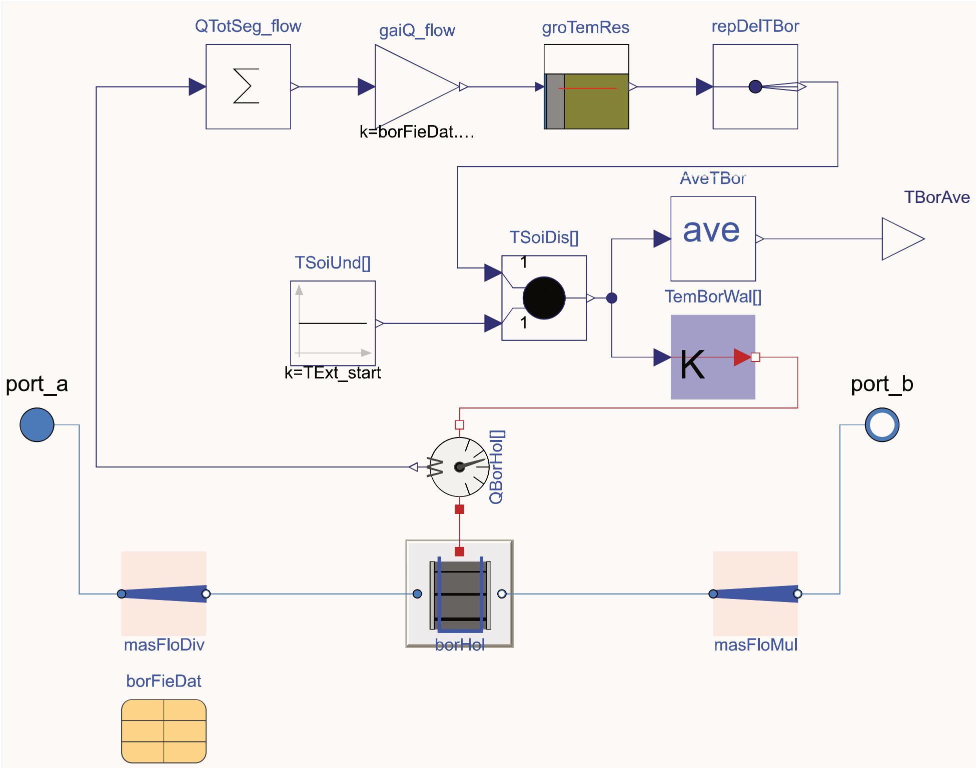

Fig. 6. Modelica implementation of the borefield [4].

borefield's thermal response factor. The load aggregation method presented by [18] is used to reduce the time required to calculate the changes in the borehole wall temperature resulting from the heat injection and rejection. The readers are advised to refer to [4,12,19] for the detailed explanation related to modeling of the borefield in Modelica.

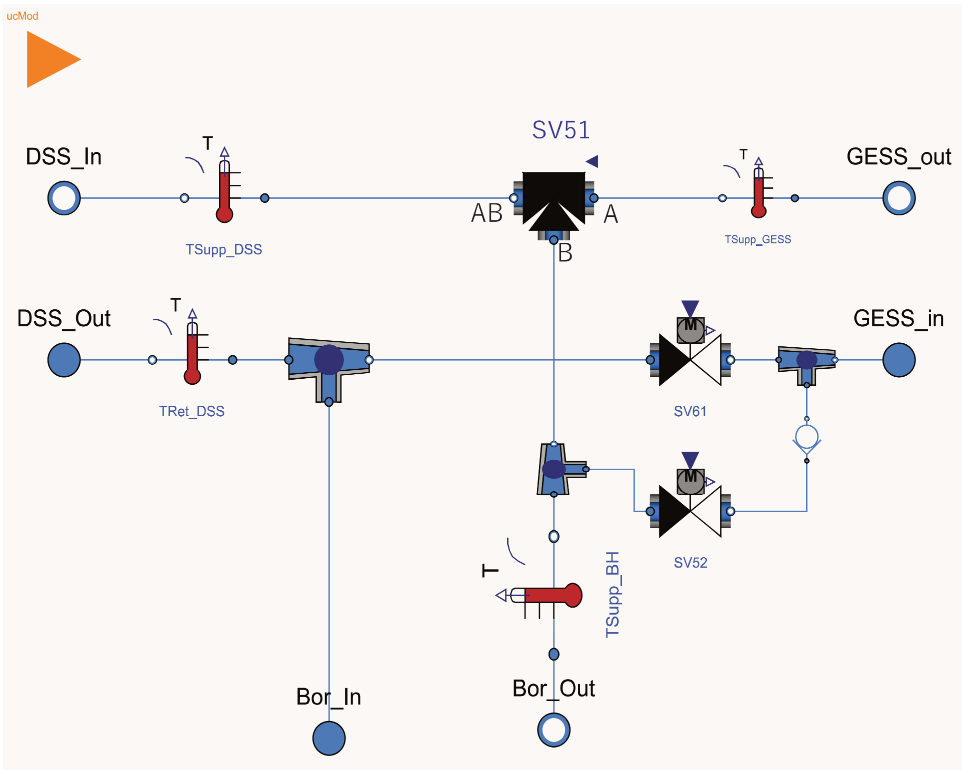

Fig. 7. Geothermal Sharing Control.

