D2.1 - REWARDHeat planning schemes database

Renewable and Waste Heat Recovery for Competitive District Heating and Cooling Networks

REWARDHeat

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1 Summary

REWARDHeat is an Horizon2020 research project dealing with next generation district heating and cooling networks. The goal of the project is to demonstrate low temperature thermal networks and recovery of available urban waste heat and renewable energy. This deliverable is part of WP2 - Design of low temperature networks with multiple energy sources which has an objective of developing a database of solutions for next generation DHC networks and develop REWARDHeat predesign tool.

The deliverable serves as a database for literature review and best practice examples for ultra-low and neutral temperature district heating and cooling networks. Firstly, it provides detailed overview of existing knowledge and published research papers on the different related topics such as: renewable and urban waste heat sources, supply technologies, thermal networks, and end-user substations. Then, the overview of existing next-generation networks is presented, while focusing on their characteristics such as temperature regimes, thermal sources, network topology, etc. This information is organised as a publicly available database hosted on Zenodo platform, available on this **link**.

Then, the overview of different system components is shown, both for ultra-low and neutral temperature district heating networks: end-user substations, thermal networks configurations, thermal sources, and connection configuration. For every system component, a SWOT analysis has been carried out and a comparison with "traditional" low-temperature district heating systems is provided. The SWOT analysis has been expanded with energetic, economic, and environmental analysis of ultra-low and neutral district heating networks. For this purpose, an Excel-based calculation tool has been developed, also made publicly available via the Zenodo platform, through this **link**. More than 30 district heating and cooling configurations have been proposed which differ in temperature regimes, end-user substation types and thermal sources. The analysed system topologies have been compared with traditional low-temperature district heating systems and individual-based solutions such as air-source heat pump and natural gas boiler. The impact of different boundary conditions such as space heating share and plot ratio has also been considered, while sensitivity analysis on electrical energy price and investment has also been carried out. Finally, a PESTLE analysis of ultra-low and neutral temperature district heating networks has also been carried out.

This deliverable also serves as the starting point for development of deliverable D2.2 – REWARDHeat planning guidelines which will filter presented information into clear and concise design rules and recommendations.

2 Introduction

District heating systems can be divided in various ways based upon their characteristics (most commonly network temperatures). Conventional district heating systems are characterized by high temperatures of water in the system and use of fossil fuels as heat sources. These two characteristics cause: dependency on foreign countries that export fossil fuels, excessive emissions of CO_2 and high heat losses in the thermal network. So, to reduce these negative effects, or even to eliminate them, new district systems are being developed. They are usually named as follows: low temperature (LTDH), ultra-low - (ULTDH) and neutral temperature (NTDH) district heating system. Operating temperatures of these systems are much lower than in conventional district heating systems which enables incorporation of low-temperature renewable energy and waste heat sources in the thermal network.

The main difference between mentioned district heating systems is the supply network temperatures and end-user substation type. In LTDH systems temperatures can reach up to 75°C, in ULTDH up to 50°C and in NTDH up to 35°C. Depending on temperature of the network, different consumer substation for space heating (SH), space cooling (SC), and domestic hot water (DHW) preparation are used. It must be noted that there is no universal definition of these systems regarding network temperatures, system configuration or consumer substations because these systems are still developing. However, most of the researchers agree on the following:

- **LTDH** network supply temperatures are mostly in range between 55 and 70°C. These temperatures are high enough for space heating and theoretically for domestic hot water preparation. To enable DHW preparation with such supply temperatures, instantaneous heat exchangers and district heating storage units on primary side are being implemented at the consumer substation.
- **ULTDH** systems achieve network temperatures up to around 50°C. These temperatures are high enough to satisfy consumer space heating needs, but for the domestic hot water preparation booster device is needed to prevent Legionella growth. Different technologies could be used for temperature boosting such as heat pumps, electrical heaters, solar collectors, boilers, etc.
- **NTDH** systems have such low temperatures (up to 35°C) which are not high enough both for space heating and domestic hot water preparation. So, every consumer substation is equipped with booster heat pumps to rise temperatures to desired levels needed for SH and DHW preparation. Due to the low temperature regime, these systems also offer the possibility of SC. Furthermore, these networks can enable bidirectional energy exchange between supplier and customer.

LTDH systems are usually considered as the fourth generation of district heating (4DH), the term coined by Henrik Lund et al [1]. Most of the researchers are considering ULTDH and NTDH systems as the fifth generation of district heating (5DH). The evolution of DH systems is shown in Figure 1. It can be noticed that every next generation follows supply temperature reduction and increase of energy efficiency, due to lower distribution heat losses. Lower supply temperatures enable

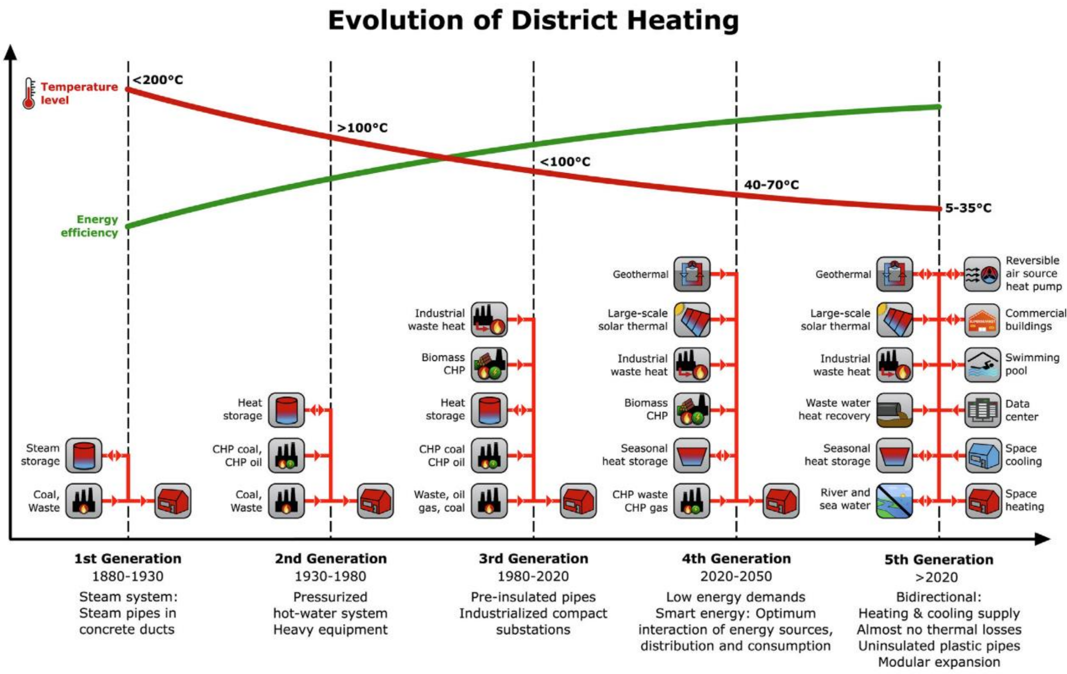

Figure 1 Evolution of district heating systems [2]

In the future energy systems, with a high share of intermittent renewable energy sources, district heating will have a crucial role by using demand response through implementation of power-to-heat technologies. According to [1], district heating will have to satisfy several criteria in to face future challenges of energy systems:

1. Ability to supply low-temperature DH for space heating and domestic hot water
2. Ability to distribute heat in thermal networks with low thermal losses
3. Ability to recycle heat from low-temperature and integrate renewable energy sources
4. Ability to be integrated part of smart energy system
5. Ability to ensure suitable planning, cost, and motivation structures in relation to the operation and investment

Definition of smart energy system is proposed in [3] as follows "a system in which smart electricity, thermal and gas grids are combined and coordinated to identify synergies between them to achieve an optimal solution for each individual sector as well as for the overall energy system".

Meesenburg et al have shown that listed criteria could be satisfied with ULTDH and NTDH systems [4]. Heat pumps are mentioned as the crucial part of the system due to the several reasons. Firstly, coefficient of performance (COP) is increased with thermal network supply temperature reduction. Secondly, they enable power and heating sector coupling. Thirdly, heat pumps can be integrated with thermal storage thus increasing flexibility of the system and enable smoother operation of the district heating system.

Pellegrini et al provide sound reasoning for integration of NTDH networks in smart energy systems [3]. First of all, they enable power-heating sector coupling through heat pumps, solar thermal and photovoltaics integration. Secondly, they can offer bi-directional energy exchange between network and the users. This could be revolutionary aspect since the thermal price is not the main economic driver anymore. Both network operator and end-user can have benefits of such configuration. Thirdly, NTDH can potentially have interconnection with the gas sector. For example, biomethane could be used as a back-up boiler or integrated with DHW production in multi-purpose heat pump. In combination with thermal storage, it can offer great flexibility.

Reduction of supply temperatures brings additional benefits to an overall energy system. They should be considered when developing new ULTDH and NTDH systems since these changes enable operational cost reduction and increase economic feasibility of the needed investments. Ommen et al have listed potential benefits of lowering DH supply temperatures [5]. Supply temperature reduction improves performance of renewable heating technologies, either by direct utilization (e.g., solar thermal collectors) or by use of heat pumps. Furthermore, temperature reduction has positive influence on central heat supply units, such as cogeneration and heat-only boilers. Finally, it gives possibility for decreased heat losses in distribution networks.

On the other hand, low temperature DH systems have lower temperature difference between supply and return lines. Thus, it is subject to increased investment and pump operation due to the larger volume flow rate for a fixed heat delivery. Besides this, there are additional aspects which should be considered when developing ULTDH and NTDH networks, such as additional investments needed for substation *and* decentralised heat booster technologies. For DH networks in transition, some authors recommend the use of 65-70°C as the optimal forward temperature for DH networks, since lower temperatures require high investment, among others DH booster HP units in each dwelling [6].

3 Thermal sources

One of the main parts of every district heating system are heat sources. Number of heat sources vary in each network. More heat sources mean that heat supply will be more continuous and more reliable. Reduction of supply temperature enables integration of additional low-temperature thermal sources. In this section, the focus will be put on natural and urban waste heat sources which are often utilised in ULTDH and NTDH systems.

3.1 Natural thermal sources

3.1.1 Groundwater

Groundwater is commonly used in NTDH systems since it provides relatively constant temperature due to high thermal large thermal capacity of the source. Pellegrini et al provide good overview of ground water thermal source which can be utilised in NTDH [3]. It should be mentioned that groundwater is most often utilised through ATES (aquifer thermal energy storage). Groundwater can transfer energy directly to the thermal network, as in NTDH systems, or can serve as the heat source/sink for the heat pump, as in ULTDH and LTDH systems.

In fact, the concept of ATES in NTDH networks is that in summer, groundwater is extracted to provide cooling. The heated groundwater is injected back into the aquifer to create a heat storage. In the winter season, the flow direction in the system is reversed such that the heated groundwater is extracted to provide heating and create a cold storage. The heating and cooling purpose of ATES is periodically shifted thus maintaining wanted equilibrium on annual level. However, it should be mentioned that there are numerous limits to groundwater exploration which are always defined on the national level. One of the limits is water flowrate extraction capacity (which can be determined through pumping test realized accordingly to ISO 22282-4 standard). Additional limitation is discharge temperature. Temperature is a key driver of hydrogeochemical and biological processes. Anthropogenically-induced temperature changes can be presumed to influence natural water systems. In ATES systems, the reinjection of heated groundwater can lead to carbonate precipitation, increased dissolution of silicate minerals, the mobilization of organic compounds from sediments, a decrease in groundwater oxygen saturation and effects on aquifer bacteria and fauna. Different limits are set on country level (varying +/- 5°C), thus setting aquifer temperature increase or decrease after utilization. ATES are often used in combination with remediation to improve groundwater quality.

3.1.2 Ground

Ground as a natural thermal source is already well known and its potential is already being widely exploited. The ground is a very stable and reliable source of heat energy and offers the possibility to serve as a heat storage tank [7]. The surface part of the earth has a variable temperature due to external environmental conditions, while already at a depth of two meters the ground shows a very stable and suitable temperature for exploitation. Tubes can be installed in the subsurface vertically or horizontally. At a depth of two meters in the ground, the temperature is above 10°C even in winter. Such temperature stability without large variations during the year allows the use of the ground for heating during the winter period and for cooling during the summer period [8].

The most common way to use the ground as a thermal source is as Borehole Thermal Energy Storage (BTES). BTES uses the ground as a tank that allows the earth to warm up during the summer period, and the use of that heat during the winter period. The borehole for the tank can be depths from 30 to 200 m, depending on the garden and the composition of the ground. Ground heat exchangers (GHX) are then placed in the boreholes [9]. By using GHX it is possible to exploit the heat from the ground in heat pumps which are usually then placed in central heat station. Heat pumps raise the energy level to a higher level which is suitable for use in the DHC network [8]. BTES can achieve coefficient of performance (COP) values from 4 to 8, which is significantly higher than using a conventional ground source heat pump.

Usually, there is no environmental restrictions for the exploitation of the ground thermal energy, so such systems prove to be flexible for exploitation by allowing greater differences between the inlet and outlet temperatures in the boreholes. From economic point, the capital cost of large BTES systems can be significant because many boreholes are needed, but there won't be much difference comparing to conventional ground source heat pump due to the higher COP values. Also, higher COP values will result in a lower total lifecycle cost. The most common constraint is on the available land are in which to construct BTES.

3.1.3 Superficial water bodies

Besides ground water, superficial water resources (lakes, rivers, sea) can also be utilised [3]. However, such heat sources have temperature variations which are usually correlated with ambient temperature. To limit this issue, preheating can be used by using different sources such as cogeneration, heat-only boiler, etc. There are also limitations for exploitation of superficial water bodies, however not as rigorous as ground water. The energy exploitation of surface water is thus generally favoured if compared with underground water, since the first allows a higher temperature variation between inlet and outlet flows, with a consequent reduction of water flowrate at constant heat exchange (thus reducing pipeline diameter, heat exchanger size, etc.). Typical temperature increase can be up to 10-15°C, water mixing is then needed to reduce temperature.

3.2 Urban thermal sources

3.2.1 Urban water systems

Paper [4] proposes utilisation of urban water bodies for utilisation in DH systems, such as sewage water and water treatment plants. Although sewage water is always available in cities, where heating demand density is relatively high, there are several limitations which should be mentioned. Sewage water has constant temperature, which is relatively high, around 25°C. Due to this, it is excellent heat source for heat pump operation in ULTDH or even LTDH systems. This temperature is also relatively high for utilisation in NTDH systems through heat exchangers. Due to this, it is not suitable for free cooling in NTDH since chillers are required. The most important aspect of sewage water are its physical-chemical characteristics, which may have some implications on network operation and maintenance costs such as clogging potential and corrosion risk.

