Final report

1. Project details

Project title	KOHESYS - Køge Nord thermal energy system (pre-study)
File no.	64019-0548
Name of the funding scheme	EUDP
Project managing company / institution	Aalborg University, Department of the Built Environment
CVR number (central business register)	29102384
Project partners	Aalborg University (BUILD and ENERGY), Køge Municipality, PlanEnergi and VEKS
Submission date	24 November 2022

2. Summary

English

The main objective of the project KOHESYS was to conduct a pre-study to assess the technical and economic feasibility of an ambient-temperature district heating and cooling (DHC) system in the municipality of Køge.

During the project, an early-stage design of four different thermal network configurations was carried out. An economic feasibility of such four configurations was performed taking into consideration both investment and operational cost. The results showed in some cases rather similar system costs between the scenarios. However, changes in the chosen boundary conditions and some of the main assumptions have a large impact on which solution is preferable. When assuming a high cooling demand covered by a cold source available for free, the cold combined DHC system was seen to be economically preferable. If cooling was not considered, the warm district heating scenario showed lower total costs than the cold scenario. The two most economically feasible solutions were then selected for detailed energy analyses to calculate electric energy consumption and CO_2 emissions.

Results from simulations show that ambient-temperature DHC systems can lead to significant electric energy savings and CO_2 emissions reduction in comparison to conventional systems. In particular, electric energy savings and CO_2 emissions reduction are obtained when the Carnot efficiency of the decentralized heat pumps is higher than about 0.25-0.35, depending on the temperature level of the heat source.

Despite the potential electric energy savings at no extra cost, the lack of experimental knowledge, monitored data and case studies in Denmark, make the implementation of such systems too risky for stakeholders, especially for large-scale projects. The consortium expects to address these barriers in a new R&D project where a small-scale pilot site could be implemented.

Danish

Hovedformålet med KOHESYS-projektet var at udføre en forundersøgelse for at evaluere den tekniske og økonomiske gennemførlighed af et fjernvarme- og fjernkølesystem, der udnytter den omgivende temperatur (DHC-system), i Køge Kommune.

I løbet af projektet blev der udarbejdet et tidligt design af fire forskellige termiske netværkskonfigurationer. Den økonomiske gennemførlighed af disse fire konfigurationer blev undersøgt under hensyntagen til både investeringer og driftsmæssige udgifter. Resultaterne viser i nogle tilfælde ensartede samlede omkostninger når scenarier med koldt og varmt net sammenlignes. De valgte betingelser og antagelser viser at have stor betydning for hvilken løsning, der er mest rentabel. Antages et højt kølebehov, som kan levere gratis køling i scenariet for et koldt kombineret varme- og kølenet, bliver denne løsning mest rentabel. Hvis køling ikke inkluderes ses et varmt net at have lavere samlede omkostninger end et koldt. De to mest økonomisk gennemførlige løsninger blev derefter udvalgt med henblik på yderligere analyse til at beregne strømforbruget og CO_2 udledning.

Resultater fra simuleringerne viser, at sammenlignet med konventionelle systemer, kan DHC-systemer føre til signifikant strømbesparelser og CO_2 udledning reduktion med samme omkostninger. Strømbesparelser opnås især, når Carnot-effektiviteten af decentraliserede varmepumper er højere end omkring 0,25-0,35, afhængigt af varmekildens temperatur.

På trods af de potentielle strømbesparelser uden ekstra omkostninger gør manglen på eksperimentel viden, overvågede data og danske casestudier implementeringen af sådanne systemer for risikabel for interessenter, specielt ved store projekter.

Konsortiet forventer at afhjælpe disse hindringer i et nyt F&U-projekt, hvor et lille pilotområde kan blive etableret.

3. Project objectives

The project KOHESYS (pre-study) aimed to assess the technical and economic feasibility of a novel thermal energy system serving the new urban area of Køge Nord. The novelty of the system is its ability to provide simultaneous heating and cooling to buildings using the same piping network with water near ground temperature. Decentralized “prosumer” substations are installed at building (or cluster) level and they feature heat pumps, direct-cooling heat exchangers and circulation pumps. This system design allows each customer to not only draw, but also provide thermal energy to the network by rejecting low-grade waste heat from cooling and refrigeration processes. Such systems, which are referred to as “ambient-temperature networks”, “5th generation DHC systems" or “cold thermal networks", represent a promising technology towards the decarbonization of the heating and cooling sector in cities and communities thanks to their ability to exploit a multitude of renewable and waste heat sources.

In particular, this pre-study project aimed to:

- Determine different system configurations for the thermal energy network in Køge Nord based on criteria identified in terms of range of operation, best practices, and critical aspects.
- Develop detailed mathematical models of the thermal energy network to calculate primary energy use and CO_2 emissions.
- Assess the cost-effectiveness of such system in a Danish case study.

4. Project implementation

The project evolved almost as initially planned, but with a delay of 6 months. The delay was caused mainly by the need for more detailed techno-economic analyses. Traditional district heating systems in Denmark are based on well consolidated business models, however, ambient-temperature district energy systems rely on new paradigms (e.g., prosumer substations), which required further investigations. To accomplish this task, the consortium asked for a 6-month extension. No additional funding was required from EUDP.

In addition, the Covid-19 pandemic forced most of the meetings to be held online, hence reducing the networking opportunities and making it not possible to organize some of the in-person activities that were initially planned, such as a technical tour of an ambient-temperature DHC system in Switzerland. The risks associated with the project implementation were low, as it was mainly based on energy calculations and economic analyses. Thanks to the 6-months extension, all milestones and objectives were achieved.

5. Project results

5.1 Overview of Køge Nord urban development

Home to an important harbor, large industrial companies, agriculture, Scandinavian Transport Center and the busiest highway in Denmark, the municipality of Køge has a CO_2 emission that is above the national average. Nonetheless, Køge has adopted a very ambitious Climate Action Plan which includes 40 specific actions, that will help reduce the greenhouse gas emissions, both within the municipality border and outside, as the municipality also addresses the question of scope 3 emissions from consumption [1]. When the municipality of Køge aims to become climate neutral in 2050, it means reducing their global climate footprint to zero. This also includes phasing out the use of biomass in the production of heat and power. The green transition path of the municipality will be based on the principles of circular economy and the Doughnut Model, which means that social needs shall be fulfilled without exceeding the so-called planetary boundaries.

In the municipality of Køge there are plans for several new urban areas. One of them is Køge Nord. In the Master Plan for the development of Køge Nord, it is described how the aim is to form a new urban area, which fulfils the highest standards of sustainability through a DGNB certification [2].

To become environmentally sustainable, the new urban area must have a low energy consumption and be based on 100% renewable energy. Through a project proposal from VEKS in 2011, the area in Køge Nord has been determined as a district heating area [3] [4]. As noted in the climate action plan of Køge, district heating is the best option if we want to have a coherent and efficient energy system. Especially in an area as Køge Nord, where we have different sources of surplus heat from nearby industries, the district heating system shows great advantages over individual solutions.

However, it is crucial that we rethink how future district heating systems can become even more sustainable. Due to climate change, we investigate a future, where the summer temperatures rise several degrees Celsius, with an increased risk of heat waves, which means that many office buildings and dwellings may need cooling systems. Moreover, it is also well known that there is a close link between energy consumption and perception of comfort at home [5]. Increasing expectations of thermal comfort can therefore also lead to a higher demand for cooling indoor environments. The question is therefore if it makes sense to develop a combined heating and cooling system, and how such a system should be designed to lower the overall climate footprint.