2.2.5. Energy sharing control design

Energy sharing between the substations is the core idea of this system which is achieved by an optimal control of GESS control algorithm shown in Fig. 7. The main component for sharing is a combination of a three-way valve (SV51) and a set of control valves (SV61, SV52). The configuration or mode of operation of these valves defines whether the substation operates as a standalone/independent system or as a part of an energy sharing system/energy community. Different modes of substation operation which can be achieved through the control of this sharing system is described below as follows.

Mode 1: Standalone system.

In some cases, it is in the best interest to operate each substation as a separate entity. This could be in cases such as the same nature of thermal needs in all substations, or a disruption in the central pipe network or a more favorable temperature in the borefield than on the main pipe loop. Then the three-way valve SV51 can be configured to direct the entire flow from port B to port AB whereby the entire return flow from the building is channeled through the borefield and back to the substation. In this case, there will be no flow in and out of the GESS system. The substation in question can be in standalone heating mode or standalone cooling mode whereby its own borefield will act as a primary energy source/balancing unit.

Mode 2: Energy Sharing to GESS.

If different substations have opposing thermal needs, for instance, if one substation has a heating demand and the other has a cooling demand, then energy sharing can be realized at its peak potential. Furthermore, energy sharing may also be realized if one substation extracts heat or rejects heat to the borefield of another substation.

Sharing energy through GESS begins first with identifying whether the substation has a heating need or a cooling need. If the substation has a heating need then extracting higher fluid supply temperatures to the substation is beneficial. Hence, the control logic for SV51 checks for the GESS supply temperature and the BH supply temperature and regulates SV51 such that flow to the substation is directed from the port having higher fluid temperature. Conversely, if the substation has a cooling need, then SV51 is regulated to supply colder fluid to the substation.

The regulation of the control valves SV61 and SV52 ensures whether the entire return flow from the substation is injected to the borefield or directed to the GESS. The control logic is designed such that a substation with a heating demand sends as colder fluid as possible to the GESS and a substation with a cooling demand sends out as hotter fluid as possible. The piping connection to the GESS makes sure that a substation with a cooling demand extracts colder fluid rejected by the other sharing substation and vice versa for the substation with a heating demand. This algorithm is opted to maximize the sharing between substations. Such a regulation is achieved through a logical evaluation of the substation return and the borefield supply temperature at each simulation time step.

To achieve energy sharing between the substations, two-way communication between the substations is required. The communication is typically regarding information about the nature of thermal demand at each substation and whether the substations are prepared for sharing. The input signal "ucMod" shown in Fig. 7 is responsible for this information transfer to each substation.

2.3. Network Connections

The central distribution network consists of two pipes which serves as both supply and return nodes for substations. As shown in Fig. 8, two distribution pipes are connected via a check valve at both ends ensuring unidirectional flow of the working fluid. The return node of substation 3 is connected immediately before the supply node for substation 1. Similarly, supply node of substation 3 is connected immediately after the return node of substation 1.

In this study, energy sharing through the GESS distribution network is initiated when substations have opposing thermal demands, the above presented connection ensures the most favourable inlet temperature for both substation during sharing. As an example, the high temperature return fluid to GESS from substation 1 during its active cooling operation is immediately used by substation 3 to meet its heating demand. Similarly, the cold return from substation 3 is used by substation 1.

3. Results and Discussion

3.1. Substation energy demand

A bar graph plot presented on Fig. 9 represents the year-round monthly energy demand profile of two connected substations: UC1

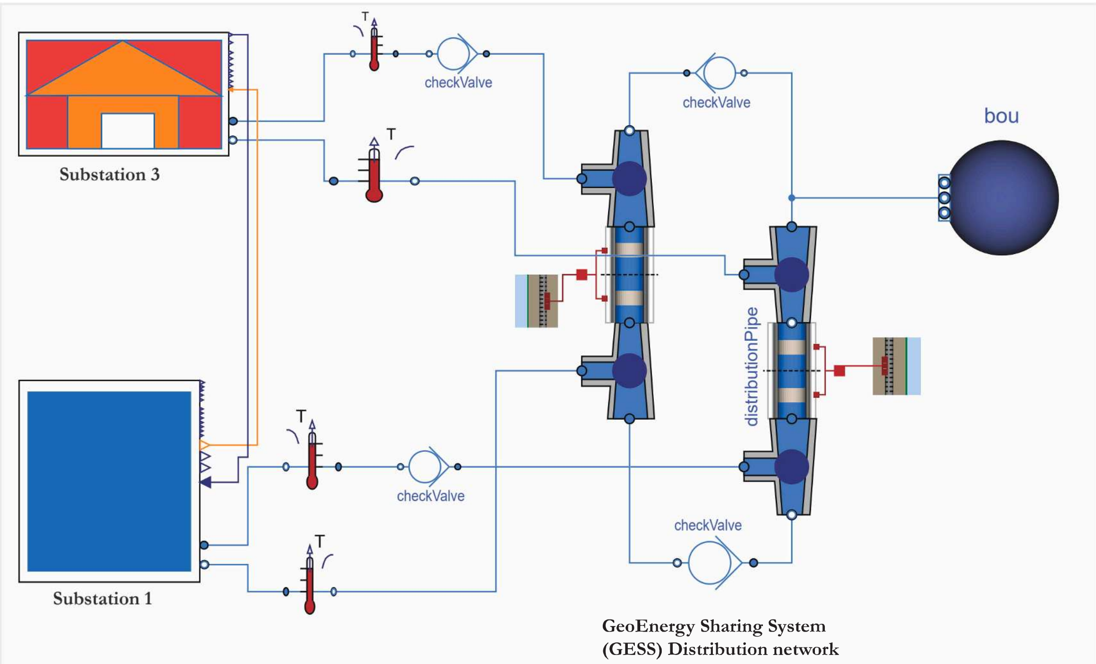

Fig. 8. Substations connection to the central distribution network.