Interesting proposition is utilisation of drinking water as a heat source. Water networks usually exists in urban areas and can be used directly. However, the drinking water quality must not be affected. The use of certified components (i.e. sanitary use) may be required, with relevant cost increasing.

3.2.2 Supermarket's refrigeration and HVAC systems

Supermarkets are essential part of any larger city. Increase of supermarkets is followed by the constant increase in their surface area [10]. To ensure quality, sanitary regular, and fresh food, in supermarkets three types of refrigeration units are used; stand-alone, condensing, and centralized, each are driven by various technologies and refrigeration cycles. Refrigeration takes a large part in the energy consumption of the average supermarket. Average annual energy (electricity) consumption is between 327 and 600 kWh/m^2 and refrigeration covers between 35% and 50% of that consumption [10]. There is a correlation between the geographic location of supermarkets and energy consumption, presented in [11], which shows that energy consumption is higher for southern locations, due to higher ambient temperatures. Also, the report [11] brings up an hourly consumption for several supermarkets on various locations. Refrigeration has a relatively constant consumption which is easily comparable for the same period of the year in different locations.

Different refrigeration processes utilize different refrigerants. Due to the large energy consumption, hydrofluorocarbon (HFC) refrigerants represent a large environmental challenge because of their impact on the atmosphere in terms of high Global Warming Potential (GWP) and Ozone Depletion Potential (ODP) values. Due to this, other refrigerants are often used, such as CO_2. Main benefits of CO_2 are improved heat transfer, which enables smaller system dimensions, and high heat content at high temperature. Together with low GWP (equal to unity) and ODP (equal to zero) values, this makes CO_2 environmentally friendly refrigerant [12]. Its main advantage is that it can be easily and efficiently applied to two-stage refrigeration systems, such as those in supermarkets. Two-stage refers to two temperature loads – medium and low. Evaporation temperatures are in range from -10 to -5°C for chilled food (medium-temperature load) and from -35 to -30°C for frozen food (low-temperature load) [10] [13]. As in every counter-clockwise cycle, refrigeration system emits significant amount of waste heat which should be rejected from the system. Some authors [14] state that after on-site heat recovery, e.g. for space heating, there is still between 5 and 45% of waste heat which has to be rejected to the atmosphere through the gas coolers. This heat can be used in district heating and cover different thermal loads.

The important aspect of waste heat utilisation is a temperature of heat source. In this case, it is temperature CO_2 temperature before entering gas cooler, i.e. after the compressor. Due to this, it is sometimes referred to as compressor discharge temperature. There is a strong correlation between compressor discharge temperature and ambient temperature as shown in [15]. Rise of ambient temperature is followed by constant rise of compressor discharge temperature defined by optimum compressor pressure. Waste heat source temperature values are in the range from 50 to 120°C. It is a decisive parameter for optimizing and evaluating the waste heat source temperature and their further analysis as described by authors in [16].

If DH network temperatures are lower that compression discharge temperature, then direct utilisation through heat exchanger can be used, as shown in Figure 2. In paper [17], the authors gave a correlation of (COP) and thermal network temperatures. With the high optimal discharge pressure also comes to a very high waste heat temperature, entering heat exchanger. Considered temperatures are up to 140°C.

In case that DH network temperatures are higher than waste heat source, booster heat can be integrated which utilizes CO_2 as the heat source and district heating network as heat sink. Furthermore, combination of booster heat pump and direct heat exchange can be used as shown in Figure 3. Detailed comparison of different work fluids for boost heat pump is given in [18], where gas cooler outlet temperatures reach between 10 and 28,7°C.

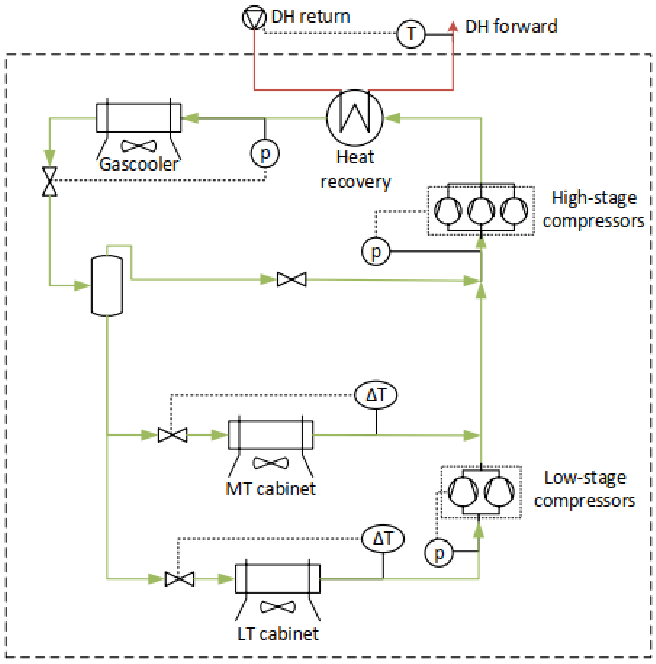

Figure 2: Scheme of CO_2 refrigeration system and waste heat utilisation with heat exchangers [17]

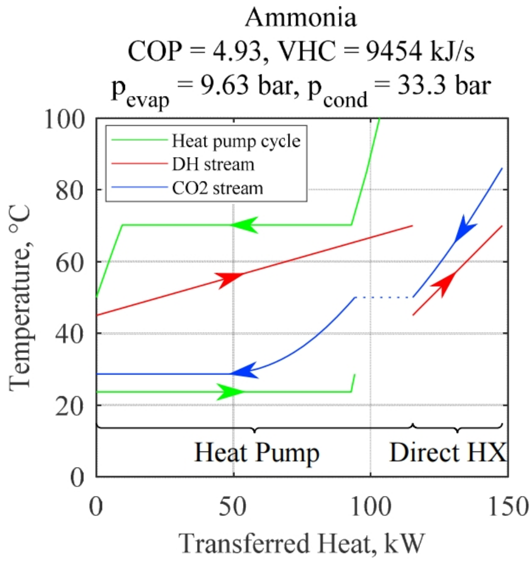

Figure 3: Temperature-heat diagram of an ammonia booster heat pump [18]

3.2.3 Shopping malls and supermarkets HVAC systems

Heating, ventilation, and air conditioning systems (HVAC) in supermarkets and shopping malls can be easily observed as identical system. HVAC purpose in both of these objects is to ensure optimal thermal comfort. Average annual energy (electricity) consumption is between 327 and 600 kWh/m^2 for supermarkets and between 118 and 300 kWh m^{-2} for shopping malls [10]. Various share of energy consumption can be detected depending on the climate zone. Share of energy consumption for cooling is between 1 and 8%. The main waste heat potential in HVAC systems represents heat discharge in coolers. Thermal comfort is maintained in the temperature range between 22 and 26°C for most of the stores in shopping malls. Exceptions are specialized stores with groceries where the suggested temperature is between 18 and 22°C, such as in supermarkets. There are three fundamental ways of designing the HVAC systems. The first of them is a combination of Variable Refrigerant Volume (VRV) and Ventilation Air Mounted (VAM). The purpose of the VAM is to secure fresh air in combination with VRV's room unit. There are also some compact one-zone systems that are especially used in small malls. Those systems are located on the roof, and they contain everything that is needed for appropriate air conditioning. Even though they can recover some part of the waste heat, the efficiency of those systems is still very low. The cooling supply unit is a rooftop heat pump.

In report [11] authors gave a methodological analysis of hourly energy consumption for malls in different climate zones. Here can be noticed that energy consumption is directly related to average ambient temperature. Hourly demand shows a peak in the day at 2 or 3 pm with a correlation of solar irradiance and internal heat gains.

3.2.4 Data centres

With the increasing digitalization of the services, data centres are becoming important worldwide and it is expected that the role of data centres in the future will be significant. Raise in the number of the data centres, due to the raising demand, necessary effects on energy consumption, i.e. consumption of electric energy. It is estimated that the consumption of data centres takes a part of 1% of total electric energy consumption and it will grow. Two main electric energy consumers in data centres are Information Technologies (IT) systems, used for processing and storage of data, and HVAC (Heating, Ventilating, and Air Conditioning) systems [19]. The HVAC system needs to ensure a working environment in a set range for the proper functioning of IT equipment.

An important part of the HVAC system is the cooling system. The cooling system needs to provide removing of the heat dissipated inside the data centres. Heat dissipated in data centres may vary depending on the performance of the devices. Considering that fact, two types of data centres can be distinguished:

- conventional data centres – heat dissipation rates in the range of 430 – 861 W/m^2 [20],
- high tech data centres – heat dissipation rates in the range of 6.458 – 10.764 W/m^2 [20].

Due to the variation in data centres heat dissipation rates, there are three main cooling techniques in data centres:

- Air-cooled systems – for small conventional data centres, low-quality waste heat,
- Water-cooled systems – mid- and large-scale data centres, high-quality waste heat,
- Two-phase cooled systems – large-scale data centres, high-quality waste heat.

A wide range of dissipated heat presents a significant amount of the waste heat that can be captured and reused, due to this It is estimated that 68% of dissipated heat can be recovered. Heat dissipation increases powering and cooling cost of data centres, while the reuse of the waste heat energy can potentially reduce operational costs [21], [22]. In Europe, today, the most common used technique for cooling in data centres is air-cooled systems. As mentioned above, the temperature grade of data waste heat in air-cooled systems is low (under 45°C), which presents a challenge for further integration and application on a large scale. One of the possible solutions for this problem is the usage of advanced heat pumps and other low-temperature heat pumps to upgrade the temperature grade of waste heat [19]. Using heat pumps also allows the integration of waste heat in the district heating (DH) network. Heat pumps for reuse of the waste heat can use and combine different thermodynamic cycles: single-stage compressor cycle, two-stage, one compressor cycle, and two-stage, two compressor cycles [19].

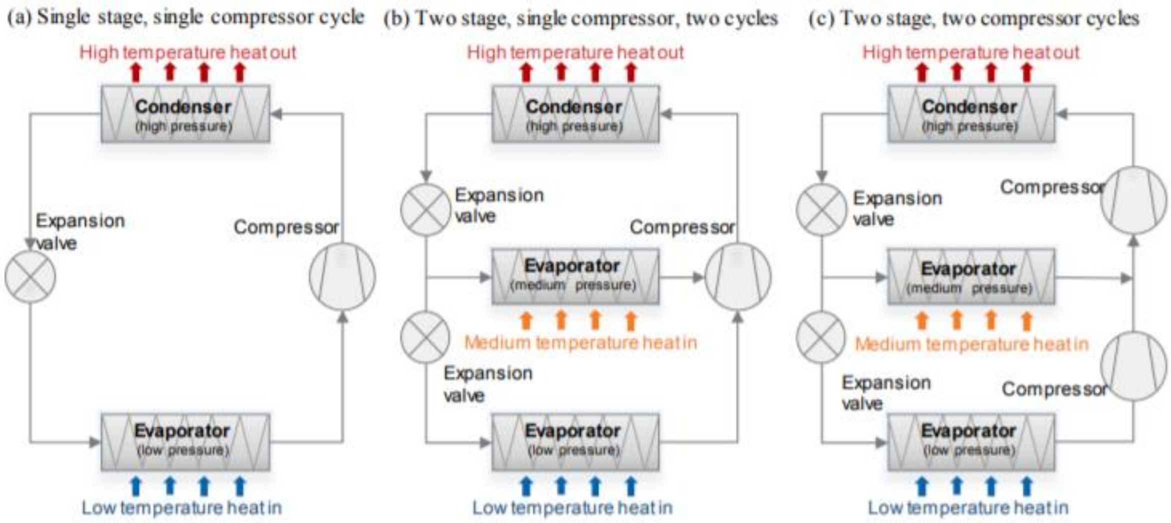

Figure 4: Potential thermodynamic cycles for upgrading data centre waste heat (a) Single stage, single compressor cycle (b) Two-stage, single compressor, two cycles (c) Two-stage, two compressor cycle

To capture waste heat from data centres there are two most common ways: capturing return hot aisle or on the chiller condenser.

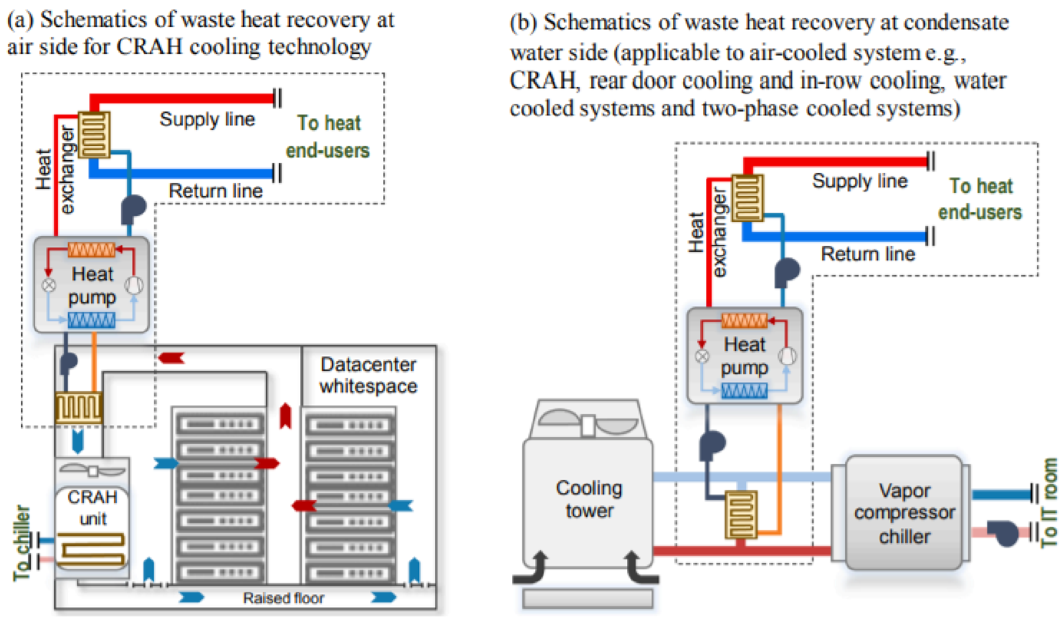

Figure 5: Schematic diagram of the heat reuse solutions – on the left schematic of waste heat recovery at air side for CRAH cooling technology; on the right schematic of waste heat recovery at the condensate water side

Waste heat recovery in the return hot aisle is usually implemented in CRAH (Computer Room Air Handler) cooling systems since the hot air streams in IT facility rooms are gathered at relatively high temperatures (about 45°C) and delivered in a common duct to the air-handling units. The return hot air will be cooled down in an air-to-water heat exchanger (HE), this principle will also reduce cooling needs from the chiller in the CRAH system. Warm water from HE will feed evaporator in HP in which the temperature level of waste heat will be upgraded to a higher level [23], [24].