5.2 Heat supply scenarios

The following section is based on the KOHESYS deliverable D2.1 and D3.1 report in which the descriptions can be found together with additional information about the scenarios and analyses.

After defining the boundary conditions of the study, possible heat supply scenarios were described and discussed both internally among project partners and externally with relevant stakeholders. The development of these has been a main task in the KOHESYS project. The designs have therefore developed during the process after discussions in the project group, presentation at a conference in September 2021 and presentation and discussion at a workshop in November 2021. Ultimately, the following main scenarios were considered relevant for further investigation in the study:

1. **Reference:** Warm combined heating and cooling - warm and cold network:
   The area is supplied by separate district heating and district cooling networks. Both heating and cooling can be provided from the same central heat pump, which thereby needs to be able to deliver a heating supply temperature that is high enough to cover heating demands directly and cooling supply temperatures that are low enough to cover the cooling demands directly. However, the dwellings are cooled by individual air conditioners.

2. **Warm loop:** Warm combined heating and cooling – combined network (55/30):
   Network temperatures are high enough to deliver heat directly through a heat exchanger. The temperatures are too high to be utilized for direct cooling, and therefore cooling is provided through chillers. The chillers can be connected to the district heating network, to make use of the surplus heat from the cooling process in the network.

3. **Cold loop:** Cold combined heating and cooling (15/10):
   Network temperatures are low enough to deliver free cooling directly to the buildings. The temperatures are too low to deliver heating for domestic hot water and space heating, and therefore a heat pump is utilized to boost the temperatures. The heat pump can use the cold network as a source.

4. **Cold network:** Cold combined heating and cooling (15/10-20):
   Network temperatures are low enough to deliver free cooling directly to the buildings but heating for both space heating and domestic hot water is provided through individual heat pumps located in each building. The network has a traditional tree structure. Surplus heat from cooling cannot be recovered in the system.

Each of the network scenarios are presented in the sections below. Note that bidirectional district heating and cooling systems have not been investigated in this project. The reason is that recent studies pointed out that pump-to-pump interactions present a control challenge in bidirectional networks. Problems occur when prosumers of different sizes act in the same network. In this case, prosumers with large circulation pumps strongly affect the mass flow rate through prosumers with small circulation pumps [6]. It is worth mentioning that, as theoretically shown in literature [7], the overall energy efficiency of bidirectional and unidirectional ambient-temperature (or cold) networks is similar.

Reference

The reference situation is a traditional tree structure network that is operated with low-temperature district heating. This scenario provides a reference for the cold combined heating and cooling scenarios and is thereby considered the most traditional solution to combined heating and cooling supply of an area. The network layout is illustrated in Figure 1. It is seen how the district cooling network only stretches to supply the office buildings whereas individual chillers (not visible on the illustration) will be required to cover any cooling demand in the dwellings.

At the beginning of the project, it was suggested that office buildings were connected to the network through a chiller that would make it possible to provide cooling to the office buildings and reject surplus heat into the network through a return-to-supply connection. Therefore, office buildings were located at the beginning of the supply line/end of the return line. This location ensures that pipe sizes are large enough to deliver the surplus heat into the area and that the return flow is large enough to be circulated back into the supply pipe after reheating in the prosumer station. However, during the project workshop, the idea of district cooling was discussed as an alternative solution for the office buildings that are located rather closely in one end of the building area. This idea was therefore chosen for the final scenario.

All dwelling units are assumed to have individual air conditioners installed for cooling purposes. Customer installations for heating are assumed to be indirect with heat exchangers for domestic hot water preparation. In apartment buildings, each apartment is assumed to have their own district heating substation with a domestic hot water heat exchanger.

Benefits of this type of substation have been described in several studies and include reduced risk of Legionella and the lowest possible temperatures while still providing heat for both space heating and domestic hot water [8]. Other benefits are reduced pipe lengths in buildings [9] and simplified individual heat accounting. On the other hand, drawbacks are increased substation costs, larger number of substations to maintain (substations should have individual wireless data collection and be accessible from the stairway for easy access of technicians [10], and possible need for a third return circulation pipe in the district heating network to avoid high return temperatures due to district heating circulation in the building [8]. Simple sketches of the customer installations for the reference scenario are seen in Figure 2.

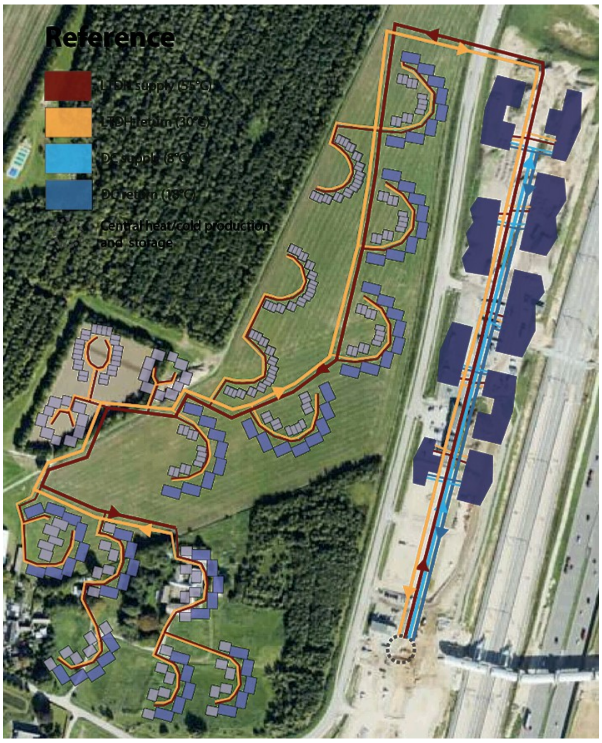

Figure 1: Layout of the low-temperature district heating branch network that is considered in the reference scenario.

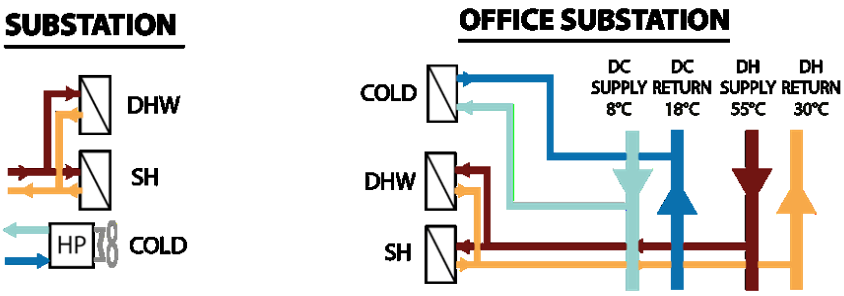

Figure 2: Simple sketch of customer installations for the reference situation. Cooling with individual air conditioners is assumed in the dwellings and surplus heat from the office buildings is assumed to be delivered into the district heating system when possible, by use of a central heat pump that delivers both district heating and cooling.

The benefits of the reference scenario include:

- Simple and well-known hydraulic (tree) network structure
- Low heat-losses due to low temperatures
- Simple and cheap customer substations
- Central heating station:
    - Possible mix of heat sources increases security of supply
    - Simultaneity in the network reduces overall peak demands
    - Economy of scale for heat production plants
    - Flexibility in heat production is possible through central heat storage tank

The reference case is described for each of the three relevant heat supply options for the area:

I. heat provided by VEKS from the existing heat network nearby,

II. heat provided from a central heat pump based on 30°C excess heat at the data center nearby,

III. heat provided from a central heat pump based on 15°C excess heat from industry wastewater.

For the heat pump scenarios (II and III above), the central heat production is also assumed to consist of an electric boiler and a hot water storage tank. The electric boiler serves as peak load production and can provide back-up to the heat pump in the system in case it is necessary. The hot water storage tank provides daily load balancing. This makes the electricity consumption of the heat pump more flexible and improves the balancing between heat demands and available surplus heat from district cooling in the summer.