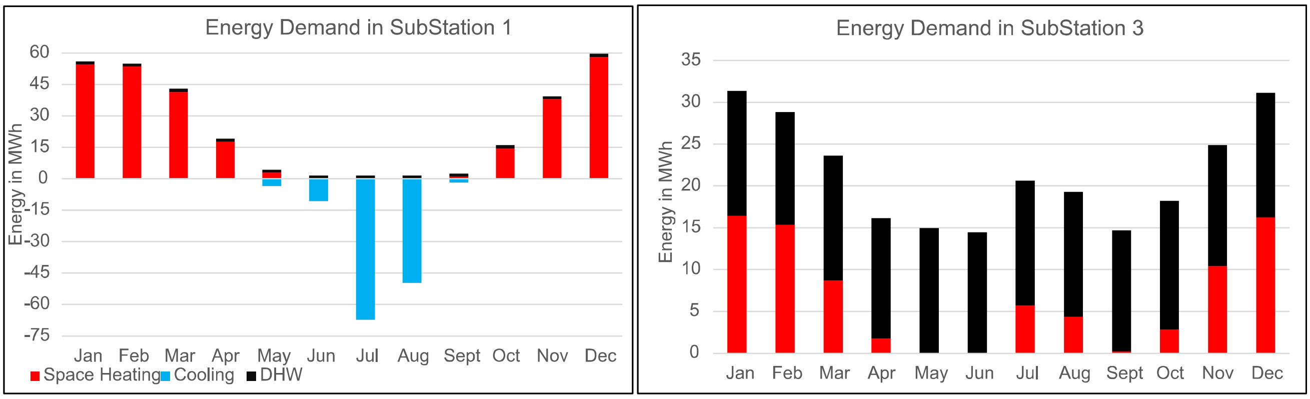

Fig. 9. Thermal Energy Demand profile in the connected substations.

(office) and UC3 (residential apartment). The cooling energy demand is represented with negative values in Fig. 9 to represent the energy removed from the building. UC 1, which is an office building has peak heating load of approximately 200 kW while in summer has a peak cooling loads of 580 kW. The accumulated yearly energy demand of substation 1 is approximately 457 MWh of which 137 MWh is the energy use for space cooling and 320 MWh energy is used for space heating and domestic hot water production. It is worth noting that, though substation experiences higher peak loads for space cooling, it only represents about 30 % of the total energy demand.

Similarly, it is evident from the bar graph on Fig. 9 that UC 3, which comprises of apartments, does not have a cooling need during summer period. The accumulated yearly heating energy demand is approximately 250 MWh of which 176 MWh energy use is for domestic hot water production comprising slightly above 2/3 of the total energy use of the substation.

3.2. Borefield and energy sharing

The average working fluid temperature from the borefield of two substations over 25 years period for two modes of operation is presented in Fig. 10. The blue curve represents the temperature profile during standalone operation mode and the red curve denotes the temperature profile during networked operation of two substations. It should be noted that UC 1 and UC 3 are equipped with 31 and 12 single U-Tube BHEs respectively. The most interesting highlight of the temperature profiles on Fig. 10 is the reasonably high average fluid temperature reaching as high as 30 °C on UC 1 which is the main basis for energy sharing between two substations.

The benefits of this synergy can be visualized through the temperature profile presented in Fig. 10. The minimum and maximum brine temperature from the borefield over 25 years period is of particular importance as it has major impact on the performance of heat pumps. Over the studied period, the brine temperature is lowest for the 25th year which shows that for a standalone operation, the brine temperature can fall as low as 0 °C in UC 3 whereas for a networked operation, it falls to around 1.3 °C suggesting further useful lifespan of the borefield. Similarly, in a standalone operating scenario, the maximum brine temperature is around 10 °C in year 1 for UC 3 which gradually decreases down to a maximum of around 7 °C by the year 25. This is due to the constant heat extraction from UC3′s borefield to meet its heating demand.

In case of a networked operation, we observed that brine temperature is largely affected due to energy sharing with UC1 and reaches as high as 26 °C in year 1 and a maximum of approximately 24 °C by 25th year. The high average brine temperature in UC 1 is the result of replenishment of borefield with excess condenser heat output from the heat pumps during active cooling operation. The design and control algorithm opted to achieve this heat exchange between heat pumps and borefield was described in section 2.2.5. The high brine temperature of UC 1 is beneficial for UC 3 as UC 3 has heating needs for DHW production during summer and similarly, the low brine temperature of UC 3 benefits to meet the cooling needs of UC 1 during the summer.