In many cooling systems, the return water temperature of the coolant circuit is usually low and thus it is also not viable for heat recovery. A feasible solution is to capture heat from the chiller condenser. Waste heat recovery in the chiller condenser applies to the air-cooled systems, water-cooled systems, and two-phase cooling systems. For heat recovery from the chiller condenser of CRAH systems, water-to-refrigerant heat exchange is installed in parallel with the condenser of the chiller. Part of the rejected heat from the chiller goes to the surrounding environment, and the remaining heat is captured by a secondary water circuit. The temperature can reach a higher temperature level (about 50°C). The low-grade heat in the warmed water is fed into a heat pump for upgrading to the temperature that can be used by the DH network [24].

There are also different ways of connection between the distributed heat sources and the DH systems, more precisely, four main ways of the connection:

- Return/Supply: the water is withdrawn from the return pipe, heated to a correct temperature, and fed back into the supply pipe.
- Return/Return: the water is withdrawn from the return pipe, heated to any temperature higher than the temperature on the return line, and fed back into the return pipe.
- Supply/Return: the water is withdrawn from the supply pipe, heated to any temperature, it has already a higher temperature than the temperature in the return line, and fed back into the return pipe
- Supply/Supply: the water is withdrawn from the supply pipe, heated to any temperature higher than the temperature on the supply line, and fed back into the supply pipe.

In a scientific article [25] authors gave the hourly distribution of operating modes of cooling systems in district heating, from which it is visible that cooling systems will mostly operate during summer, while the rest of the year outdoor air will be used for cooling. It is expected that waste heat hourly distribution will vary through the year with the changeable COP of the heat pump.

3.2.5 Power substations

Power substations are an important part of electric power systems (EPS), they are a segment of transmission and distribution grids that includes electric energy sources and electric energy consumers. These parts are crucial in every EPS. Power substations are steady electromagnetic devices which with help of electromagnetic induction converts alternative currently in currents on different stages with the same frequency. The main parts of substations are an iron core, a primary and secondary winding, insulation, housing, construction reinforcements, and a cooling system.

Today's substations have a high efficiency up to 99.8%, and the losses in substations are usually divided on energy dissipation due to no-load losses which are related to using iron core, and losses due to the load which is related to using copper wiring. Those losses are the main sources of waste heat in substations. Substations cooling system may be described with four letters, the first letter describe coolant winding, the second letter describe a technique of cooling, the third letter describes external coolant cooling, and the fourth letter describes a cooling mode for external cooling [26].

Table 1: Labelling the cooling systems with power transformers [26]

Refrigerant		Cooling technique	
Label	Media	Label	Principle
O	Mineral oil	N	Naturally
L	Synthetic oil		
G	Gas	F	Forced
W	Water		
A	Air	D	conducted
S	Solid material		

Cooling substation with air is economically most effective because there is no need for pumps and ventilators, the lifetime of the cooling system is long, there aren't any maintenance costs, the main disadvantage of this cooling technique is a requirement for a large area. Forced cooling allows great flexibility and the working range is wider with a smaller exchange surface, the disadvantage is noise from ventilators. Cooling with water has a greater cooling capacity with the smallest number of contacts with substations. Another advantage is operating without noise or with little noise. The biggest disadvantage is the possibility of pump failure.

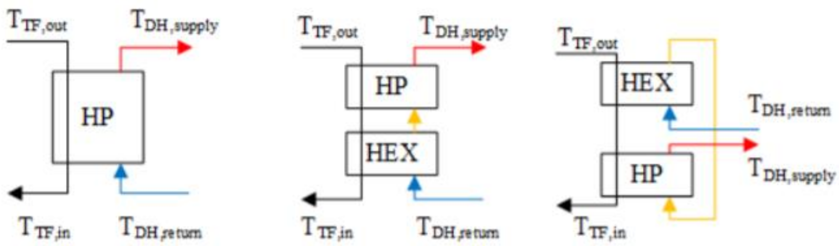

Figure 6: Configuration for the possible waste heat recovery systems of the transformer [27]

The temperature level in the substation depends on the load of the substation, but usually, those temperatures are low (about 35°C) [27]. Inlet and outlet temperatures on substation and district heating sites will determine if a heat pump, a direct heat exchanger, or a combination of both is required. The direct utilization of the waste heat is possible when the outlet temperature on the transformer site is above the supply temperature of the district heating area. This case is rare, and it is possible only in low-temperature district heating networks. The inlet temperature needs to be fixed to obtain the necessary cooling effect; direct utilization is possible only if the return temperature in district heating is by the minimum temperature difference below the required inlet temperature. If no direct utilization is possible, a heat pump will be used to provide the temperature lift to make possible integration of the waste heat in district heating, as shown in Figure 6 [27].

Currently, studies showed that utilizing waste heat from substations will not satisfy a significant share of district heating demand on a high level, but it can still be important on the local level. The waste heat from substations is appropriate to use in hospitals, shopping centres, industrial facilities, and facilities that require heat during the whole year [27].

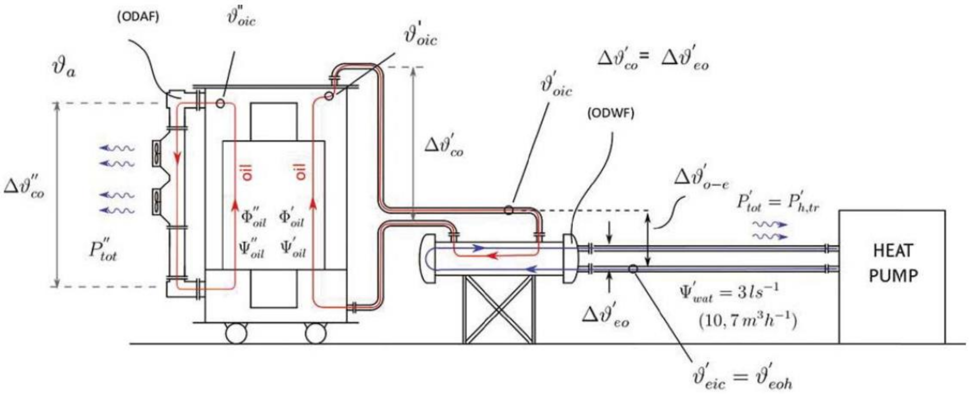

Figure 7 Power transformer waste heat utilisation scheme [26]

3.2.6 Metro stations

Metro systems consume a large amount of electric energy for different purposes, electric energy is used in metro systems, and due to that, it is transformed into heat energy. The heat energy in metro systems causes a rise in the temperature, and in this, part HVAC systems have an important role. Through air ventilation and cooling systems, heat is dissipated out and ensured that the temperature in metro systems stays at a level acceptable in sense of thermal and humidity level for people and equipment. Throwing away this amount of heat causes a rise in the operational cost of metro systems and can cause thermal pollution. One of the possible solutions for this is waste heat recovery. Recovering heat from metro systems through heat exchangers and heat pumps directly linked to the tunnel body is already shown viable. Typical waste heat temperature in metro systems is between 20°C to 35°C [28], [29], [30]. The heat pump is used to upgrade the temperature of recovered heat may be located at either at decentral unit (Shaft head house) or at central unit (Energy Centre) as shown on Figure 8 above. Upgrading temperature level of recovered heat is making heat suitable to use in district heating network.

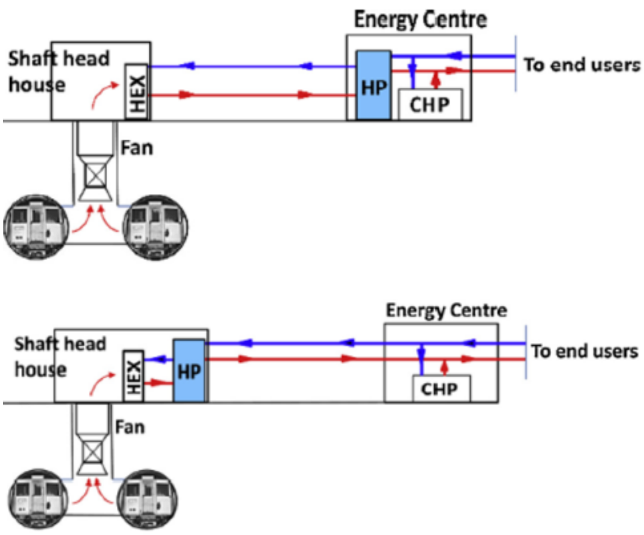

Figure 8 Scheme of recovery system in Metro system [30]

3.2.7 Wastewater treatment plants

Wastewater treatment plants produce significant quantities of waste heat energy and show great potential for usage. Wastewater has a high heat capacity, density, and it can provide a concentrated source of heat. Wastewater heat could be used in heating and cooling of the residential, social, and administrative buildings on a narrower scale or in district heating on a larger scale [31].

Unlike other low-temperature heat sources, wastewater possesses multiple advantages. For example, wastewater is available in large quantities throughout the whole year, and it is characteristic for cities, the temperature variations throughout the year are small. Through heating season average temperature is about 10°C, while during the cooling season average temperature is about 22°C [32]. Another advantage is that through summer wastewater has a lower temperature than the outdoor temperature, while during winter it has a higher temperature than the outdoor temperature enabling the usage of the heat pumps for cooling and heating buildings. Combination of using wastewater heat and heat pumps is already developed, proven and it has been shown that this technique is simple and proven. The heat pump is necessary to increase wastewater temperature level to a higher level so that it can be integrated into the district heating network.

There are three different techniques for extracting heat or cold in wastewater treatment plants:

- Sewer-integrated heat exchanger – heat exchanger placed directly inside the sewer tunnel; heat exchangers consist of heat-exchanging surfaces through which a medium flows. Pipes transport the medium to the heat pump.
- Sieved wastewater sewer-integrated heat exchanger – the raw wastewater flowing in the sewer is first fed to a sieving stage in which solids are separated, this is necessary to protect the heat exchanger from blockages and decreasing efficiency. Then the wastewater is passed through the heat exchanger and then returned to the sewage system
- Collecting shaft heat exchangers – collecting shaft heat exchangers can be installed, collecting shaft is used for filtering and collecting wastewater. The shaft is always filled with wastewater to ensure continuous heat transfer [33].

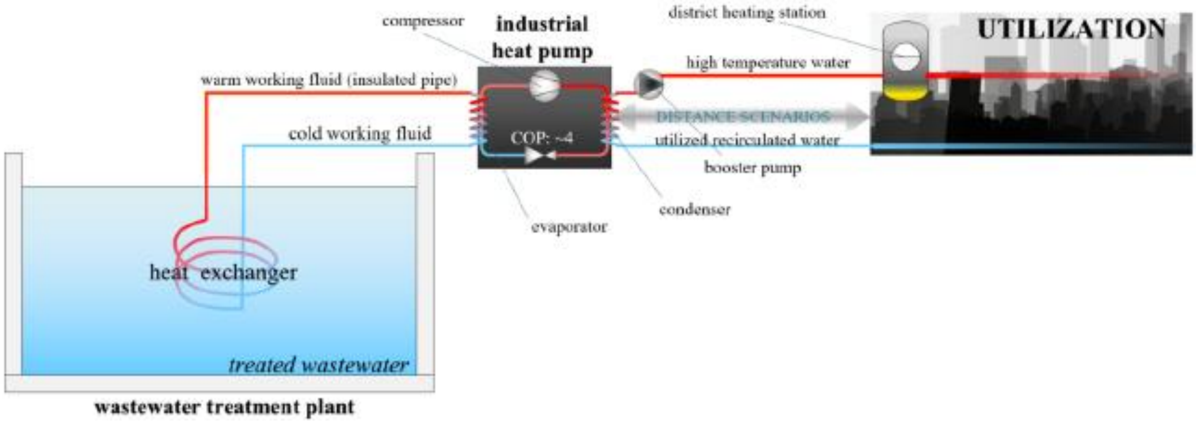

Figure 9: Scheme of the wastewater utilization in the district heating systems [34]

There are two types of heat utilization from wastewater through heat pumps:

- Indirect type – wastewater to circulating water

- Direct type – wastewater to the refrigerant [35].

Wastewater temperature is depending on the amount (flow) of wastewater, region, sewage sources, and season. Flow into sewers is related to the variability of demand by users. The flow has an hourly, daily, and weekly pattern, which is different on working days or at weekends. It is expected that through the day it is greater flow, while through the night it Is lower flow. Variation of flow is the result of the climatic conditions, work activities, and habits of the users [36].

Due to the report [34] heat extracted from sewage water by heat pumps is assumed to be proportional to the population of towns and cities and it is estimated that 5% of heat demand can be covered in towns and cities with more than 10 000 people.

4 Supply technologies

In this section, different supply technologies will be presented, while focusing on their role in energy transition from conventional to ULTDH and NTDH systems. Furthermore, the impact of temperature reduction on the technology characteristics is discussed. Since central heat pumps are the most used technology in ULTDH and NTDH systems, special emphasis is put on this supply unit type.

4.1 Cogeneration

Cogeneration, or combined heat and power (CHP), is technology which can simultaneously produce heating and electrical energy. Generally, there are two types of CHP, called back-pressure and extraction cogeneration. In the back-pressure CHP, heating and electrical load are directly correlated, i.e. there is no flexibility in plant operation. Cogeneration only operates if there is district heating load. However, flexibility of such plant can be increased if thermal storage is installed. On the other hand, extraction CHP is relatively flexible since electricity production does not necessarily follow heating load, as shown in Figure 10. The figure shows operating regions for two mentioned CHP types by using so called power-heat (P-Q) diagrams. It can be noticed that P-Q diagram for extraction CHP is a whole operational region, while P-Q diagram for back-pressure CHP is a single line.