Warm loop

The general idea of the warm and the cold loop, is to be able to deliver either heating or cooling directly. Thereby one of the two could be delivered without additional local electricity demands or extra installations of heat pumps and local hot and cold storages. In the warm loop, the idea is therefore that heating is provided to the customers directly from the network, while cooling is delivered by a chiller. The chiller makes it possible to recover part of the surplus heat from comfort cooling and supply it into the network for heating purposes.

Two main concerns led to the current layout where the network is based on a loop and dwellings are connected to small cooling clusters: First, cooling clusters are introduced to avoid a situation where each building was equipped with an expensive local chiller for cooling purposes, since expensive building substations were previously found to be a main reason for poor economic feasibility of cold district heating systems. Second, a loop structure is applied to avoid hydraulic issues in case too many buildings would function as prosumers with additional return-to-supply connections and to avoid that the whole network was built as a large loop, which would result in a long pipeline. The suggested layout is visualized in Figure 3.

Customer installations would in this case be like those of the traditional low-temperature district heating network since the end of the heating network is constructed in the same way. Similarly, all the central heat sources considered in the reference could provide heating to the warm loop system.

For cooling purposes, it was assumed that a local heat pump and chiller would deliver cooling to each building area, through a local cold network. The chiller would be connected to the main loop through a return-to-supply connection, which would make it possible to feed surplus heat from comfort cooling into the heat network. To ensure some balancing between heating and cooling demands, each chiller is connected to a heat storage tank.

Inside the buildings it is assumed that the only additional investment is a separate heat exchanger for the connection to the local cooling network. It is assumed that typical building installations in new buildings, such as floor heating and ventilation systems would make it possible to deliver the cooling into the dwellings area. A simple sketch of the customer installations and the local chiller stations is given in Figure 4.

The scenario shows some disadvantages. First, the amount of surplus heat available from comfort cooling in the summer exceeded the heat demands. Therefore, the cluster chillers will have to be larger than what is necessary from a heating point of view. To both provide cooling in the local building clusters, and provide heating based on a central excess heat source at relatively low temperature, such as the data center, a “double investment” in heat pumps/chillers is required (since the excess heat source would need to be boosted in temperature before feeding into the 55°C network). Essentially, if a large heat pump/chiller is installed in the local cluster to make use of some of the surplus heat from cooling in the summer, the same heat pump could potentially be utilized for heat production in the winter, thus making the main network redundant and representing rather an “standalone cluster solution”.

A second disadvantage is that a significant amount of surplus heat needs to be rejected to the ambient during the summer as it is not directly usable for the relatively small domestic hot water heat demand. If this is done at a central cooling station, surplus heat from cooling must be boosted to meet the temperature that is required in the network warm pipe. Thereby electricity is spent raising the temperature to get rid of the surplus heat from the chiller when it is ejected into the network. This electricity consumption will be a waste in case the heat is not made useful, and the surplus heat is simply rejected at a central location. Therefore, the scenario requires detailed control of the heat production in the summer, and each local cluster heat pump should also include the possibility of simply ejecting the surplus heat into the air locally.

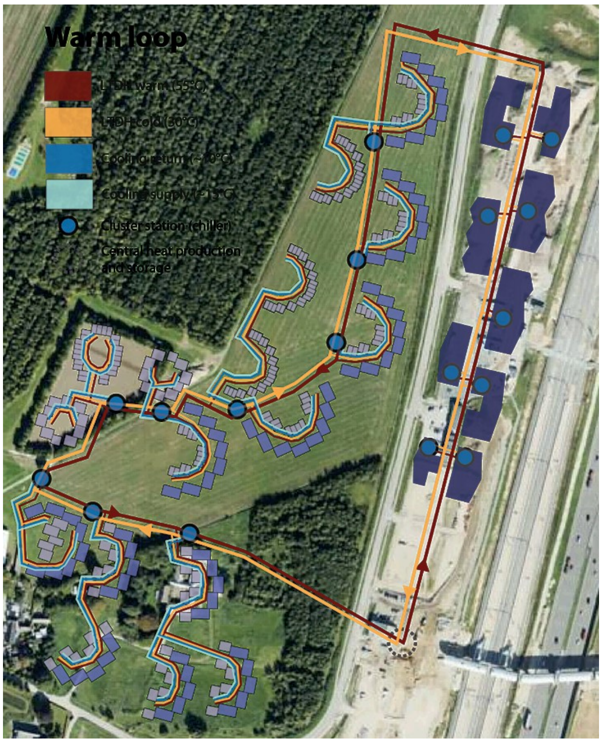

Figure 3: Layout of the warm loop network.

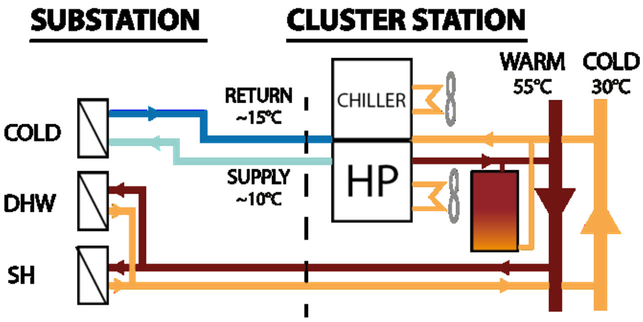

Figure 4: Simple sketch of customer installations and cluster stations in the warm loop scenario.

<u>Cold loop</u>

The cold loop scenario consists of a main loop that transports excess heat at around 15°C from the wastewater source to several cluster stations, from where heating and cooling is provided to a smaller area of dwellings. Opposite to the warm loop, this solution makes it possible to deliver cooling directly from the network, while heat delivery requires a heat pump.

The cold main loop is assumed to consist of uninsulated plastic pipes. The supply temperature is assumed to be around 15°C whereas the return temperature is assumed to be around 10°C. Small scale district heating and district cooling networks are designed to supply heating and cooling from the cluster heat pump to each of the buildings in the clusters.

The idea behind the layout is to use heat pumps that provide low-temperature district heating to smaller areas, instead of individual heat pumps to avoid high costs for customer substations. The loop design was once again chosen to avoid hydraulic issues while cluster stations were designed as prosumers. The heat pump in the cluster is connected to the warm line of the loop to obtain the highest possible COP for the heat production. At the same time, the cooling in the clusters is provided from the cold flow, which ensures that temperatures are low enough for direct cooling and that surplus heat from cooling is recovered in the network.

Several pumps are needed in the network to decouple clusters from the main loop pressure. The investment cost is assumed part of the cluster station costs and extra electricity consumption due to these pumps are neglected in this study. The network layout is illustrated in Figure 5.

Typical heating installations are similar to the installations in the low-temperature district heating reference. Cooling in dwellings is assumed to be delivered through existing building installations for heating and ventilation. The only additional investment for this purpose is a central heat exchanger for cooling in each dwelling or apartment and each office.

Heat is provided to the networks from local heat pumps in the cluster stations. The heat pumps use the cold loop as a heat source. The cluster heat pumps are used to balance the heating and cooling demands, which means that they are also operated in the summer to provide cooling and get rid of excess heat from comfort cooling. In order to provide balancing in the network, a heat storage tank is installed in each chiller station. A simple sketch of the customer installations for the reference scenario are seen in Figure 6. Each office building is considered a small cluster station.