A synergy can thus be established because of the opposing thermal

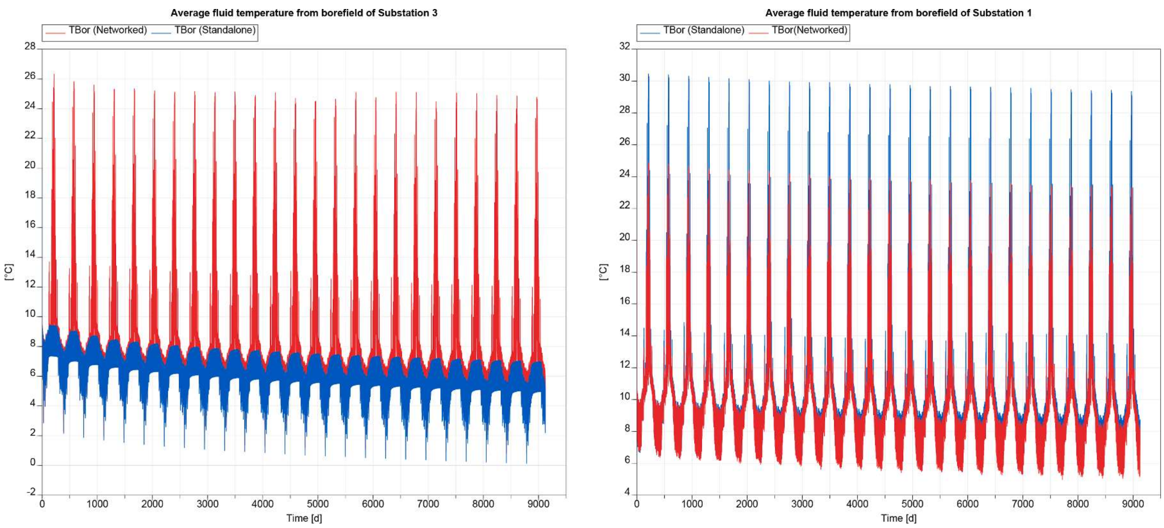

Fig. 10. Average fluid temperature in two substations under different operation scenarios.

needs and favourable brine temperature. The effects on the system performance owing to the connection between two substations forming an energy sharing network is discussed in the following sections. Fig. 11 and Fig. 12 depicts the hourly profiles of thermal load, and net energy extraction from the borefield in substation 1 and substation 3 respectively. The positive thermal load refers to the heat extraction and the negative thermal load refers to heat injection into the borefield. The parameter "net energy extracted" refers to the difference between the energy extracted and injected into the borefield. Since both substations have dominant heating demands, the net energy extracted is a positive value.

It was discussed in the preceding section that during active cooling operation, heat is injected into the borefield of UC 1. As seen in Fig. 11, when the UC 1 is running in a standalone mode, heat is injected at the rate of almost 800 kW at its peak resulting into high brine temperature as presented in Fig. 10. As a result of this high heat injection, it was observed that around early August (ca. 6000 h in Fig. 11) the net energy extracted from the borefield tends towards zero which suggest energy balance in terms of heat extraction and injection. The practical implication of this is observed with an operational longevity for the borefield.

However, when substation 1 is coupled with substation 3 to form a network, and as a result of energy sharing during the summer period, the aforementioned energy balance is not achieved on UC 1 which can be observed with a higher net energy extraction represented by blue curve in Fig. 11. On an annual basis, the net energy extracted from the borefield of UC 1 is around 106 MWh when operating as a standalone substation and approximately 156 MWh as networked substation suggesting 50 MWh higher energy extraction when operated in energy sharing mode.

Another observation from Fig. 12 is that heat is injected into borefield of UC 3 during summer because of networked energy sharing between two substations. This has two practical implications. First, the immediate benefit with higher operational COP is achieved with higher brine temperature and heat injection replenishes the borefield thus increasing the lifetime or longevity of the borefield which otherwise would not have been possible if substation 3 were to operate as a standalone system.

One most interesting observation to consider is that the net energy extracted from the borefield for UC 3 when operating as a standalone system is around 180 MWh and approximately 135 MWh as a networked substation. The additional 50 MWh energy burden on the borefield of UC 1 as a result of being a networked system has resulted into an approximately 45 MWh lowered net energy extraction from the borefield of UC 3. This quantifies the load and energy sharing between two substations through their borefields. The net benefit with sharing can further be quantified with the amount of reduction in the primary energy demand to run the heat pumps and replenishment of the borefield core of each substation.

3.3. System performance

The effects on the performance of the heat pumps quantified in terms of coefficient of performance (COP), and a seasonal coefficient of performance (SCOP) for the substation which is the ratio of total delivered energy to total electrical energy used to operate heat pumps is detailed out in this section. The coefficient of performance of one of the heat pumps and average brine temperature from the borefield for standalone, and networked operation of substation 3 is presented in Fig. 13. It was observed that in a standalone operation the COP of around 5 is achieved during space heating operation and around 3.1 during the DHW production.

In contrast to the standalone mode, it is evident from Fig. 13 that average fluid temperature from the borefield which is also the fluid source for the heat pumps, increases drastically because of energy sharing. The difference in temperature between two operating modes is around 16 °C at the peak meaning that fluid inlet temperature to the heat pumps in networked substation 3 can reach 16 °C higher than when operating as a standalone substation.