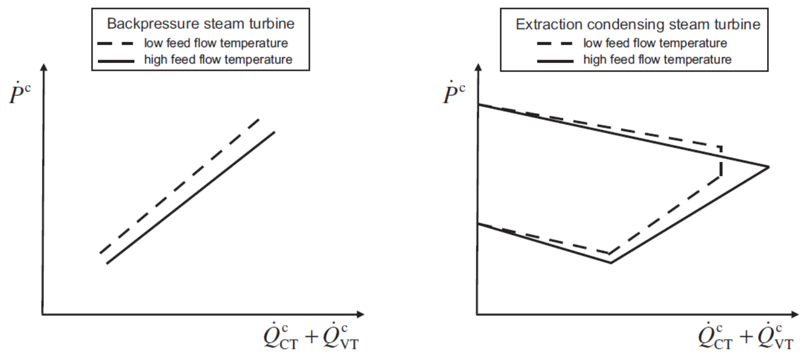

Figure 10 P-Q diagrams of different CHP types and the impact of DH network temperature reduction [37]

It is crucial to observe that P-Q diagram is influenced by DH supply temperature. It can be noticed that for the same level of heat production, electricity production is higher for lower DH supply temperature. Furthermore, loss of electricity production in extraction CHP is also reduced for lower DH supply temperatures. This loss of electricity production is defined with so called power-loss factor usually marked with Greek letter beta, β.

This correlation between CHP efficiency and DH network temperature, presents essential element for DH systems in energy transition. Figure 11 shows impact of supply temperature reduction on electrical efficiency and power-loss factor, when transitioning from high to low temperature DH systems. It can be noticed that parameters change could be up to 20% for temperature reduction of 80°C. Lower power-loss factor and higher electrical efficiency of CHP correlates to higher electricity production for the same amount of fuel input, which finally results in higher income. This can be translated to lower operational cost of CHP system. In other words, lower the temperature of a DH network, higher economic feasibility of the overall energy system.

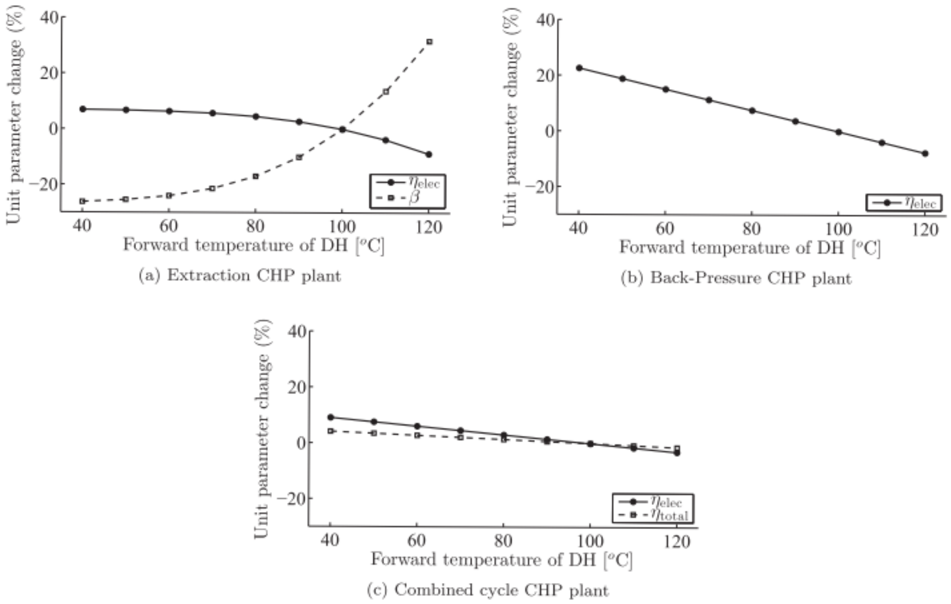

Figure 11 The impact of supply temperature reduction on various CHP types [6]

Cogeneration systems are an important part of the system since they provide power-heating sector coupling and offer high energy efficiency of fuel utilisation. Nevertheless, it should be mentioned that CHP systems are rarely directly connected to ULTDH or NTDH networks. Fifth generation networks are usually linked to CHP units through shunt valve connection, as explained in Section 4.3. In other words, CHP systems are important for DH systems in energy transition. To fully cover thermal demand of ULTDH and NTDH systems, natural or waste heat sources should be primarily used.

The authors of the paper [5] even conclude that temperature reduction of DH network connected to CHP can have negative effect on the overall system efficiency. They have shown that power-loss coefficient of CHP is drastically reduced when lowering supply temperature regimes from LTDH (60-75°C) to ULTDH (36-50°C). However, it has been shown that further reduction of supply temperature does not result in optimal efficiency of a whole system. Further reduction in supply temperature resulted in reduction in coefficient of system performance (COSP), which was mainly ascribed to a significant increase in pump work due to the given low difference between supply and return temperatures. Optimal system efficiency for CHP based ULTDH system is obtained for 50°C of supply and 24°C to 32°C of return.

Power-loss factor of CHP can be translated to power-to-heat efficiency (inverse of power-loss factor). For medium and high temperature DH systems, CHP has higher COP than HP. Due to this, CHP is more favourable technology than heat pump, for systems in transition from LTDH to ULTDH networks [6].

4.2 Solar thermal collectors

Solar thermal collectors can produce thermal energy with wide variety of temperatures, depending on thermal load and collector type. Generally, solar thermal technology can be divided in two main groups: flat plate collectors (FPC) and evacuated tube collector (ETC) [38]. FPC have relatively simple design constituting of flow pipe which are placed inside absorber. On the other hand, ETC has flow pipes located inside vacuum tubes, thus reducing thermal losses due to conduction and convection which presents main drawback of FPC. Of course, ETC have higher investment cost, however they maintain more constant efficiency for different ambient conditions as shown Figure 12. Energy efficiency of the collector is tested for various ambient conditions and different heat loss factors could be defined for every collector [38].

The most important parameter for studying efficient operation of solar thermal collector is so called mean temperature of the collector. It is defined as arithmetic mean of the inlet and outlet temperatures of the collector fluid [39]. In case that inlet and outlet of the collector represent return and supply of the DH system, it can be assumed that mean temperature of the collector is equal to arithmetic mean of the DH network [40]. Higher the mean temperature, lower the collector efficiency, as can be noticeable from Figure 12. Transition from high temperature to ULTDH and NTDH systems has significant impact on the collector efficiency. Temperature reduction can cause over 30% efficiency increase.

To use solar energy as much as possible they should be coupled with thermal storages to store heat when there is excess of it and use it when there is high demand [41]. If solar thermal share in DH is above 20%, seasonal thermal storage could be used.

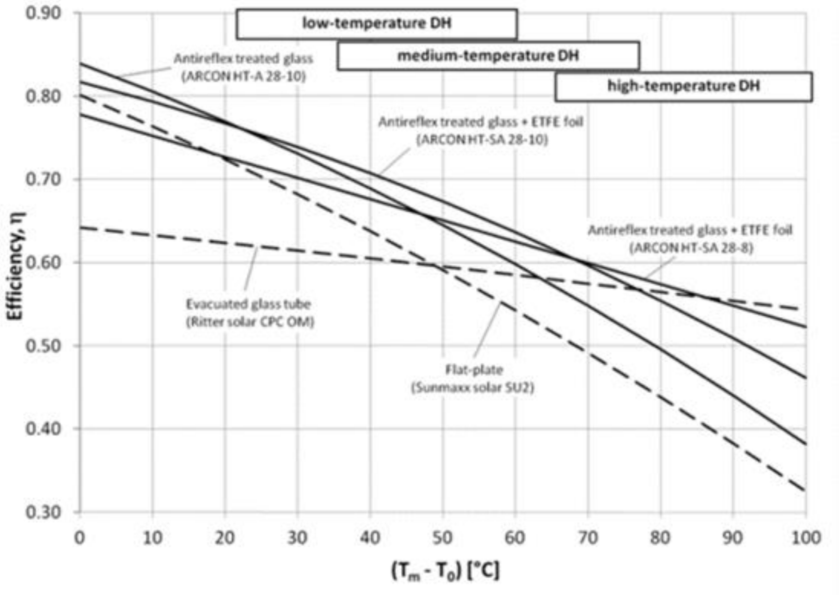

Figure 12 Efficiency of solar collector as a function of the difference between the mean collector fluid and ambient temperature [42]

4.3 Existing DH networks connection

LTDH and ULTDH system can be integrated into larger DH network by using various connection technologies. This enables creation of low-temperature subnetworks which can easily be integrated into existing DH systems. This could be achieved by using heat exchanger, heat pumps or direct connection. In case of direct connection of LTDH or ULTDH, mixing shunt or 3-pipe connection can be used [42].

Heat exchanger solution connection

ULTDH can be connected to high-temperature DH network by using heat exchanger system as shown in Figure 13. Heat exchanger area is directly related to the temperature difference between networks – higher the temperature difference, lower the heat exchanger area, i.e. investment. In Figure 13 two heat exchangers are shown. One is used for delivering heat from primary to the secondary network, while the second one is used for heating the retention flow. This is generally used for LTDH systems where secondary network temperature is increased for DHW purposes. In case of ULTDH systems, this heat exchanger is not needed since heat booster units are available in end-user substations.

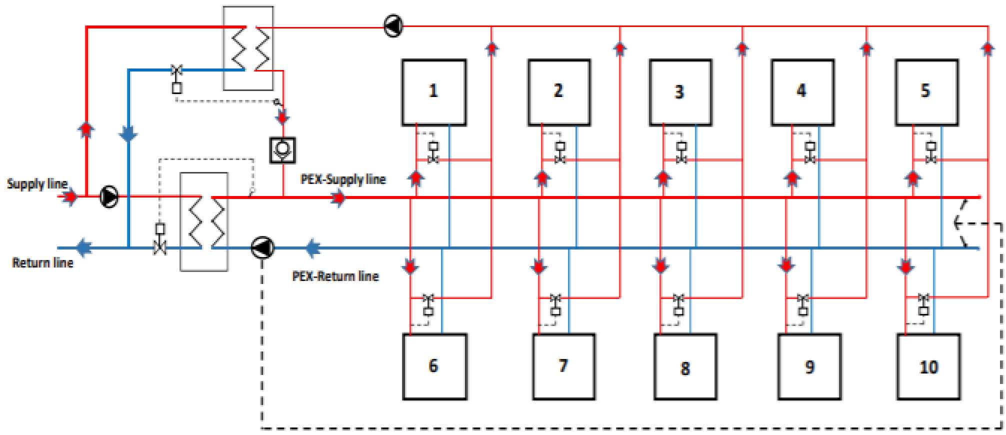

Figure 13 Connection of low-temperature network to high-temperature DH system via heat exchangers [43]

- Mixing shunt connection

Mixing shunt is a direct connection of existing DH and secondary subnetwork where the supply coming from existing DH is mixed with the return flow of the secondary subnetwork. Performance of the mixing loop is controlled by a temperature sensor in the main supply pipe in low-temperature network. That sensor controls a valve in the return line of the secondary network. Valve opens/closes and by that it controls supply temperature of LTDH [42]. This is relatively simple technical solution since secondary network can easily established, as shown in Figure 14.

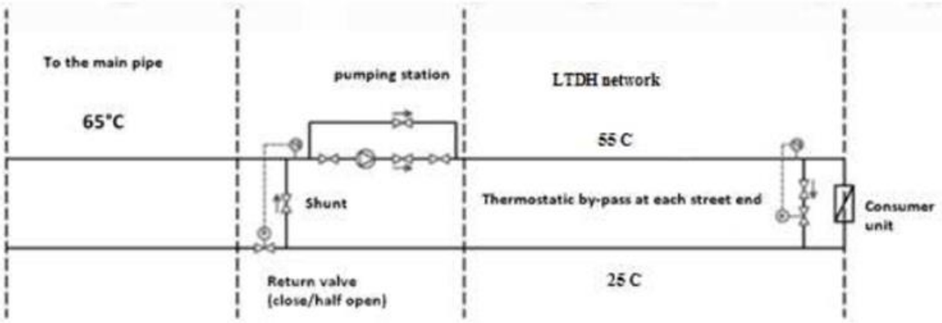

Figure 14 - Mixing shunt between existing DH and secondary network [42]

- Three pipe connection

Three pipe connection is solution similar to shunt valve. However, in this case primary network supply and return flow are mixed to provide supply flow of the secondary network. Primary heat source comes from the return line of medium temperature DH. When temperature of the return line is not sufficient, water from supply line of medium temperature DH is mixed with return water to achieve desirable supply temperatures of the subnetwork. Therefore, system consists of two pipes: two supply pipes and one return pipe [44]. The 3-way valve is regulating ratio of the mixture for subnetwork system, as shown in Figure 15. This system enables expansion of the network without the need to increase network capacity [42].

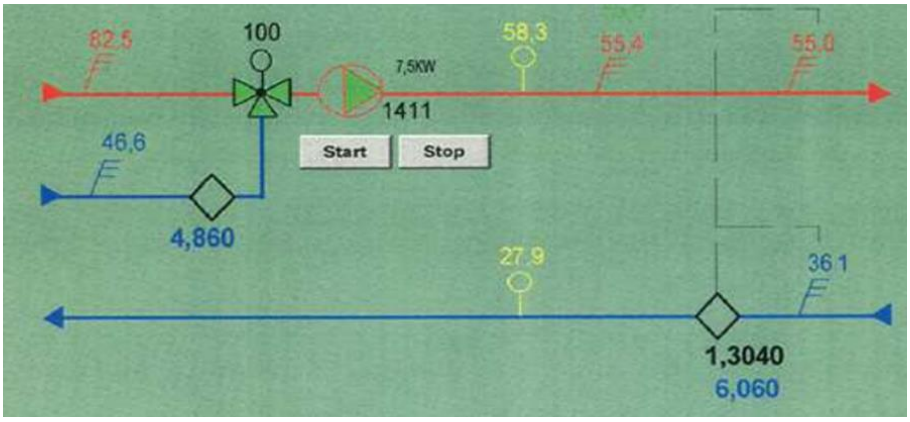

Figure 15 - 3-pipe connection [42]

- Heat pump connection

Low-temperature DH subnetwork can be connected to the existing DH network via HP. It is alternative to use of mixing shunts, since mixing shunts require more pumping energy. Figure 16 shows schematic representation of heat pump implementation. In displayed example, return water from primary DH network at 40°C passes through heat pump condenser after which temperature is risen to 55°C, i.e. it serves as the heat sink. It becomes supply temperature of the secondary DH network. Return water from secondary network passes through evaporator and serves as the heat source. By doing so, it is cooled before it is returned to the primary DH network [41].