One issue of this solution concerns the security of supply. The cluster stations are assumed to consist of a heat pump that delivers the entire heat demand of the area. The heat pumps are in the range of traditional apartment building heat pumps, due to the small areas connected and the limited heat demand in the low-energy buildings. The heat demand cannot be covered from the network without the cluster stations. This means that the clusters have limited security of supply. Furthermore, the accumulated heat pump capacity is larger than in the reference, and thereby the investments are higher. Sizes are further increased if the building clusters are small and the full benefit of the simultaneity in the networks is not obtained. Also, flexibility in electricity demand is reduced because the individual storages are smaller.

Figure 5: Layout of cold loop scenario

Another disadvantage is the fact that the temperature of the available heat source has a large impact on the system. If temperatures become too high, it is not possible to deliver direct cooling. Furthermore, if the return water from heating is utilized for cooling this also means that there is a lack of cooling capacity in case the cooling demand is higher than the heating demand. This would lead to the requirement of additional chiller capacity (in clusters or centralized) although the system was intended to provide direct cooling without the need of local chillers and their associated electricity consumption.

If the temperature becomes too low, it is relevant to ensure that the heating process in the heat pump will not create a risk of freezing in the pipes, as it is assumed that the pipes hold traditional water and not glycol.

In respect to the available source temperatures, it becomes clear that this type of network will set strict requirements to the available building installations for cooling. To make use of direct cooling at a high temperature, it is necessary that the building installations can provide this service. In other words, when no chiller is installed and direct cooling is utilized, the system is completely dependent on the source temperatures. In general, an essential draw-back of the solution is therefore the dependence on very limited temperature swings in the heat source and in the network, which causes cold networks to often be based on geothermal sources or water sources that provide constant temperatures within a narrow span.

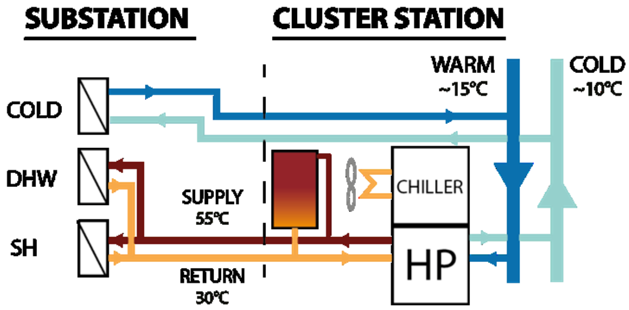

Figure 6: Simple sketch of cluster heat pump station (right end) and building substation (left end) in cold loop scenario.

<u>Cold network</u>

The cold network is built up with a traditional tree structure, but pipes are assumed to be uninsulated PEX pipes, and the supply temperature is 10-15°C. The supply line serves as both heating and cooling supply. When supplying heating, the return line temperature is lower than the supply. Correspondingly, when supplying cooling, the return line temperature is higher than the supply line. It is assumed that cooling can be delivered directly from the supply pipe, while heating is provided with individual heat pumps in each building that use the cold network as a heat source. An illustration of the network is given in Figure 7.

Figure 7: Layout of the cold network

Due to the structure of the tree network, it is not possible to recover surplus heat from cooling (unless it is possible to make use of an ATES/BTES system, which is not included in this study because the buildings are in a drinking water zone. Instead, the return pipe will have a higher temperature than the supply pipe in the summer when cooling is utilized. In the winter, the return temperature will be lower than the supply, as the heat pumps in each dwelling draws heat from the pipe network to cover the heat demands in the buildings.

In this scenario, there are strict limits to the supply temperature, and thereby the temperature of the excess heat source. The temperature must be low enough to allow direct cooling in the buildings. In the winter it must be high enough to avoid freezing when heat is removed from the network in the heat pumps in the buildings. If network temperatures are expected to be close to freezing point of water, it will be necessary to use a glycol-water mix as district heating water, which would increase the investment and operation costs.

The customer stations in the scenario are assumed to consist of heat pumps. A simple sketch of the sub-stations is seen in Figure 8.

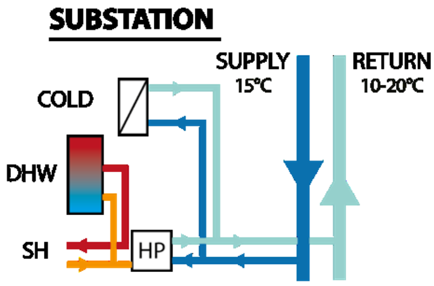

Figure 8: Simple sketch of customer substation in cold network

It is assumed that each building has a central heat pump, which means that for apartment buildings there is one central heat pump in the building and not individual heat pumps in each flat. The heat pumps are connected to a domestic hot water tank, to avoid that heat pumps need to be dimensioned for peak domestic hot water demands and to avoid on/off operation of the heat pump. This means that there is also domestic hot water circulation in the apartment buildings. Costs and heat losses due to circulation pipes and necessary individual heat meters to split costs for heating between occupants are neglected.

5.3 Economic comparison of scenarios

Figure 9 shows the comparison of the total annualized costs of each of the investigated scenarios. It is seen how the total annual costs for the two reference cases using wastewater or data center heat are relatively similar though the higher temperature heat source of the data center improves the feasibility slightly. The scenarios involving the cluster solutions are seen to be somewhat more expensive – especially due to the higher costs for heat pump/chiller investments.

The cold network total cost is similar to the reference cases indicating that this concept could be realized at similar costs as the more traditional reference provided that the assumptions can be applied in practice. The lower temperature of the network makes it possible to utilize low-grade heat sources which could in practice reserve higher grade heat sources for other purposes. Such externalities have not been quantified in this feasibility study.

It should be noted that the results vary significantly when changes are made to the main assumptions and conditions applied in the analysis. Therefore, a main conclusion of the analysis is that the economic feasibility of the various scenarios depends largely on local conditions and boundary conditions. While the above figure shows that the cold network is economically favorable, the reference scenario for example becomes more feasible if cooling is not assumed to be delivered by the network.