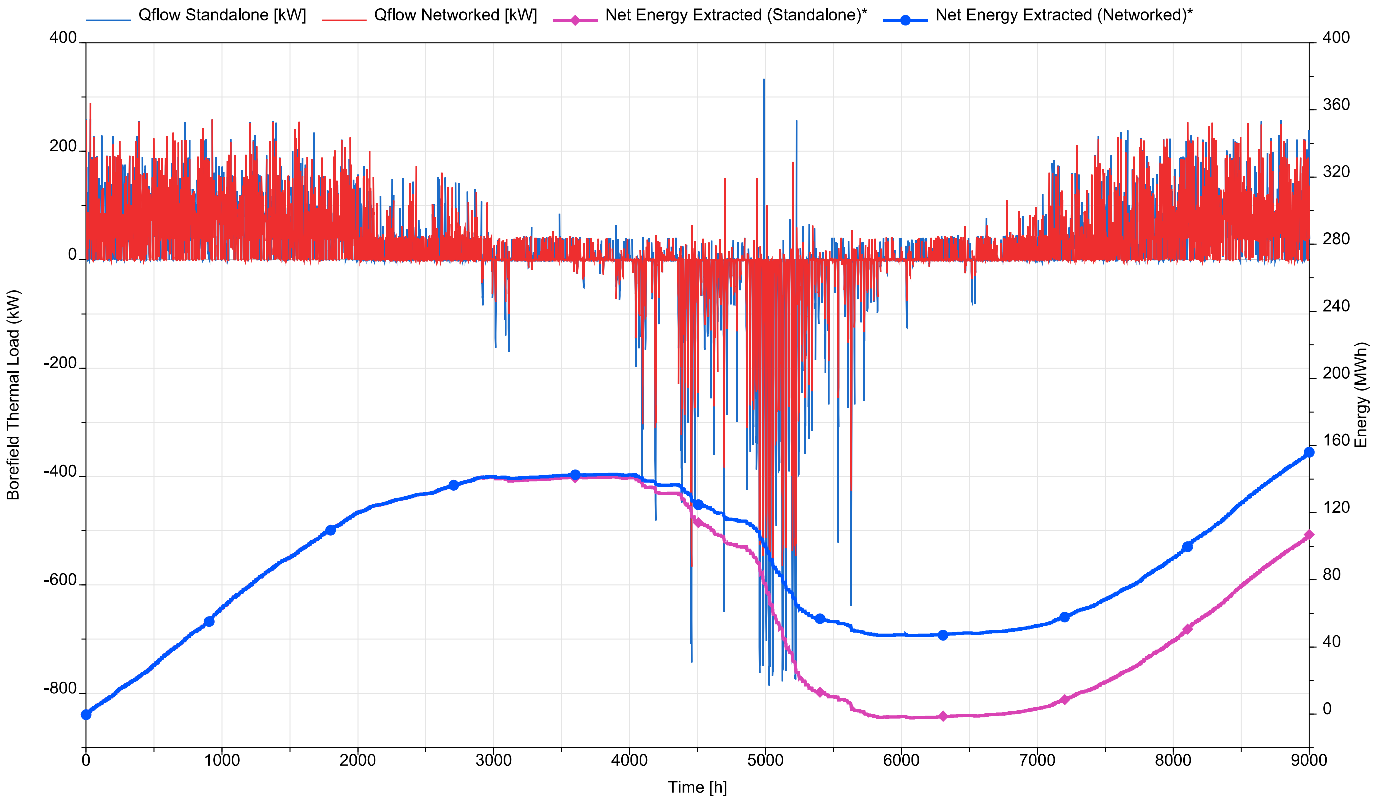

Fig. 11. Hourly energy balance of borefield – Substation 1.