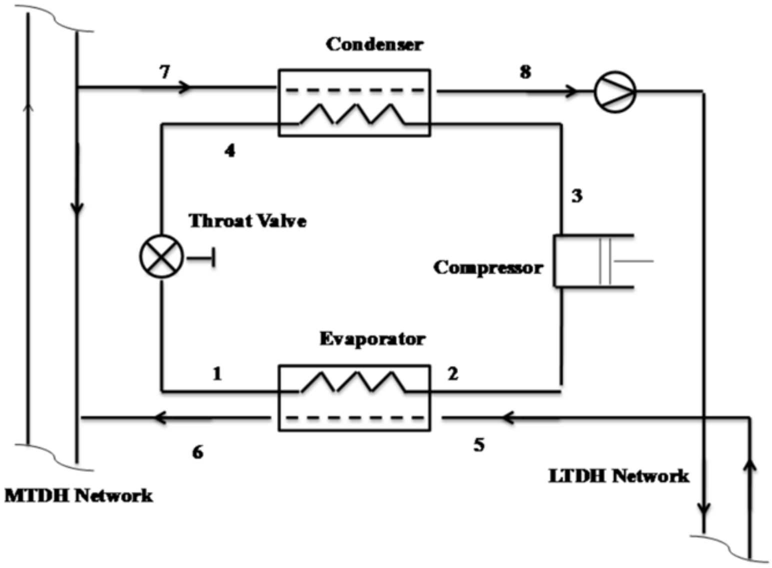

Figure 16 - Integration of medium temperature DH and low-temperature subnetwork with HP [41]

Pumping energy presents crucial issue when analysing network interconnections. There is always a need for additional pumping energy in cascade network connection, due to the different pressure levels between primary and secondary network. The 3-pipe system has pressure height of zero (the flow is taken from the same pipe where should be directed to return). To ensure flow in secondary DH network, additional pumps must be installed. In shunt connection (primary energy source is the high-temperature supply pipe, where the return flow will be mixed into) the pumping cost will be lower because it is possible to use the difference in the HTDH supply and return pipe and utilize pumping only for mixing the return (30% decrease in electricity consumption compared to 3-pipe system [45].

4.4 Central heat pumps

Heat pump is technology which enables transferring heat from lower temperature (heat source) to higher temperature (heat sink) by means of mechanical input through compressor. Overview of a heat pump cycle and related temperatures is shown in Figure 17. It is important to mention that COP of the heat pump greatly depends on the temperature lift, which is defined as the temperature difference of heat source and heat sink. Lower the temperature lift, higher the heat pump's COP. In other words, lower DH network temperatures (heat sink) cause increase of heat pump COP, for the same heat source type.

In this section, the focus will be put on central heat pumps, which are located in the network, i.e. on the heat supplier side. They are utilizing available heat source to provide thermal energy for the district heating network, i.e. heat sink.

In ULTDH and NTDH networks, heat pumps are also used as local booster units usually located in customers' substation. Booster heat pumps have smaller thermal capacity than central units and different operating conditions. They are explained in detail in Section 7.

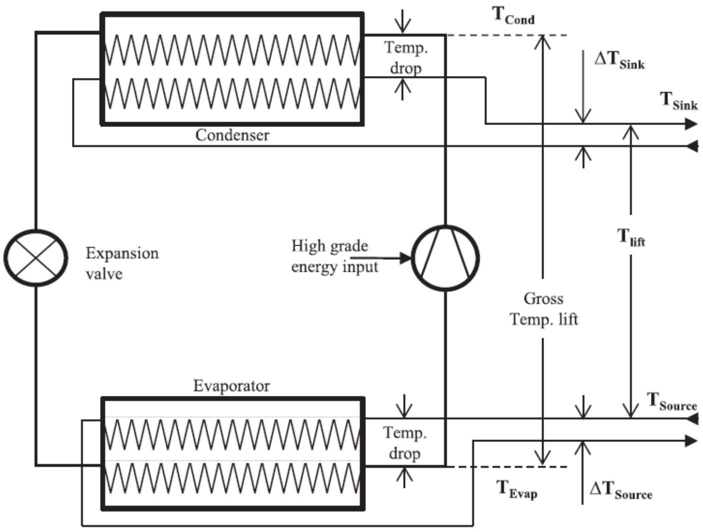

Figure 17 Overview of heat pump cycle and temperature levels [46]

4.4.1 Heat pump configurations

Paper [46] defines different heat pump configurations and, each with different implications on the system efficiency and operational characteristics. Each configuration has different temperature lift level – difference between heat source and heat sink. In Source-Forward (SF) configuration, the temperature lift is achieved between heat pump source and DH supply temperature. In such configuration, heat pump can operate independently from other technologies in the network. Source-Demand (SD) configuration is individual heat pump installed at the building location and does not require DH network to operate. This is also called de-centralised heating. Source-Return (SR) configuration is using heat pump to pre-heat return water entering the central heating facility, e.g. CHP. In this configuration, temperature lift is the smallest, resulting in the highest heat pump COP. However, this potentially reduces central heating unit efficiency, e.g. CHP since it increases condensing pressure. Return-Forward (RF) configuration is utilising return line of the DH network as the heat source and forward line as sink. This enables return temperature reduction. However additional technology is needed to increase the temperature again to the forward temperature. The final proposed configuration is Return-Demand (RD) which uses return of DH network as the source and demand temperature as the heat sink. Such heat pump configuration allows higher capacity in the DH network pipes, as the temperature difference between the forward and return is increased. This is also de-centralised heat pump option since individual pumps are installed at the final customer location. It is important to notice that optimal configuration, i.e. optimal temperature lift, depends on overall system characteristics and should be analysed in detail.

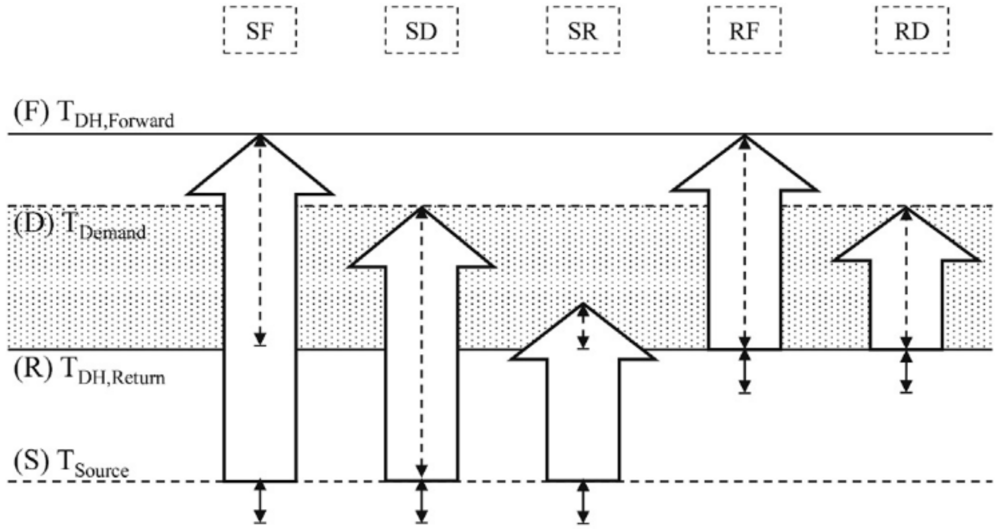

Figure 18 Different heat pump configurations in district heating system

4.4.2 Frequently used refrigerants

Heat pumps are using various working mediums, i.e. refrigerants which have different thermodynamic properties. They are selected by considering numerous boundary conditions such as heat source and heat sink temperatures, pressure levels and state of matter (liquid or gaseous). Furthermore, important issue which should be taken into account are GWP and ODP levels defined for each refrigerant [47]. Different papers are proposing various refrigerants. Paper [5] proposes refrigerant R717, with pinch temperature of 5°C in heat exchangers. In other papers, R134a is frequently used as refrigerant. Although paper [48] deals with booster hear pumps, the authors also analysed the optimal refrigerant mix for central heat pump. If the use of mixtures as working fluids is applied additionally in the central heat pumps, the COSP of LTDH increases from 3.68 to 4.16 while the COSP of ULTDH increases from 4.18 to 5.09 in case the booster heat pump and the central heat pump are both using a mixture.

4.4.3 Central heat pump integration in ULTDH and NTDH systems

Meesenburg et al have analysed ULTDH networks (three different DHW booster configurations) with different central heat pumps heat sources: theoretical excess heat at different temperatures (20, 30 and 40°C), groundwater at constant 10°C and outside air [4]. The feasibility of ULTDH with central HP depends greatly on various factors such as plot ratio (ratio of building and total land area), space heating share and linear heat density. It has been shown that ULTDH based on excess heat (at 40°C) HP is economically better than classical LTDH systems only for space heating shares higher than 0.7 and for plot ratios higher than 1 (the factor of 0.2 is for rural and 2 for densely urban areas). ULTDH with air source central HP are economically feasible only for the most dense regions with plot ratio higher than 2 and high space heating shares.

Paper [49] shows case study where central ground source HP is boosting waste heat. Cold ground water at around 6-12°C is used for industrial cooling purposes and is heated up and then boosted to 47°C to be utilised in a small ULTDH which consists of 21 buildings. Furthermore, local electrical booster heaters are used for DHW preparation. Central HP COP was in range 3.35-5.04, gradually reducing due to the ground water temperature changes. HP idling period should be considered to recover the ground thermal storage. During the idling period other heat sources such as CHP and heat-only boiler must be used. Paper [50] proposes using central heat pump in combination with booster heat pumps at individual level. Temperature levels in the grid without booster heat pumps are in range 55-70°C, while for implemented booster heat pumps are in range 25-35°C. Paper [5] analyses optimal system efficiency (which includes pumping power and heat pump compressor) for an ULTDH network with a central heat pump. is obtained for DH network supply temperature of 42°C to 46°C and return 22°C to 27°C.

5 Thermal storage technologies

Thermal energy storage (TES) is a technology which enables storage of thermal energy and its utilisation in periods when is needed. They can be used to store thermal energy on different levels of temporal scale such as: hourly, daily, weekly, or seasonal. As such, they differ in size, temperature levels or technology. In this section, the focus is put on characteristics of TES which are primarily used in low-temperature DH systems.

5.1 Thermal storage overview

Table 2 General characteristics for any low-temperature district heating [51]

Type	TTEA (tanks)	PTS (Pits)	BTES (Boreholes)	ATES (Aquifers)
Storage medium	Water	Water (gravel-water)	Soil surrounding the boreholes	Groundwater in aquifers
Specific capacity [kWh/m³]	60-80	60-80 (30-50 for gravel-water)	15-30	30-40
Water equivalents	1 m³ TES= 1 m³ water	1 m³ TES= 1 m³ water	3-5 m³ TES= 1 m³ water	2-5 m³ TES= 1 m³ water
Geological requirements	Stable ground conditions Preferably no groundwater 5-15 m deep	Stable ground conditions Preferably no groundwater 5-15 m deep	Drillable ground High heat capacity High thermal conductivity Low hydraulic conductivity Groundwater flow <1 m/s 30-100 m deep	High yield aquifer
Application	Short-term/diurnal TES, buffer TES	Long-term/seasonal TES for production higher than 20.000 MWh/year Short term TES for large TES	Long-term/seasonal TES for DH plants production higher than 20.000 MWh/year	Long-term/seasonal heat and cold TES
Storage temperatures [°C]	5-95	5-95	5-90	7-18
Specific investment cost [€/m³	110-200 €/m³ (if > 2.000 m³)	20-40 €/m³ (if > 50.000 m³)	20-40 €/m³ (if > 50.000 m³ water equivalent	50-60 €/m³ (Cost depends on charge

water equivalent]			including buffer tank)	capacity rather storage capacity)
Advantages	High charge/discharge capacity	High charge/discharge capacity Low investment cost	Most underground properties are suitable	Provides heat and cold TES Many geologically suitable sites
Disadvantages	High specific investment cost	Large area requirements	Low charge/discharge capacity (potential need of a buffer tank)	Low temperatures and temperature differences

The specific investment cost (C) of TES is a function of the storage capacity of the TES (Q), a temperature difference of the TES (ΔT), density (ρ) and specific heat (c_p) of the storage medium, and coefficients (a, b) which represent the effect of the economies of scale on the investment cost. The coefficients a (a >0) and b (-1< b <0) are specific for given TES technology and determine the shape of the fitting curves of the specific investment cost based on a collection of existing cases. [51].

$$C = a \cdot \left(\frac{Q}{\rho \cdot c_p \cdot \Delta T} \right)^{b+1}$$

The equation shows that the lower the temperature difference across TES, the higher investment cost. For ULTDH and NTDH, because of the small difference between supply and return temperatures, they would require any TES to be larger (more expensive) than those in conventional DH. If excess heat is available on a temperature higher than low-temperature levels, it is stored in a TES at the heat source temperature. This more considerable temperature difference could lower the required storage volume and investment cost. The utilisation of excess heat depends on the price of transmission pipes. The surplus heat source should be closer to the network so that the heat value to outweigh the transmission pipes cost [51].

Water is mostly used as a medium because of its characteristics (high specific heat per volume, low cost, and non-toxicity), but a mix of glycol can also be used to avoid freezing (in solar thermal fields, cooling systems and shallow geothermal systems). Disadvantages of glycol use are lower heat capacity than the water, higher viscosity, and density than water, resulting in a more increased need for pumping energy and higher cost (around 30%). Water is most used for storing at temperatures below 100°C, but it can be used for storing at temperatures above if pressurised.

5.2 District heating network as a thermal storage

The storage capacity is determined by temperature difference in the network and the medium's properties. Storage capacity for various mediums is shown in Table 3. Water has the highest storage capacity, while glycol mixtures have lower [52].

Table 3 DH network capabilities for thermal storage

Storage capacity [MWh]						
T_{supply} [°C]	T_{return} [°C]	$T_{diff.}$ [K]	Water	30% propylene glycol	40% propylene glycol	50% propylene glycol
20	10	10	24	23	22	21
30	15	15	36	34	33	31
40	20	20	47	45	44	42
50	25	25	59	57	55	53
60	30	30	70	69	66	64
70	35	35	82	80	78	74
80	40	40	93	92	89	86
90	45	45	104	103	100	97

Previously, in Denmark's DH systems, temperature differences in networks were used to reduce morning peaks by raising supply temperature well before the actual load peak. In NTDH systems that are not applicable because network pipes are not insulated, which would lead to high heat losses. Instead, return temperature can be lowered, which then requires the use of glycol mixture [52].

Research has shown that the network can be used as a storage for DH systems in Denmark. Still, it has not sufficient heat capacity for optimising systems with solar thermal plants, heat pumps, etc. even with higher network volume. Conclusion of research is that network has not sufficient storage capacity, but it could be used for peak shavings. Despite that, the network should not be dimensioned for such purpose [52].