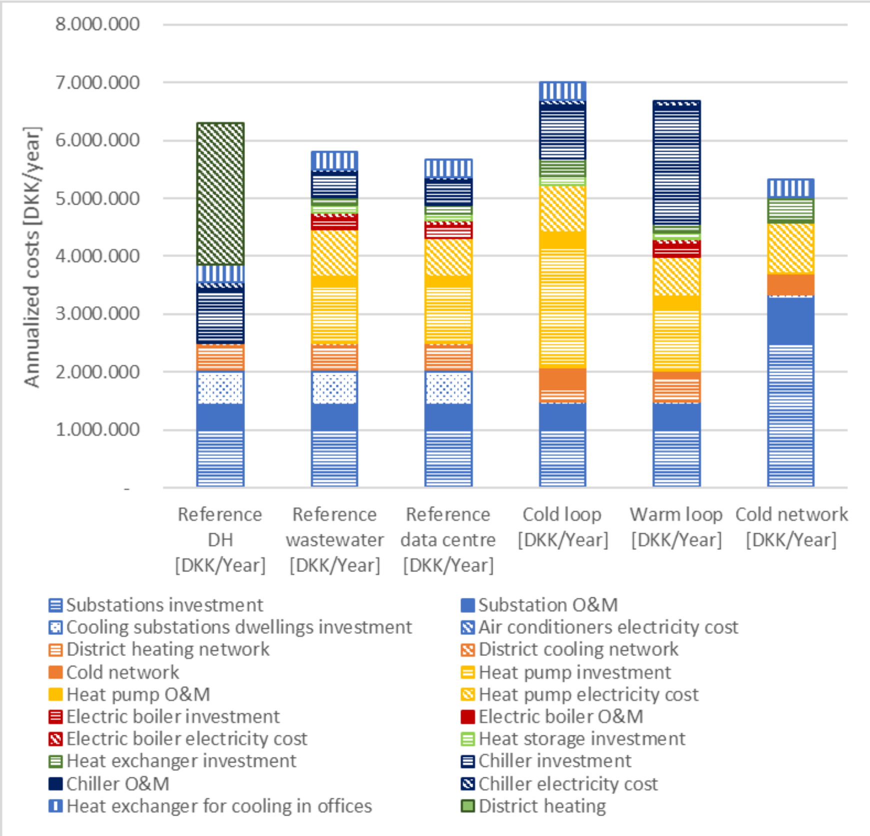

Figure 9: Total annualized costs of each of the investigated scenarios

5.4 Detailed energy simulations

In the previous section, different system configurations have been presented, together with the related cost. In this section, the two most economically feasible solutions, which are the reference and cold network, have been further analyzed to calculate the annual electric energy consumption and CO_2 emissions. Dynamic energy simulation models were built using the open-source, equation-based and object-oriented Modelica language. A graphical and hierarchical modelling approach was adopted, enabling a well-structured modeling process that supported system models with different levels of detail in the sub-models. Basic models for transport of heat and fluids, such as pipes, valves, heat exchangers and heat pumps were retrieved from the Modelica Buildings library [11], while more complex models, such as substations and data centers were developed in-house during the project.

<u>Heating and cooling demand</u>

To calculate hourly heating and cooling demand of the urban area, four representative building models were developed: terraced house (TH), multi-family house (MFH), block apartments (BA) and office buildings (OB). Since only little information was available about the characteristics of the buildings, most of the input parameters for the models were assumed based on Danish Building Regulation and modeler's assumptions. These parameters are shown in Table 1. Note that the three residential building typologies (TH, MFH and BA) only differ in terms of geometry and boundary conditions (e.g., terraced houses have some adiabatic walls). Cooling demand in residential buildings was not considered. Figure 10 illustrates the geometries of the four building typologies, while Figure 11 shows the annual heating and cooling total load profiles.

Table 1: Input parameters for typical building typologies

Parameter	**Residential (TH, MFH, BA)**	**Office (OB)**
Total floor area	80,000 m^2	50,000 m^2
U-values (walls / roof / floor / windows)	0.3 / 0.2 / 0.2 / 1.1 W/m^{2}K	0.3 / 0.2 / 0.2 / 1.1 W/m^{2}K
Internal heat gains	5 W/m^2 (weekly schedule)	25 W/m^2 (weekly schedule)
Window-to-wall ratio	0.25	0.4
DHW Load	4 W/m^2 (constant profile)	1.5 W/m^2 (constant profile)
Air change per hour	0.4 h^{-1}	1.25 h^{-1}
Heating set-point	20°C	21°C
Cooling set-point	No cooling	24°C
Heating system	Floor heating (supply at 35°C)	Active beams (supply at 40°C)
Cooling system	No system	Active beams (supply at 18°C)
DHW system	Supply at 55°C	Supply at 55°C

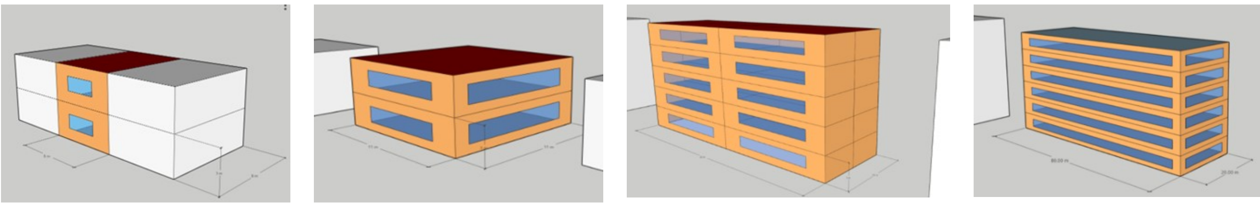

Figure 10: Geometries of the building energy models. From left to right: terraced house, multi-family house, block apartments and office building

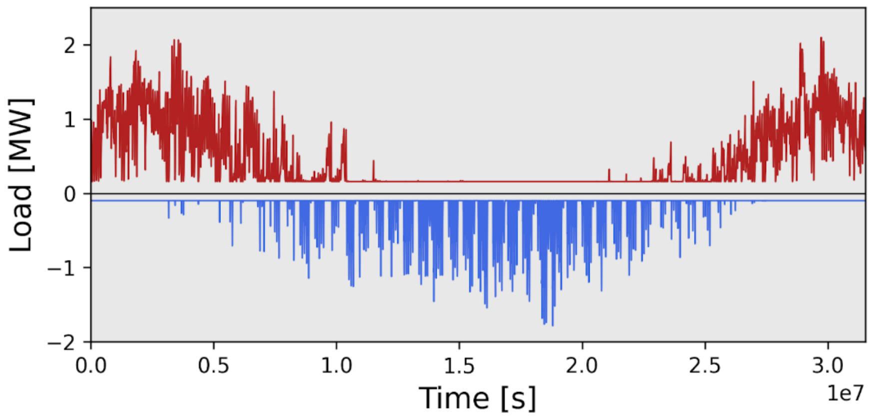

Figure 11: Simulated total hourly heating and cooling load profiles of the urban area

<u>District system layouts and modeling</u>

As mentioned before, the reference and the cold district networks were selected for further analyses. Detailed energy models including production, distribution and substations units were modeled. Annual simulations were performed to calculate the electric energy consumptions associated with the operation of such systems.

The schematic layout of the reference system is illustrated in Fig. 12, which is substantially the same as Fig. 1. The plant consists of a large-scale heat pump that makes use of waste heat at 15°C (industrial facility) to deliver supply water at 65°C in the network. The heat pump model has an idealized internal control that causes the heat pump to track the set point of the water temperature leaving the condenser. A COP of 3.9 was assumed at nominal conditions [12].

The pipes are dimensioned using a pressure drop per pipe length of 150 Pa/m and they are insulated according to the insulation class "series 2". Substations consist of a heat exchanger that provides direct heating to meet the space heating and domestic hot water demand. A temperature difference of 25 K was assumed between supply and return. Cooling is provided by a district cooling network, which makes use of the source at 15°C. This means that, assuming the use of high-temperature cooling systems in the office buildings, no electricity is required for cooling purposes.

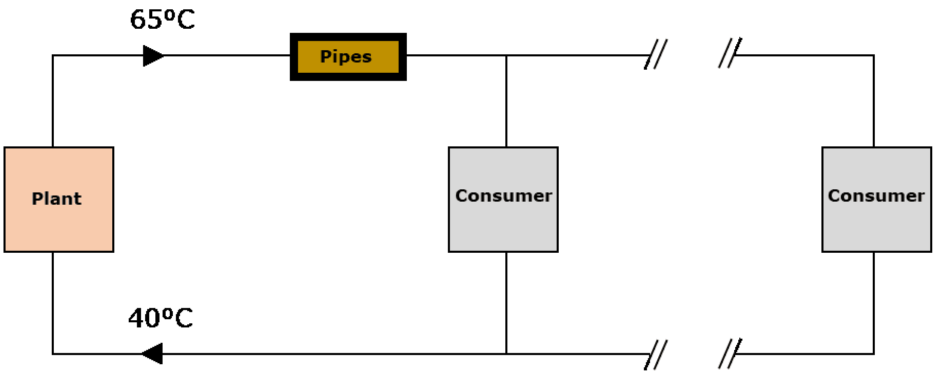

Figure 12: Layout of the reference system

The schematic layout of the cold network is illustrated in Fig. 13. The plant consists of a heat exchanger connected to the industrial facility, which keeps the supply water temperature in the network at 15°C.
Pipes were dimensioned as mentioned before, using a 150 Pa/m pressure drop per pipe length. In this case, the pipes are un-insulated. Prosumer substations consist of three components:

- A decentralized heat pump for space heating
- A decentralized heat pump for domestic hot water
- A heat exchanger for direct cooling (only in offices)

A temperature difference of 4 K was assumed at the substations for both heating and cooling.