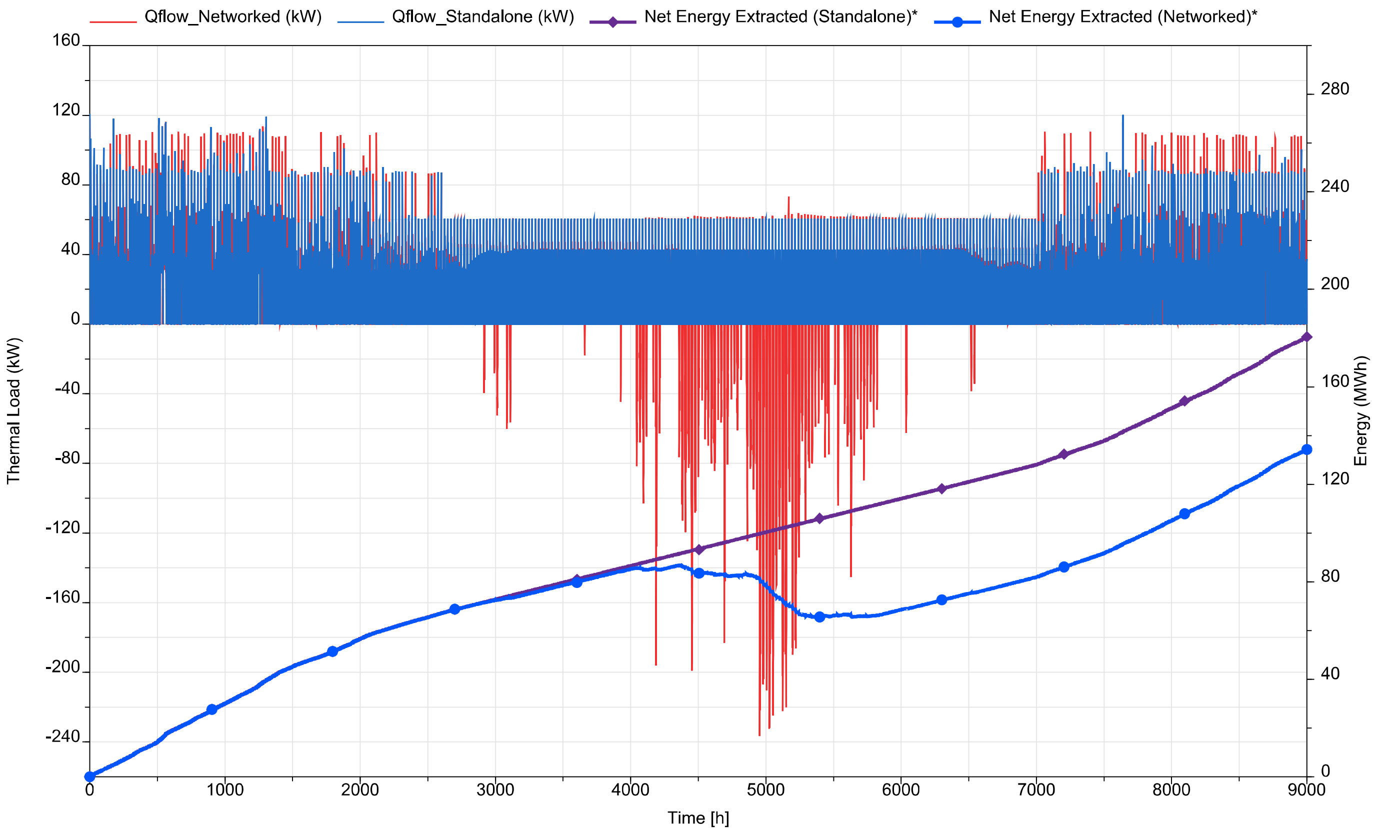

Fig. 12. Hourly Energy balance of borefield – Substation 3.

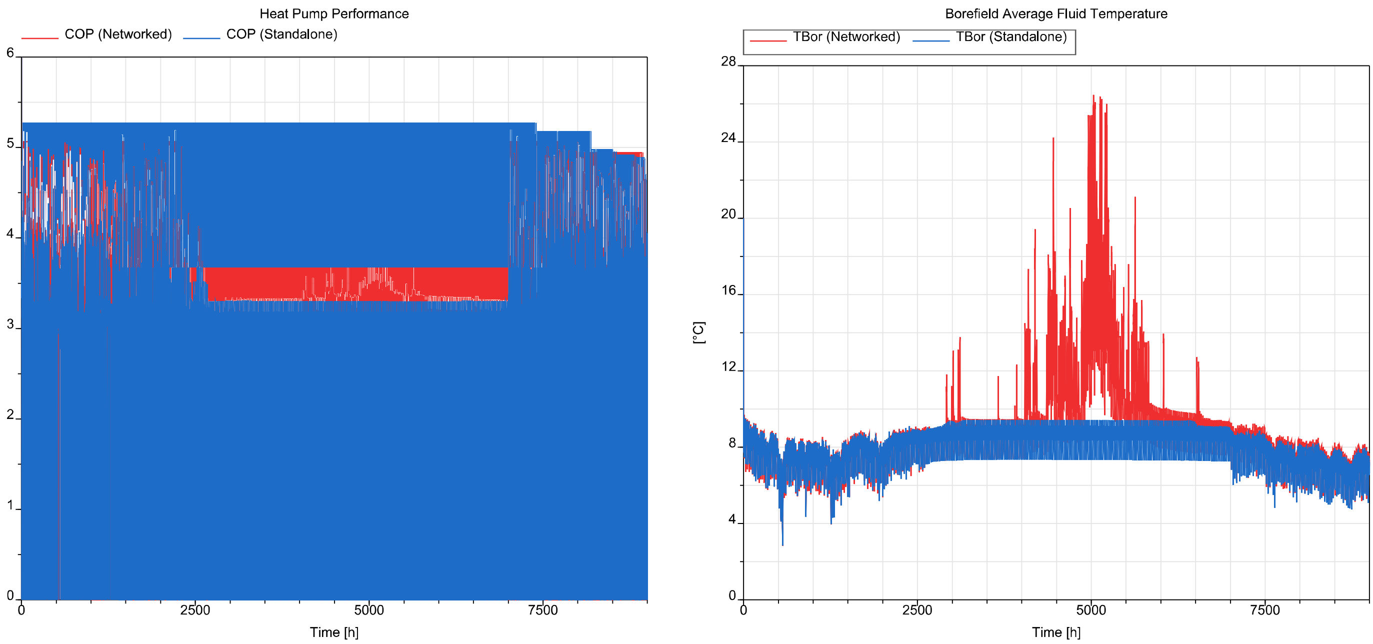

Fig. 13. Effect of energy sharing on borefield temperature and heat pump performance (Left: COP for networked and standalone substation, Right: Average fluid temperature from the borefield for networked and standalone substation for year 1).

The concurrent effect of this is realized with an increase in coefficient of performance of the operating heat pumps. It was observed that COP of individual heat pump increases by almost 1 unit compared to standalone operation of the substation. The author would like to point out that as the heat pump is operating only for DHW production during the summer period, even with a higher fluid inlet temperature during the energy sharing period, the relative effect on COP is not considerably high when compared to standalone operation.