5.3 Storage types

Before storage planning, it is essential to consider whether is more feasible to store at lower temperatures (lower investment cost because there is no need for extensive insulation and availability of low-temperature surplus heat) or higher temperatures (higher energy density and thus smaller storage for the same capacity) [52].

5.3.1 Tank thermal energy storage (TTES) – centralised daily storage

Tank thermal energy storage is usually made as cylindrical steel tank. They are mostly used as daily storages. Still, Germany cases have shown that they can also be used as seasonal storages where solar thermal plants are used for heat production. They can be underground or above the ground. If they are underground, the area above them can be utilised. Materials used for their construction are mostly stainless steel, concrete, or glass-fibre reinforced plastic. Mineral wool is used as insulation for steel tanks. Figure 19 shows underground TTES.

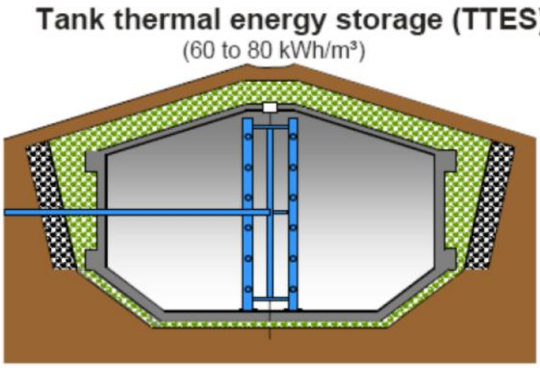

Figure 19 Tank thermal storage overview

Thermal storage temperature is mainly chosen to provide supply temperature for the network. The temperature stratification in the tank is managed with a pipe system. This system tries to avoid hot and cold temperature layer mixing to keep storage efficiency as higher as possible. Tanks with pipes with several outlets can extract heat at different heights, which means that water at the desired demand temperature can be used while maintaining high temperature on the top of a tank. This is important for large thermal storages to keep the high-temperature difference to avoid entering a too low temperature in the network. In Figure 20, specific investment cost for tank thermal storage is shown [52].

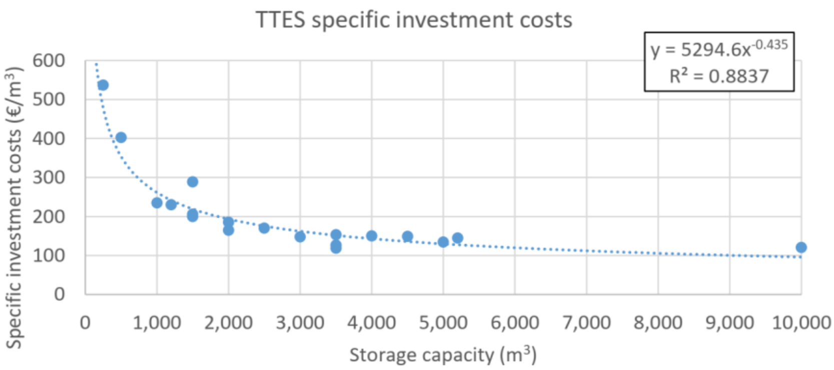

Figure 20 Tank thermal storage specific investment

Largest TTES is in Germany with a volume of 60.000 m^3. These storages heat losses vary from 2% per week for 500 m^3 storage to 1% per week for 5.000 m^3 storage. [52]

5.3.2 Pit thermal energy storage (PTES) – centralised daily to seasonal storage

Pit thermal energy storage (PTES) are usually connected to solar thermal plants. They consist of a pit excavated in the ground with the mostly plastic membrane on the bottom and the walls (with low slope) of storage. This prevents storage leaking. The pit is covered with a lid that floats on storage medium-water to reduce heat losses. Bottom and walls are not insulated because soil acts as insulation and cost of insulation would not be covered with save from heat loss reduction. To maintain thermal stratification, pipe system, similar to one in TTES is utilised [52]. The example of PTES is illustrated in Figure 21.

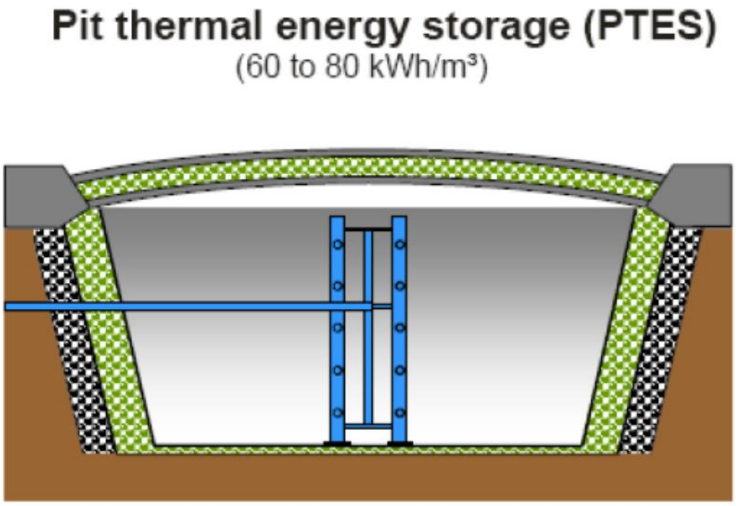

Figure 21 Pit thermal storage overview

Largest PTES has a volume of more than 200.000 m^{3,} and it is mostly coupled with a solar heating system. The specific capacity of these storages is around 60 to 80 kWh/m^{3}, which is similar to the capacities of TTES. Storage heat losses depend on temperature levels, lid insulation, volume to surface ratio, storage use, and whether heat pump is used for storage discharge. Storage efficiencies are in the range of 80% to 95%, but they are lower for single-cycle seasonal use. When it comes to water, it should have a pH value of around 9,8 by removing minerals to prevent corrosion. Pipes should be made of high-quality steel while lid material needs to avoid leakages, or at least, not lose properties if leakages occur. Storage liner lifetime depends on the storage temperature – higher the temperature, shorter the lifetime [52]. If there is a need for large PTES, it can be separated into two separate PTESs. That results in improved stratification, increased top liner lifetime, ease of taking storage out of the service in case of maintenance. Finally, two storages can be commissioned separately [52].

PTES typically have a truncated pyramid shape. Excavated soil is laid in a bank around the pit which then, together with a pit, creates storage that is partially below and above the ground. Sharp edge stones need to be removed from the sides and bottom to prevent liner damaging. Then, a layer of Geotextile is installed on top of which is HDPE liner. Liner usually has a width of a 6-7 m, and it should be long enough to cover sides continuously from bottom to top. These lines are welded together. Top cover consists of high-density polyethylene (HDPE) bottom liner floating on the water pulled across the whole pit and then fused with top HDPE liner of a top cover along the bearing area. These liners are then fixated in the soil. Then comes the drainage layer, insulation, one more drainage layer, and final HDPE top liner after the bottom liner. On top liner, multiple vacuum and drainage valves are installed to secure a lower structure's proper ventilation. Ventilation is necessary because HDPE liner is not steam diffusion proof and high moisture levels in the lid would decrease lids insulation properties.

The central part of PTES investment, as well as heat loss source, is a cover lid. Therefore, the cap should be as small as possible, which can be achieved by increasing the inner slope and the pit's depth. Maximum slope of a cavity is limited in practice by geotechnical and working conditions, and its value is about 1:2 (ratio between height and width of the sides). As mentioned before, depth also decreases lid area, but after 30-45 m, the benefit of further depth increase is not significant. Groundwater also plays a vital role in storage depth because storage should be cooled as little as possible with the groundwater [52].

PTES are suitable for large scale systems, and it is a tendency to build bigger PTESs than ones already existing. The specific investment cost per storage capacity is provided in Figure 22

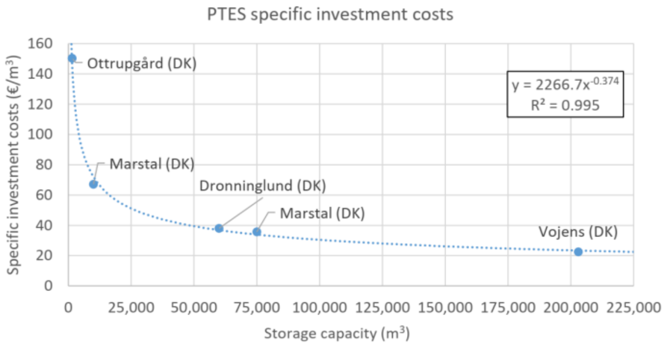

Figure 22 Pit thermal storage specific investment

5.3.3 Borehole thermal energy storage (BTES) – centralised daily to seasonal storage

BTES consists of boreholes in the grounds in which pipes are placed. The whole system is usually covered on the top with insulation to prevent heat losses. When recharging, hot water runs through the pipes, and it heats the surrounding soil, and when storage is discharging, cold water runs through the pipes and soil transfers heat to it. In this case, the storage medium is soil surrounding boreholes, and water is the heat transfer medium. Cross-section of one borehole storage system is shown in Figure 23.

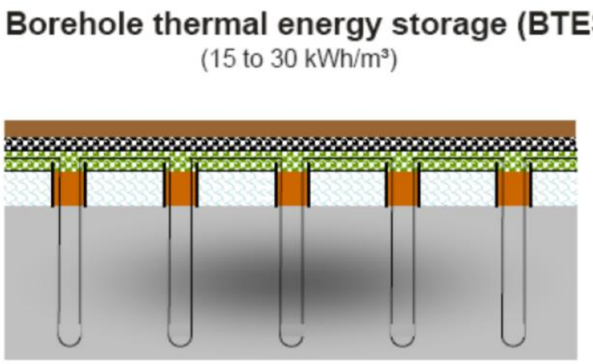

Figure 23 Borehole thermal storage overview

BTES can consist of one or more boreholes, depending on the required storage capacity. Use of one borehole correlates to the heat exchanger of a heat pump. An attractive solution is to combine BTES and short term TTES where system utilises solar heat. The TTES acts as a buffer between solar heat production variations and BTES which cannot be charged as fast as solar heat is produced. [52]

Where BTES can be installed, suitable places are the ones with high soil heat capacities and limited groundwater flow. Charging and discharging elects depend upon the convection from and to the ground's storage material and transferring medium in the pipes. For that reason, BTES is mainly used for baseload. The central part of the investment cost of BTES is boreholes drilling; for that reason, soil properties must be satisfactory and consistent through the project area. But that does not mean that these projects cover a lot of land area because most of the parts of this system are underground. Heat pumps are always needed where this storage type is utilised because heat transferred from the soil doesn't raise transfer medium temperature levels to cover district heating temperature levels. Specific invest cost per storage capacity of BTES is given on the figure below. [52]

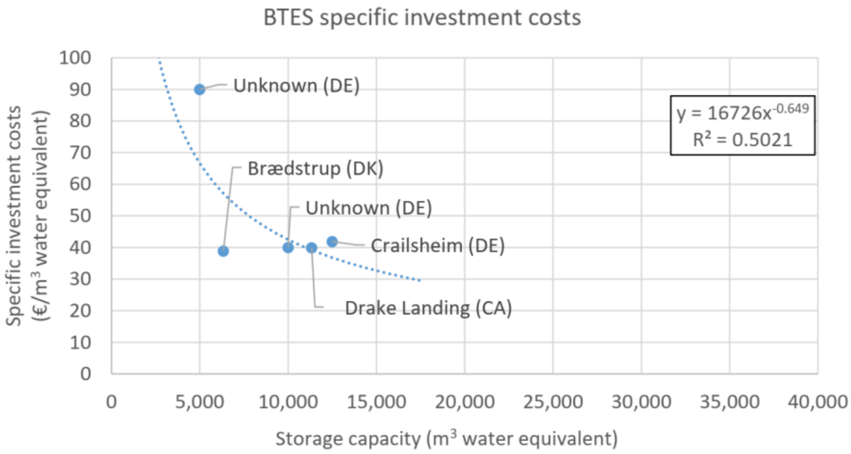

Figure 24 Borehole thermal storage specific investment

The central part of the investment in BTES is, as mentioned, drilling and exchangers, which accounts for more than 50% of total investment costs. The investment cost is also dependant on the depth of boreholes. Table representation of investment cost in each part of a project and graph representation of the correlation between borehole depth and investment cost is given below [52].

The most important aspect of BTES is that it could be used in district heating and cooling simultaneously by using seasonal (periodic) heating and cooling cycle [52], as shown in Figure 25. During winter season, warm water is being supplied from BTES, thus reducing the temperature of the boreholes. During summertime, cooled BTES are used for cold water extraction and district cooling. In this process, BTES is heated up and prepared for winter season, thus completing the periodical cycle.

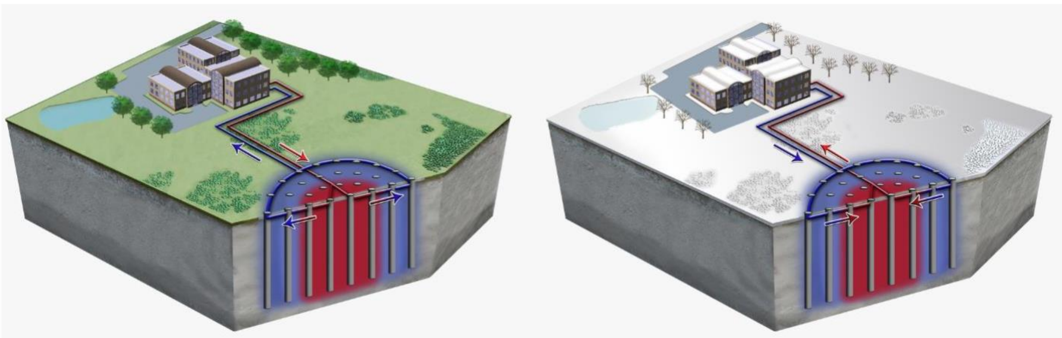

Figure 25 Borehole thermal storage operation during summer and winter season

5.3.4 Aquifer thermal energy storage (ATES) – centralised daily to seasonal storage

ATES consists of two (or multiples of two) separate wells drilled into an underground groundwater reservoir (aquifer), as shown in Figure 26.