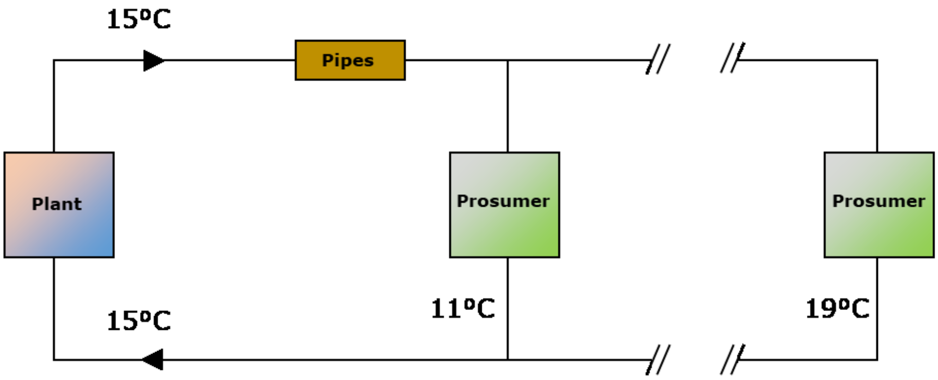

Figure 13: Layout of the cold network

To reduce modeling efforts and computational time, the buildings were aggregated in five clusters. The Modelica model of the cold network is shown in Fig. 14.

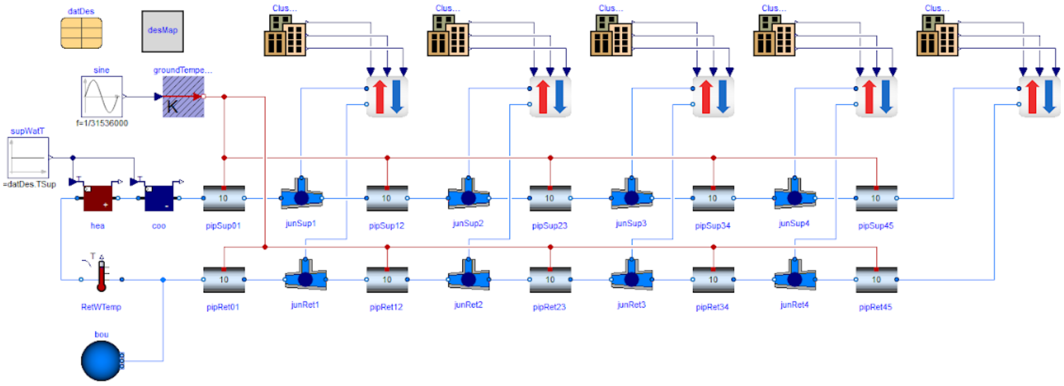

Figure 14: Modelica model of the cold network

Results

A sensitivity analysis was carried out to explore the influence of the Carnot efficiency of the decentralized heat pumps on the electricity energy consumption of the cold network in comparison to the reference network. Four variations were considered for the Carnot efficiency: 0.2, 0.3, 0.4 and 0.5.

Fig. 15 shows the annual electric energy consumption of the reference system in comparison to the four variations of the cold network. Simulation results show that the value of the Carnot efficiency has a significant influence on the potential electric energy savings. The cold network is more efficient than the reference system when the Carnot efficiency of the decentralized heat pumps is higher than about 0.35. This value corresponds to a COP of 4.3 for space heating (temperature lift of about 25 K) and a COP of 2.6 for domestic hot water (temperature lift of about 45 K). Annual electricity savings of 31% can be achieved in comparison to the reference system with a Carnot efficiency of 0.5.

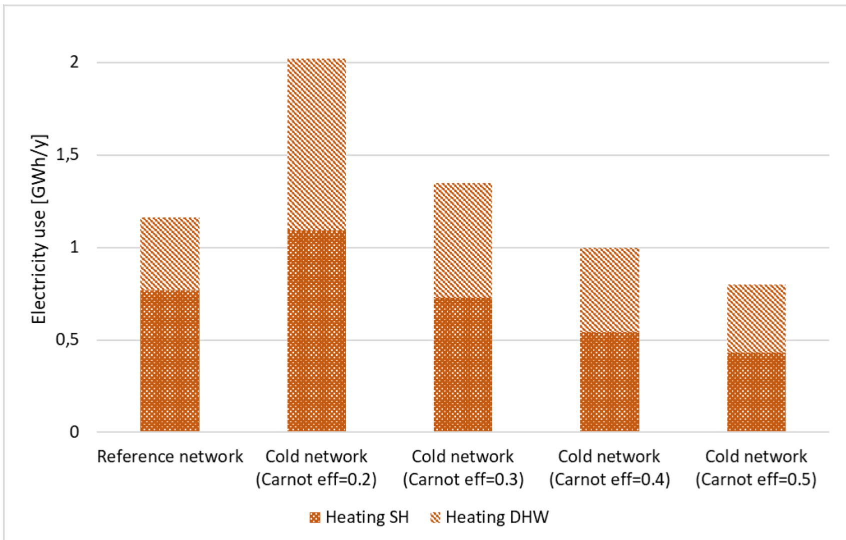

Figure 15: Electric energy consumption (waste heat at 15°C)

To analyze the potential effect of using waste heat produced by a data center, new models have been developed, and a new round of simulation was carried out. It was assumed that the data center could provide waste heat at 30°C. Regarding the reference system, the only difference is related to the higher COP of the large, centralized heat pump, which now is assumed to be 4.5 [12]. For the cold network, a new control strategy was developed. When free cooling of office buildings is possible (outdoor air temperature below 14°C), the supply water temperature in the network is set at 30°C to maximize the COP of decentralized heat pumps. When the outdoor air temperature is warmer than 14°C, the supply water temperature in the network is set at 15°C to provide direct cooling to office buildings. The results of the energy simulations are shown in Fig. 16. As expected, the electricity energy use is lower than in the previous case for both systems. In this case, the cold network is more efficient than the reference system when the Carnot efficiency of the decentralized heat pumps is higher than about 0.25. This value corresponds to a COP of 3.1 for space heating (temperature lift of about 25 K) and a COP of 1.8 for domestic hot water (temperature lift of about 45 K). Annual electricity savings of 53% can be achieved in comparison to the reference system with a Carnot efficiency of 0.5.