A year-round performance of both substations was analysed considering their different operating scenarios which is shown in Fig. 14. For substation 3, the results showed that, year-round accumulated SCOP of approximately 3.4 can be achieved with networked

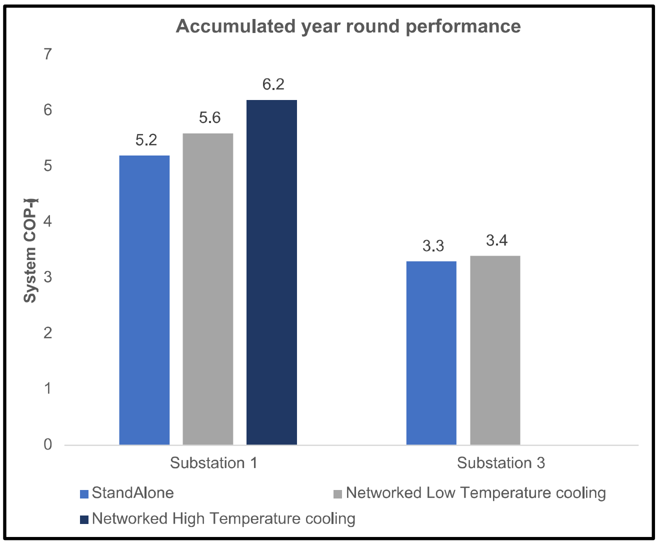

Fig. 14. Performance of the substations.

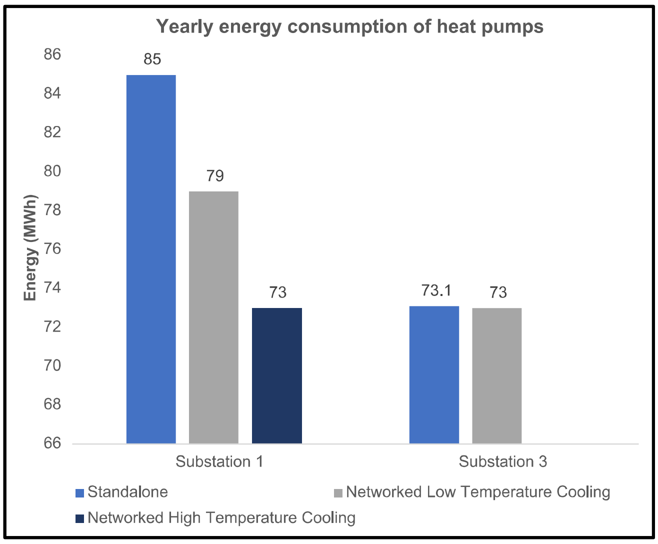

Fig. 15. Year-round energy consumption of heat pumps installed at each substation.

operation of substation which is approximately 0.1 unit higher than standalone operation. In addition to recharging of the borefield of substation 3 as discussed in previous section, the increase in SCOP explicitly reduces the electrical energy demand of heat pumps on substation 3 by approximately 0.1 MWh annually.

In substation 1 which has both heating and cooling demands, SCOP was analysed considering its operation as standalone system, as a networked substation with low temperature cooling and as a networked substation with high temperature cooling. Low temperature and high temperature cooling refers to the setpoint for cooling supply temperature. An outdoor temperature compensated curve for cooling supply setpoint was used that varies between 10 °C to 15 °C for low temperature cooling, and 14 °C to 18 °C for high temperature cooling scenarios.

As seen on Fig. 14, a sharp increase in SCOP can be achieved with high temperature cooling owing to the added potential for free cooling. The year-round accumulated SCOP of around 6.2 can be achieved on substation 1 when it's coupled with substation 3 and operated with high temperature cooling strategy. Further, with similar system configuration but when operated with low temperature cooling supply, year-round SCOP falls to around 5.6 which still is around 0.4 units higher than the SCOP for the standalone operating scenario of substation 1.

The year-round net energy consumption of heat pumps for these operating scenarios presented on Fig. 15 sheds extra light on the immediate benefits of the networked system over standalone systems. It is evident from Fig. 15 that 85 MWh energy is used annually to operate the heat pumps in substation 1 during standalone operating mode. In contrast to this, the same measure is only 73 MWh for a networked operation. This indicates that for substation 1, approximately 12 MWh electrical energy used to operate heat pumps can be saved annually with a simple control over its cooling supply temperature while operating with substation 3. This amounts to approximately 14.1 % lower energy use compared to standalone operation of the same system. In case of substation 3, the benefit of energy sharing is almost negligible with only 0.13 % lowered energy use for heat pumps. The lowered benefit is attributed to heat pumps operating for only DHW production in substation 3 during the energy sharing period.

The key takeaway from the presented results is that the holistic improvements in system performance can be achieved by coupling substations to operate as a network. In addition to which, a larger benefit can be secured by opting for wiser controls over supply temperatures.

3.4. Impact evaluation

It was mentioned in introductory section that the main motivation behind opting for a LTDN network is to decarbonize the heating and cooling needs. Hence, an impact assessment considering the combined operational energy use; B6 stage of a standard life cycle analysis was performed. As a base for the analysis, the energy demands of substations presented in section 3.1 has been used. The thermal energy use corresponding to 320 MWh for heating and 137 MWh for cooling in substation 1 was used for analysis. Similarly, for substation 3,250 MWh heating energy was used. The alternative for the LTDN solution would be to use district heating, available in the area. Thus, an analysis considering the energy mix of Malmö region, and Sweden in overall was conducted.