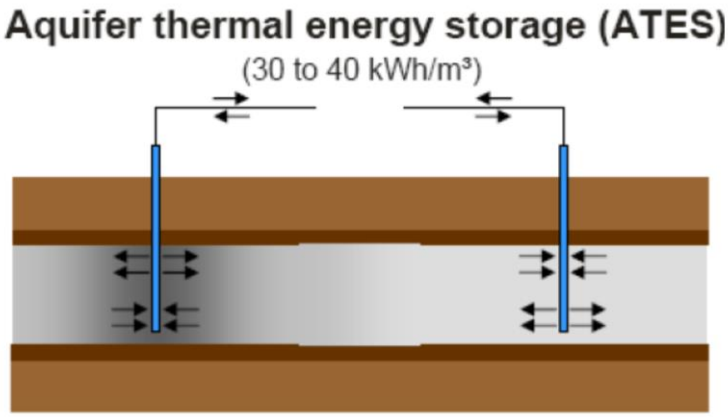

Figure 26 Aquifer thermal storage overview

One of the wells acts as heat storage, while other acts as cold storage. In winter, water is pumped from the warm well for heating purposes, thus being cooled down. It is then injected into the cold well. The reverse process happens in summer where water from a cold well is used for cooling purposes, and after it is heated, it is injected into a warm well. It is essential to notice that ATES is a closed system as the water from aquifer circulates in a loop without net water consumption. This storage type is usually used only for cooling, making this system feasible, even without heating. Typical temperatures for cold well are in the range 7-16°C and for the warm well 10-18°C, but these temperature ranges can vary depending on the season and other conditions. Most countries have regulations restricting the temperature of a discharged water (e. g. Denmark maximum water temperature pumped into the ground is 25°C, while monthly average cannot exceed 20°C). The typical storage capacity of a well is around 500 MWh, and the standard extraction power of one well is 1 MW. Investment cost, regarding this technology, is mostly power-related, not storage capacity related. Working modes of ATES in winter and summer are shown in the figure below. [52]

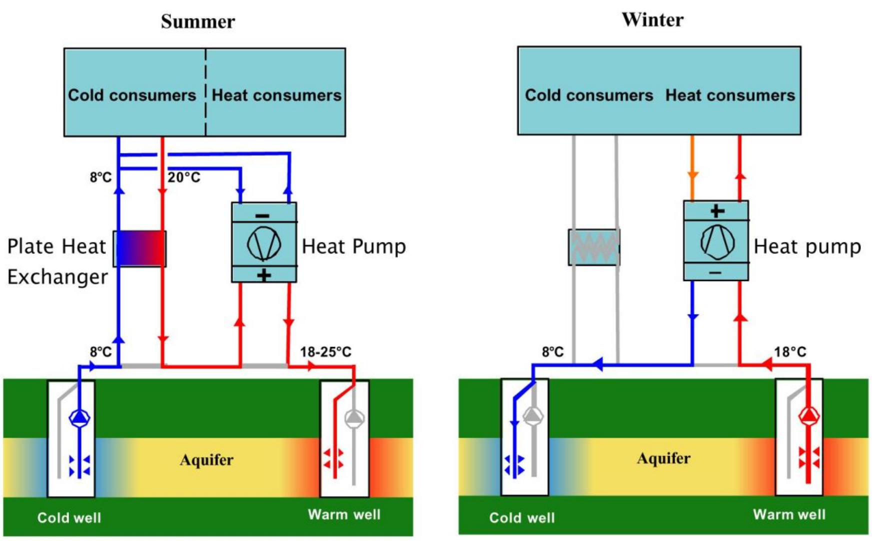

Figure 27 Aquifer thermal storage operation during summer and winter season

Feasibility of ATES depends on the site's geological conditions, particularly water yield from well and temperature difference of the storage. Specific investment cost remains almost constant for different storage capacities. Economy of scale for ATES is not achieved because these systems are modular with each borehole pair yielding similar power and storage capacity, as shown in Figure 28. Doubling of power means doubling the number of wells [52].

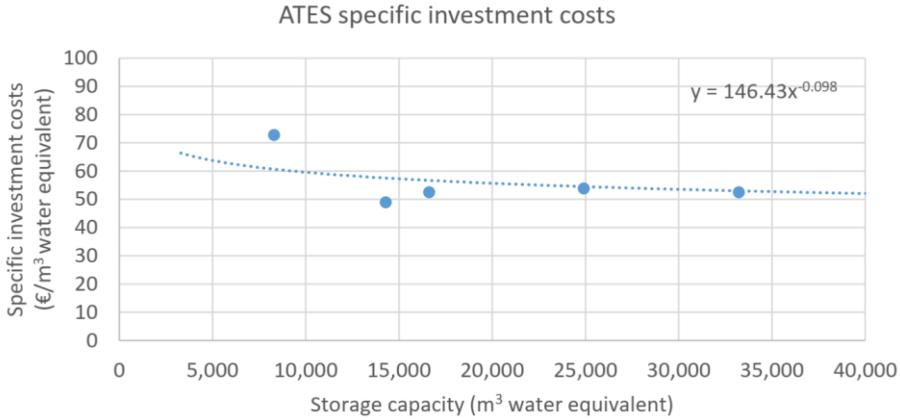

Figure 28 Aquifer thermal storage specific investment

5.4 Heat losses

Large scale TES have significantly lower specific heat losses than small scale systems. Most important parameters that affect heat losses are surface to volume ratio of the storage volume and insulation material. Since they have a lower surface to volume ratios, larger TES have lower heat losses. That is important for long-term storage. The figure below shows the proportion of heat losses to storage capacity ratio vs storage volume for the six-month storage duration. Besides surface to volume ratio and insulation, TES performance is further strongly influenced by the number of storage cycles (how often storage is charged and discharged) [52].

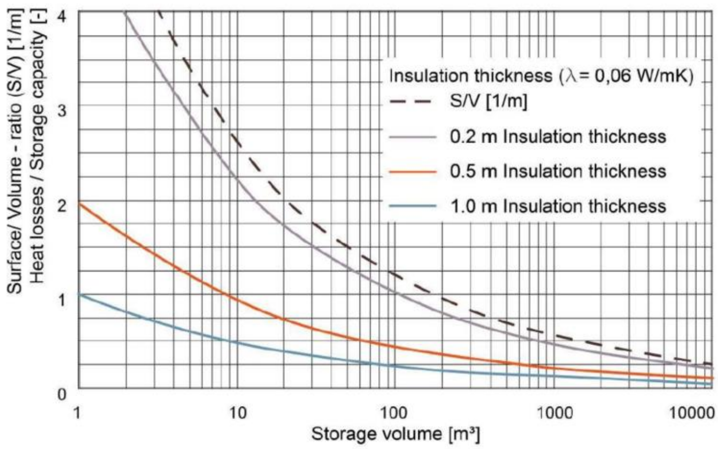

Figure 29 Heat losses and storage volume correlation

In TTES temperature levels depend upon production facility. If the heat production facility is solar collectors or heat pumps, the temperature is between 70-80°C, and for CHP units temperatures are between 90-100°C. The maximum and minimum temperature in the storage affects storage heat capacity and heat losses. Other parameters that influence heat losses are ambient temperature, charging and discharging, wind conditions, insulation thickness and material, and a tank's shape. Heat losses are minimal in TTESs that is shaped like a globe, but temperature stratification is more pronounced in cylindrical storages (which is the goal). Usually, these cylindrical storages are dimensioned that ration between diameter and height is 1,5-2,5. Usually, TTES heat losses are around 3-4%. PTES heat losses also depend on temperature levels, insulation material and thickness, and storage shape. One of the primary heat loss sources, the lid, can be minimised by altering slope of the pit and its depth, but that cannot go indefinitely. BTES heat losses depend on soil type, temperature levels, borehole depth and the shape of BTES. Because the storage medium is soil, it is difficult to control heat losses to the surrounding soil. Heat losses, also occur on the lid, placed on the top of storage. So, that is one of the few places where heat losses can be lowered. As well as BTES, ATES also depends on a project site (aquifer ability to accept and yield water). Thus, it is challenging to control heat losses from the ATES, so focus here is more shifted to monitoring and maintaining thermal balance unground.

5.5 Surplus heat sources and transmission pipes to the storage

Low network temperatures allow utilisation of low-temperature heat from surplus heat sources. Availability of excess heat rarely follows consumption pattern, and thus, heat storages are a crucial part of these systems. Because of inverse proportional dependence on both the storage capacity and storage investment cost on temperature difference, it may be more feasible to store heat at higher temperatures than those in the low-temperature network. Such storage should be located near the heat source or close to the network injection point. To be more precise, the feasibility of storage highly depends on the distance between the surplus heat source and the network. If a source is not close, it is necessary to build a transmission pipe which can make project infeasible even if surplus heat is free [52].

6 Thermal networks

In this section, the focus will be put on ULTDH and NTDH thermal network topologies. The special emphasis will be put on design guidelines, piping, temperature, and pressure levels, including losses.

Prior to talking mentioned topics, definition of ULTDH and NTDH networks should be clarified. There is no official definition, however numerous researchers are usually using similar characteristics and descriptions. Table 4 shows general overview of ULTDH and NTDH networks. The main difference between them and 4th generation, or LTDH, networks need booster heating units to provide temperatures needed space heating and domestic hot water demand.

Table 4 General overview of ULTDH and NTDH networks characteristics [5], [53]

	ULTDH	NTDH
Definition	Ultra-low temperature district heating system which needs booster heater in consumer substation to deliver DHW with suitable temperature level.	Neutral temperature district heating system which needs booster heaters in consumer substation to deliver space heating and DHW with suitable temperature levels.
Temperature	Network supply temperature up to 50°C with return of 20-35°C	Network supply temperature up to 20°C with return of 8-15°C
Heat carrier	Water-based brine in closed loop	
Space heating production	Floor heating or low-temperature radiator in a secondary loop (30-40°C). Network temperatures are high enough to provide low temperature heating.	Floor heating or low-temperature radiator in a secondary loop (30-40°C). Network temperatures are not high enough to provide low temperature heating, i.e. booster heating units in customer's substation is needed.
Domestic hot water production	Domestic hot water temperature should be increased up to 60-65°C to prevent Legionella growth. To achieve this temperature, booster heating units are needed.	
Cooling production	Not possible	Supply network temperatures enable cooling for end customers.
Bidirectional energy exchange	Not possible	Customers and NTDH network supplier can exchange thermal energy, thus achieving bidirectional thermal grid. In ideal case, heating and cooling demands in the network are balanced, thus no additional heating or cooling sources are needed.

Thermal network should be connected to the thermal source, i.e. supply technology. There are different connection types between heat producers and network. They are listed below with their main characteristics [41].

- Extraction from return line and feed in into the supply line (R/S)

Heat medium is extracted from return line of DH network, heated by the source, and then released in the supply line of the network. Required temperature difference depends on operating conditions of the network and on specifications of grid operator. Mass flow through the heat source is regulated by the temperature difference between supply and return. Pressure difference at feed in can be high and up to several bar and thus there is need for extra pumping energy. Grid operators prefer this system because return temperature is unchanged which avoids temperature strain on the pipes and change in production efficiency of other heat producers.

Extraction from the return line and feed in into return line (R/R)

Heating medium is extracted from the return line, then heated and then released back into return line of the network. Limits of temperature rise are set by grid operators, and they are in range between 5 and 15 K. Mass flow always needs to be regulated according to network temperature levels. Pressure difference at feed in is low and it can be regulated via pump or additional adjustable flow resistant in the return line of the network. The flow direction of medium needs to be known for correct design of connection and the pump. Grid operators try to avoid additional flow resistances in network since that requires higher energy demand of central supply pump. Implementation of pumps in decentralized feed in connections is not possible in small network e.g. in small loops of network because of changing flow direction. Because of low temperature difference this variant is not preferable for decentralized heat sources with high efficiencies for lower temperatures such as solar collectors and HPs. This variant also increases heat losses due to higher return temperatures.

Extraction from the supply line and feed in into supply line (S/S)

Heat medium is extracted from supply line, heated, and then returned to the supply line. Maximum temperature raise is prescribed by the grid operator, and it is between 5 and 15 K. This system increases heat losses because temperature is risen. Mass flow is regulated via pump or adjustable flow resistance in the network. Because of low temperature difference this variant is not preferable for decentralized heat sources with high efficiencies for lower temperatures such as solar collectors and HPs. There is also variant extraction from the supply line and feed in return line (S/R) but it is not commonly used, as well as S/S. Figure below shows some of the connections.

6.1 ULTDH networks

6.1.1 ULTDH network design

When it comes to network layout, the two different layouts have been developed: ring layout and tree (mesh) layout. In traditional, tree structure network, consumers close to power plant have higher differential pressures which can cause that there is more water flow at their substation, while substations that are located far away from plant have lower pressures which can lead to insufficient heating. To battle this problem valves are being installed to increase flow resistance until desirable flow at each consumer substation is achieved [41].

To avoid valve installation and hydraulic imbalances when they are applied, ring structure is used. This structure equalizes pressure difference between supply and return pipes. To achieve hydraulic balance each consumer, have equal length of pipes. The supply line begins with heat source and ends with last consumer in the network. Return line, in this network topology begins with first consumer and ends with heat source. In this network typology both supply and return flow have the same direction. Because of that, twin pipes cannot be used which might cause higher heat losses, but double pipe with different pipe diameter can be used. Visual representation of these systems is shown on in Figure 30 [41]. Branch structure of the network has higher heat losses due to bypasses implemented in the network.

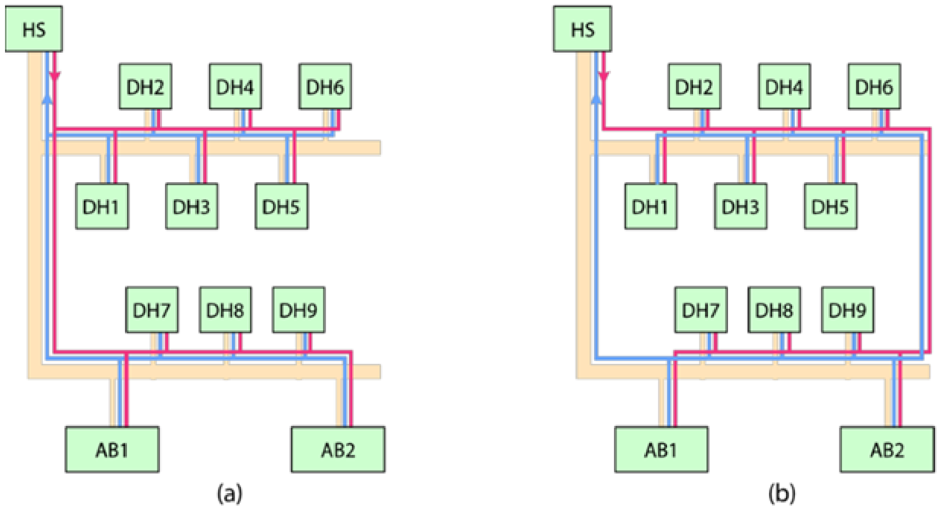

Figure 30 - Branch and loop network topology [41]

Network street circulation bypasses are used to keep network temperature above minimum temperature setpoint. These bypasses replace service bypasses at the consumer substation. They simply mix water from supply line into the return line. Result of them is increased return temperature which then causes increased heat losses. They are used in branch structure network while in loop structure network there is no need for them because network already form closed circuit. Case study have shown that significant energy savings can be achieved when supply water can flow through the whole network [41]. On the other side negative effects are higher pumping power (because of the increase of differential pressure), longer pipes and installation of additional valves and pumps to balance flow in the network. Despite all that, heat savings are significant compared to negative effects.