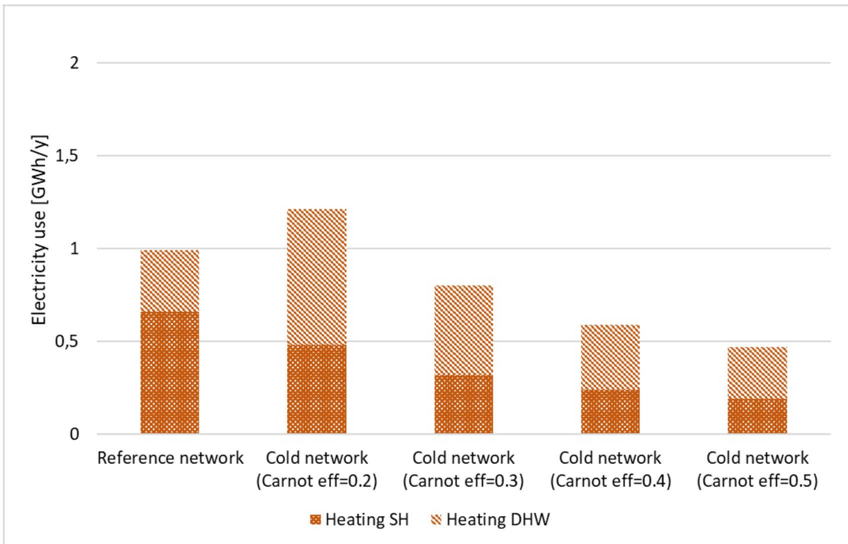

Figure 16: Electric energy consumption (waste heat at 30°C)

CO_2 emissions can be calculated using a fixed factor that represents the CO_2 emissions associated with one kWh of electric energy. Table 2 shows the CO_2 emissions of the different scenarios using a factor of 0.135 kgCO_2/KWh [13].

Table 2: CO_2 emissions of the different scenarios (values are in tCO_2)

	Reference	Cold Network (Carn. eff = 0.2)	Cold Network (Carn. eff = 0.3)	Cold Network (Carn. eff = 0.4)	Cold Network (Carn. eff = 0.5)
Industry wastewater	157	273	182	135	108
Data Centre	134	163	108	80	63

5.4 Availability of heat pump technologies

The used heat pump technologies should be implemented at different scales and operational settings. Mass produced heat pumps will generally have significantly lower cost than tailored solutions. This favors small scale systems such as heat pumps that are commercially available for individual domestic heat pump systems in heating ranges of 1-10kW [14]. Large-scale centralized heat pumps must be designed for their specific purpose, but are on the other hand favored by the economy of scale.

<u>Compressor types and dedicated compressors for low temperature lift operation</u>

Fundamentally, the components of the heat pumps must be adapted to the operational conditions, which particularly affect the choice of compressors and other flow components such as valves in the system. An overview of compressor technologies relative to the mass flow of refrigerant scaling proportionally with the system size, and the pressure ratio over the compressors are illustrated in Fig. 17.

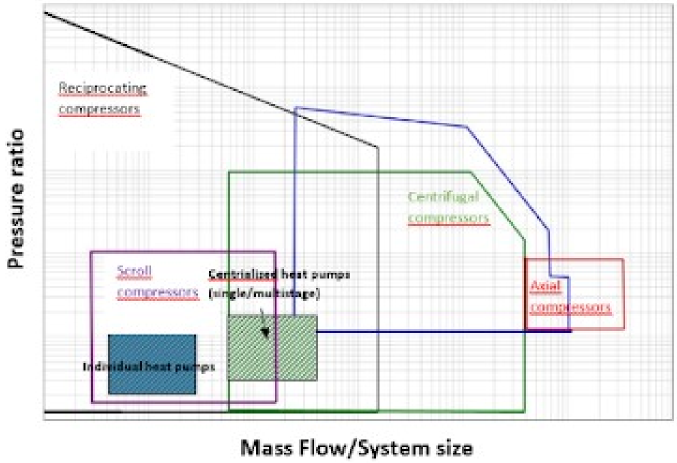

Figure 17: Overview of compressor technologies

For the individual heat pumps, commercial reciprocating compressors and scroll compressors will be the preferred choice if the temperature lift over the compressor is typically higher than 20-30K. Scroll compressors have a more expensive design, but offer higher volumetric efficiencies. However, at lower temperature lifts, current commercial compressors will operate in off-design leading to lower isentropic and volumetric efficiencies and slightly better partial-load operation performance wise. This will increase the operational cost of the systems, lower the heat pump COP, and could also possibly affect the lifetime of the components.

In the case of larger scale centralized systems, centrifugal compressors can be used in single stage systems and at higher flow the problem with operation at low temperature lift is less pronounced. However, often such large-scale heat pumps consist of multiple heat pumps coupled in series to obtain a better operational performance at partial load and switch off heat pumps depending on seasonal weather variations. A such system is illustrated in Fig. 18 [15].

In these cases, reciprocating compressors will likely be preferred used from an economical perspective due to lower investment cost, and there is a technological gap for such compressors at low temperature lift operation (i.e., a temperature difference below 20K). Prototype compressor technologies for low temperature lift based on both the reciprocal and centrifugal compressor technologies have been presented in the scientific literature, but they are not commercially available yet. [16] investigated two concepts for low temperature lift compression based on these two principles and their results are summarized in Fig. 19.

The tested low-temperature lift compressors and the traditional reciprocating reference compressor in this study could operate corresponding to heating rates of 9-20kW. The results demonstrate that significantly higher COPs could be reached with development dedicated compressor technologies for these applications. In the case of the low lift centrifugal compressors, the study demonstrated Carnot-efficiencies consistently above 60% in the entire operational range where the Carnot-efficiency of the traditional reciprocating compressor was generally below 45%. For the dedicated low-temperature lift reciprocating compressor, the Carnot efficiency was generally 5-10% higher than the traditional design.

This indicates a great potential for the development of compressor technologies specifically suited for the low temperature lift applications could greatly improve not only the system performance but also lower the operational costs of the systems. In realistic operational settings, considering the temperature differences between evaporator and heat source and condenser and heat sink as well as auxiliary losses, seasonal COPs could roughly rise from 6 to 9 in these applications.

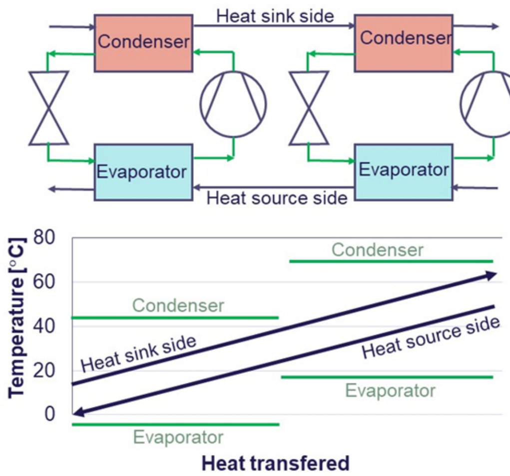

Figure 18: Diagram representing multiple heat pumps connected in series

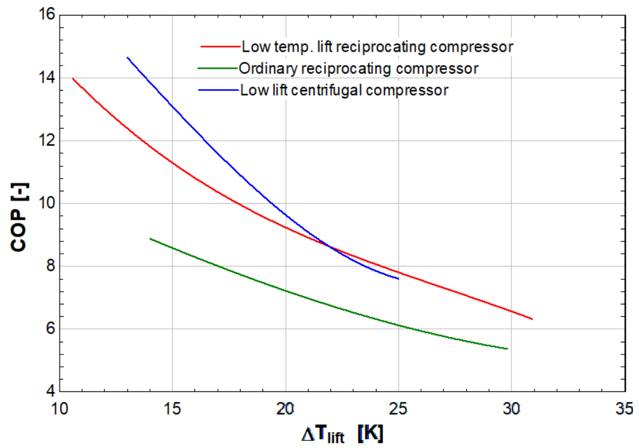

Figure 19: Concepts for low temperature lift compressors

<u>Expansion valves</u>

Another thing required to reach even lower temperature lift operation is the fact that the expansion valve must be able to have pressure losses adapted to the operational conditions as well. If the pressure loss in the valve at open conditions exceeds the difference between the condensation and evaporation pressure (considering the pressure losses in the heat exchangers), as illustrated in Fig. 20 [16], the temperature lift will be higher than the required and the advantages of low-temperature lift operation would not be possible. Thus, the system must be designed to avoid such mismatches involving an appropriate design of both the compressor but also the latent heat exchangers and the valve.