The emissions factors used in this comparison for electricity is 0.037 $kgCO_2$ equivalent per kWh, 0.056 $kgCO_2$ equivalent per kWh for district heating average in Sweden [20], and 0.137 $kgCO_2$ equivalent per kWh for district heating in Malmö region [21]. The emissions factors used for district heating is specific for the location, and not a generic data. By multiplying the emission factors for the different energy sources with the energy demand, the annual carbon impact from energy use can be estimated. The emissions for different available energy mix at the EOS property in tonnes of CO_2 equivalent is presented in Fig. 16. The results shows that the annual operational emissions would account to 84.05 tonnes of CO_2 equivalent if the EOS community was powered with the

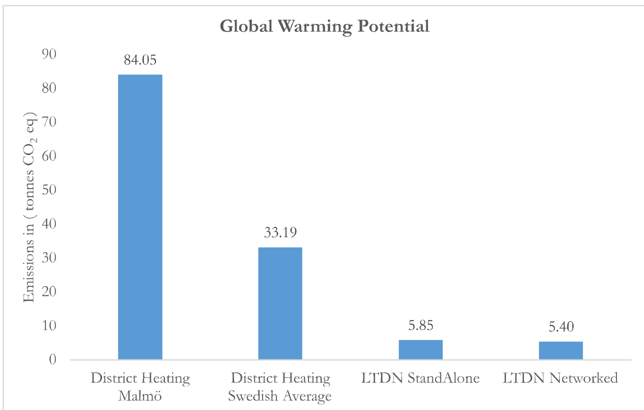

Fig. 16. Emissions related to available energy sources for the EOS community.

existing district heating grid of Malmö. In contrast, the annual emissions for the designed LTDN is only around 5.85 tonnes of CO_2 eq. when two substations operate as standalone entities and approximately 5.40 tonnes of CO_2 eq. when operated as a networked/sharing system.

There are two key takeaways from the presented bar chart. First, the emissions from the designed LTDN were only 7 % compared to using existing district heating grid in Malmö as energy source. This observation supports the claims of the decarbonization potential of a LTDN. Second, compared to the standalone operation of substations in a LTDN, approximately 8 % emissions can be further reduced if substations are coupled to share energy with each other which presents the added benefit of energy sharing in decarbonizing the heating and cooling sector. These figures will be put into context in following research where a complete LCA, including the building production, materials and components, will give a larger picture of the full differences between the two systems.

3.5. Limitations

The main limitation of this study is the absence of coupling between the HVAC distribution and energy transfer substation. The modelling of building side HVAC systems and substation thermal envelope was performed independent of this digital twin to identify the building heating and cooling demands. It is thus not possible to analyse actual thermal comfort scenario inside each thermal zone of substations through this model. Only, heat transferred to meet the total substation demands is evaluated in this study. Further, energy transfer in heat pump was modelled as a regression equation generated using the heat pump performance data from the manufacturer. Thus, the reported performance of heat pump may be subject to extrapolation errors in the operating temperature regions where manufacturer data was missing.

4. Conclusion and Recommendations

The study comprehensively investigated a practical design solution for a low temperature district heating and cooling system with an efficient control system to enable energy sharing between two substations. The results demonstrated that operating the substations as a network significantly improved the system performance. The seasonal coefficient of performance increased from 5.2 to 6.2 in substation 1 and from 3.3 to 3.4 in substation 3 highlighting the improved efficiency in a networked operation compared to their standalone operation. The small increment in SCOP for substation 3 was attributed to its operation for DHW production during energy sharing period. Additionally, the results further indicated a 14.1 % active energy reduction to operate the heat pumps in a networked operation highlighting its potential for energy savings.

Besides energy efficiency in terms of improved SCOP and energy savings, the study also identified benefits of energy sharing in form of load sharing between the substations with reportedly 50 MWh of thermal energy being exchanged with each other's borefield. The indicated energy sharing contributed to a reduced depletion rate of borefields extending their service/operational lifespan compared to their standalone operation. Moreover, emissions considering available energy sources for the Embassy of Sharing community's heating and cooling demand were analyzed. The result showed that emissions from the studied low temperature network is only 7 % of the emissions associated with the existing district heating network in the Malmö region. These findings emphasize the substantial environmental benefits and great potential to reduce emissions related to urban heating and cooling in general. Furthermore, the study shows the potential for sectoral coupling in the form of power to heat technology through the use of heat pumps. This can pave a pathway for storing electricity in the form of heat in borefields.

In overall, the study demonstrates significant benefits with energy sharing through a low temperature district network and reinforces its suitability to decarbonize the building heating and cooling. Future research will include advanced control strategies to utilize other waste heat, and renewable sources like solar thermal. This study can also be expanded to include the dynamic synchronization of energy sharing between more than two buildings. Cost and environmental impact assessment particularly considering the effect of borefield regeneration could be the potential future research directions.

CRediT authorship contribution statement

Nischal Chaulagain: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Erik Everbring:** Writing – review & editing, Validation, Supervision, Investigation, Formal analysis, Data curation, Conceptualization. **Ulla Janson:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. **Dennis Johansson:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Conceptualization.

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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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enbuild.2025.115963.

Data availability

Data will be made available on request.

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