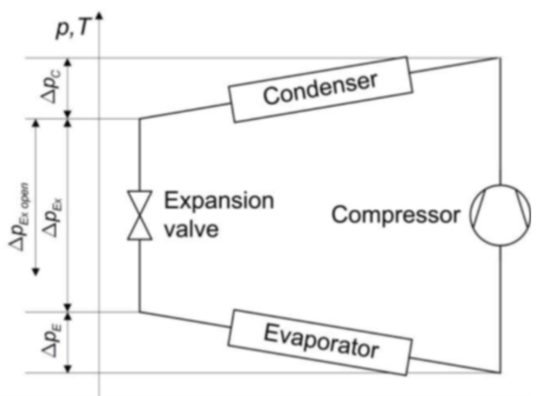

Figure 20: Pressure losses in heat pump

5.6 Dissemination activities

The following dissemination activities were carried out:

- Creation of a website
- Conference abstract and oral presentation
- Workshop

Website

The website of the project KOHESYS was created shortly after the project began and it includes basic information about objectives, partners, and meetings. The website is available at https://www.kohesys.dk/

Conference abstract and oral presentation

A conference abstract was prepared by some of the project participants, and it was submitted to the 7th International Conference on Smart Energy Systems, which was held in Copenhagen in September 2021. The title of the abstract is "Combined district heating and cooling – which solutions are available and are they applicable in a Danish context?" and it was orally presented at the conference by Dorte Skaarup Østergaard. The abstract is attached as an appendix.

Workshop in Køge about the feasibility of a 5GDHC system in Denmark

On the 18th of November 2021 the KOHESYS project united the country's foremost experts in district heating planning for a workshop, which helped shed light on the different uncertainties and barriers that may hinder a further development of 5GDHC in Denmark. The discussion at the workshop took point of departure in the different scenarios for heating and cooling of the area, that the project consortia agreed upon. The pros and cons are summed up in the matrix in appendices. In addition to the important points in the matrix, the participants at the workshop also agreed on the following points:

- The overall conclusion from the workshop was that it is very context specific whether you should go with one solution or another. It is difficult to generalize. For Køge Nord it seems that the best option would be to go with the reference scenario.
- If we have influence on the buildings, the need for cooling will be lower as new buildings should be designed so there is no need for extra cooling.
- For new areas outside the existing district heating network, where we have surplus heat available, the idea with a cold loop seems more likely, and it is something that the municipality of Køge will investigate more with hopes of implementing such a solution.

In addition to the three items previously mentioned, a scientific Journal article will be published next year. The article will illustrate the energy models developed within the project and the simulation results.

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6. Utilisation of project results

This project was a feasibility study, and therefore the development of technology prototypes and commercial products was not among the objectives. Still, the knowledge that has been generated over the past two years is expected to assist towards the deployment of ambient-temperature DHC systems in Denmark.

Even though the energy and economic calculations have shown that ambient-temperature DHC systems can lead to significant CO_2 emissions reduction and similar annualized costs compared to conventional DH systems, the overall risks to implement such systems in large scale are still considered high by stakeholders in the DH sector. This is mainly due to the lack of experimental knowledge and case studies in Denmark.

The consortium expects to address these barriers in a new R&D project where a small-scale pilot site could be implemented. The site is expected to include about 4-5 buildings, which could be also connected to a traditional DH system for back-up purposes.

7. Project conclusion and perspective

The main conclusion of the project is that the feasibility of cold combined heating and cooling systems depends largely on the boundary conditions of the given building area. A main factor is the available heating or cooling sources in the area and the balance between heating and cooling demands in the buildings. Cold combined heating and cooling systems were in some cases seen to be more economically feasible than a warm combined heating and cooling solution. The cold systems were especially relevant when cooling loads were included in the analysis and cooling was assumed to be delivered directly from the cold network. Traditional warm district heating generally showed better economy when only heating demands were considered. Results from simulations showed that, under certain conditions related to the efficiency of the decentralized heat pumps, the cold combined heating and cooling systems can significantly reduce the electric energy consumption, with a consequent reduction of CO_2 emissions from heating and cooling production.

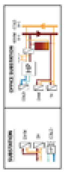
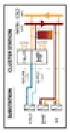
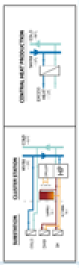
These systems are essentially based on well-known technologies, such as heat pumps, heat exchangers, pipes, and circulation pumps. However, how these technologies are combined, as well as their operation and control, represents a novelty that has not been fully analyzed in experimental and demonstration studies. For example, the development of optimized heat pumps that operate at low-temperature lift is expected to further improve the overall efficiency of ambient-temperature DHC systems. However, such products are not available in the market yet.

Therefore, by shedding a light on the possibilities for ambient-temperature DHC systems in Denmark, the results from this project may promote the development of new units and products that integrate optimally in future district heating and cooling systems.

8. Appendices

Scenario-based matrix discussed during the workshop held in Køge on the 18th of November 2021.

KOHESYS

Questions/scenarios	Scenario 1—Reference 	Scenario 2—Warm loop with building clusters 	Scenario 3— Cold loop with building clusters 
What are the advantages of this scenario?	*Well known technology.* *Resilient in terms of energy source (pipes are insulated).*		*More resilient towards the future climate.*
What are the disadvantages of this scenario?	*Cannot make use of surplus heat from dwellings.*	*Cannot make use of waste heat from industry.* *Not so flexible and without possibility of storing energy in the system.*	*Need of more back-up units.* *Dependent on cooling demands of dwellings.* *Not so flexible and without possibility of storing energy in the system.*
Utilization of surplus heat?	*Recover industrial surplus heat, but not from dwellings.*	*Recover waste heat from dwellings, but not from industry.*	*Recover waste heat from both industry and dwellings.* *Doubts whether this configuration would signify a higher heat loss from the external surplus heat.*
Costs?	*The costs are more predictable.*	*The total costs are less predictable.*	*The total costs are less predictable.* *If chillers not needed, then maybe low cost.*
Noise?	*Noise from A/C installations.*		
Climate footprint?	*Higher climate footprint if we only consider the local system, low climate footprint if we consider the global system.*		*Low climate footprint if we only consider the local system.*
Sensitivity analysis: which variables are important to consider, when defining the overall costs of the scenarios?	*Temperature levels in buildings and network. Design of the buildings (passive cooling). G-value of the windows. The existing energy source. Whether some buildings could have special needs of cooling, e.g. a server room.*		

Extra questions to reflect on:

1. When could 5G district heating be an interesting case - are possible surplus heat sources the decisive factor? - is it the economy? – other things?	***2. District cooling, when could it be an interesting case for you – will you wait for a warmer climate before you consider this as a possibility, or do you think there already is a market for it today?***	***3. Do we have the necessary technologies to make 5GDHC work – e.g., do we have heat pumps that can work optimally in the temperature range of all surplus heat sources?***	***Security of energy supply: how dependent can a district heating network be on a single heat source? – and will this affect the possibility of utilizing surplus heat locally?***
Could be a good idea in areas with few houses if located outside district heating areas.	*We see innovation in building design, which might lower the indoor cooling demand.*	*Some development is needed for Low-temperature lift heatpumps.*	*It is always an advantages with an energy supply based on more sources, as it makes the system more flexible and robust.*