6.1.2 ULTDH network pipes

To achieve lower heat losses (10 to 15%) [42] in the network and thus higher efficiencies following should be implemented: smaller pipe dimensions, larger insulation thickness (PUR foam insulation), diffusion cell gas barrier at the outer casing (that keeps the properties of PUR foam), twin pipes (or double pipes) and the reduction of pipe lengths [54].

Most used pipe type are twin pipes. There are two types of twin pipes: flexible and steel pipes. Flexible pipes usually have smaller diameters from 14 to 32 mm, while steel pipe have diameters of up to 200 mm, but they are used in straight lengths between 12 and 16 m. Twin pipe illustration is shown in Figure 31 [42]. Specifications of twin pipes are given in Table 5 [54].

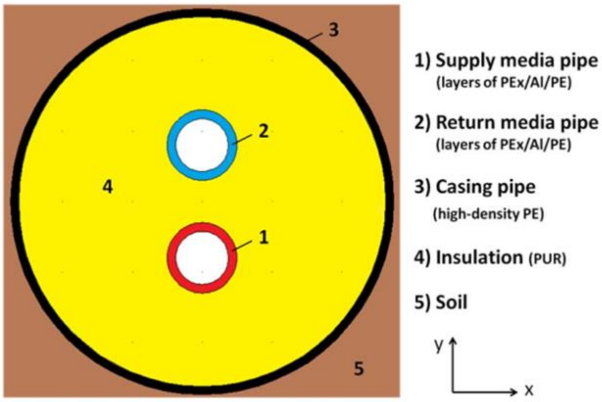

Figure 31 - Geometry and materials of a flexible, pre-insulated, twin pipe [42]

Table 5 Pipe data for the two DH twin pipe types. The heat losses are valid for Tsupply/Treturn/Tground=55/25/8°C [20]

AluFlex twin pipe - Class 2			Steel twin pipe - Class 2		
Pressure class PN10			Pressure class PN25		
Dimension (carrier pipe)	Casing pipe diameter	Heat loss	Dimension (carrier pipe)	Casing pipe diameter	Heat loss
d_{supply}-d_{return}	D	Total	d_{supply}-d_{return}	D	Total
mm	mm	W/m	mm	mm	W/m
14-14	110	2.84	42-42 (DN 32)	182.7	4.96
16-16	110	3.09	48-48 (DN 40)	182.7	5.81
20-20	110	3.66	60-60 (DN 50)	227.9	5.62
26-26	125	4.05	76-76 (DN 65)	256.1	6.57
32-32	125	5.07	88-88 (DN 80)	283.8	7.34

Double pipe networks are used when loop structure of the network is implemented. Double pipe consists of pair of media pipes with different diameters in the same casing. They can be considered as the evolution of twin pipes. One of the characteristics of these pipes is that they significantly reduce heat losses during non-heating periods because there are no bypasses that mix supply water with return. Secondly water in both supply and return flows in the same direction which leads to different sized of supply and return pipe which also reduces heat losses by lowering local pressure differences. Asymmetrical positioning of the pipes further reduces heat losses (as in earlier cases). Compared to twin pipe system, this system reduces heat losses by 6% in smaller networks and up to 12% in larger networks [42].

Besides most used twin pipes, single pipes ad well as triple pipes can be implemented. Triple pipes have two supply lines with smaller (but different) diameter and one return pipe with larger diameter. Only one supply pipe is used in summer conditions when heating demand is low. When heating demand increases, both supply pipes are used. In that way heating losses of the network are minimized, and it allows network to supply hot water at different temperature levels which increases network flexibility [42]. Triple service pipes are the pipes that connect distribution network and consumer substation. They need to be also designed with as smaller diameters as possible to reduce heat losses. But it is not recommended to choose pipes with diameters smaller than 10 mm due to malfunctioning. In Figure 32 below four possible placements of the pipes is evaluated. Placement A is standard placement. In other placements supply line is moved step by step from the centre of the casing, while recirculation line in firstly place between supply and return (cases B and C) and then below the supply in case D [42].

Geometry		Coordinates (x, y) [mm]		
		Pipe 1 (Supply)	Pipe 2 (Return)	Pipe 3 (Supply/Recirculation)
A		(14;-14)	(0;20.5)	(-14;-14)
B		(10;-14)	(0;20.5)	(-21;-7)
C		(3;-14)	(0;20.5)	(-21;-7)
D		(0; 0)	(0;25)	(0;-28)

Figure 32 - Position of media pipes inside the casing for four triple-pipes geometries [42]

Supply and the return pipe in twin pipe configuration can be symmetrically or asymmetrically oriented. One symmetrical configuration is given in Figure 31. Asymmetrical insulation means that the position of pipes in the insulation is such that centre line deviation of the supply pipe is different from centre line deviation of the return pipe. This design leads to lower heat losses from the supply line and even heat losses equal to 0 in return line (keeping isothermal conditions in return line). If commercially available casings are used there are two designing strategies of such asymmetrical pipes, depending on the pipe sizes. For small pipe sizes (Aluflex: ≤ DN 26, steel: ≤ DN 50) the best choice is to place supply line in the centre of the casing (to ensure best insulation). This ensures lower heat losses and thus lower temperature drop along the network. The return line is placed at a vertical distance from the supply pipe, so that heat transfer from them is almost 0. Distance between media pipes is not necessarily the same as in the symmetrical case [42]. Figure 33 shows asymmetrical placement of pipes in the casing.

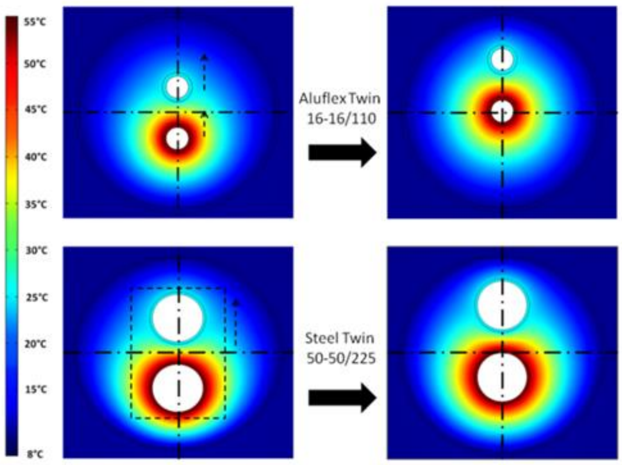

Figure 33 - Proposed modification in DH pipe design (IEA DHC, 2014.)

Degradation of pipes is heavily influenced by temperature regimes of the DH network and should be considered. Lifetime of pipes in ULTDH system can be up to 70 years compared to 30°C to 50°C years in systems with temperatures between 115°C and 120°C [42].

6.1.3 ULTDH network temperatures

Temperature in ULTDH networks is usually defined up to 55°C. However, they usually vary during the season, depending on the ambient temperature. Paper [49] is analysing case study in Bjerringbro, Denmark where temperature compensation is included. ULTDH usually runs on 47°C supply temperature with 1°C increase of supply temperature for 1°C of outside temperature reduction as shown in Figure 34. This results in average monthly temperatures reaching 52°C in January, during coldest periods. Return temperature is usually kept around 30°C.

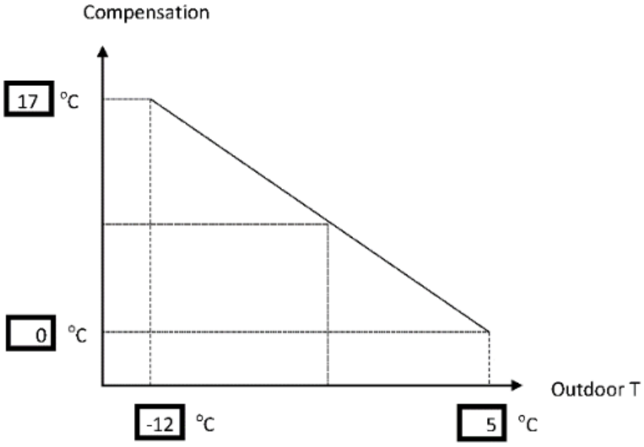

Figure 34 Supply temperature compensation in ULTDH networks [49]

Defining optimal supply temperature depends on numerous boundary conditions such as: thermal source temperature, supply technology, linear heat demand density, etc. It should be defined on case study level by using detailed analysis. For example, in paper [5], Ommen et al analysed ULTDH systems which could utilize cogeneration technologies and central heat pump. Their conclusion is that optimal return for ULTDH networks, based on CHP and central HP is between 21°C and 27°C. This is optimal return temperature since, for such conditions, system efficiency is the highest. In other paper, ULTDH network temperature are 40/25°C and are compared with LTDH temperature regime of 70/40°C [55].

6.1.4 ULTDH network thermal losses

Losses of the thermal network losses depends on many factors, such as commissioning year, heat demand density and temperature regimes [5]. Furthermore, it depends on the pipe type and diameter, as well as insulation thickness and the temperature gradient between the pipe and the surrounding ground [55]. The authors in [4] have shown strong correlation between linear heat density, temperature regimes and heat losses, as shown in Figure 35.

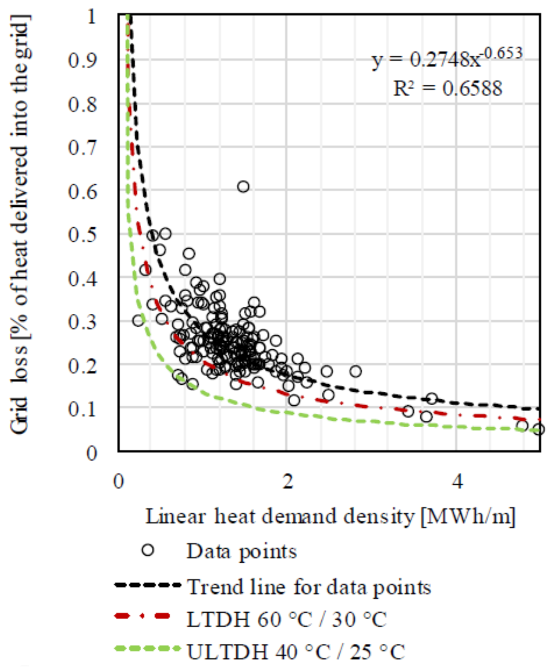

Figure 35 Correlation between heat demand density, DH temperature regimes and specific network thermal losses [4]

According to [55], heat losses in 40/25°C ULTDH networks are usually lower than 10%, and two times lower than for LTDH with 70/40°C temperature regime. However, pressure losses are higher.

6.1.5 ULTDH network pressure levels

Due to low supply and return temperatures, temperature difference is rather low. Such temperature regimes demand increased mass flow rate to establish same level of the thermal load. Increase of the mass flow leads to velocity increase. This results in high specific pressure drop, leading to the higher pumping power needed [5]. Permissible specific pressure losses vary in the literature. However all of them agree that the permissible specific pressure drop is around 50 Pa/m and 150 Pa/m. Paper [5] proposes permissible specific pressure drop around 50 Pa to 100 Pa. Authors in [55] also proposed pressure losses of 100-150 Pa/m to avoid increased pump energy consumption and corrosion, while thermal network is dimensioned for the peak load. E.g. for ISOPLUS maximum flow velocities are 1.2-1.5 m/s for small diameters. In case of composite aluminium and cross-linked polyethylene (PE-X) pipes even higher flow velocities are allowed because of lower surface roughness (k = 0.007) of the pipe and lower risk of corrosion issues. Regarding PE-X pipes manufactures list flow velocities up to 3.0 m/s.

Figure 36 shows flow velocities for different pipe sizes. It can be noticed that increased pipe size increases possible flow velocity [55].

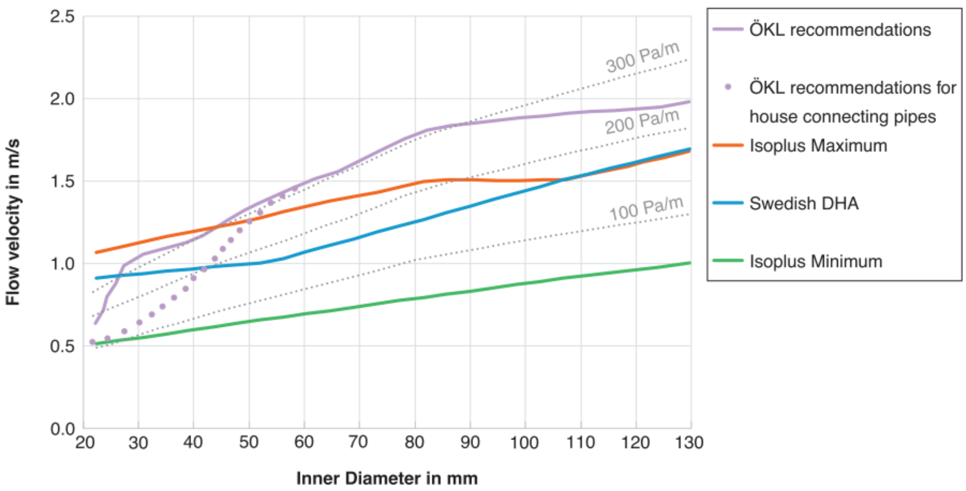

Figure 36 Maximum flow velocities for different pipe sizes and specific pressure losses optimal economic operation of the DH network [55]

6.1.6 ULTDH network dimensioning

Due to lower DH temperatures, temperature difference could be reduced. This could mean that flow in the network needs to be increased. That could cause increase in pipe diameters, but despite that, networks are still designed according to the largest hydraulic load (they need to withstand pressure 1,2 to 1,5 times the nominal value). This is especially important in networks that will not expand any further. Smaller pipe dimensions reduce heat losses. However, DH networks are typically dimensioned according to a permissible specific pressure drop in the range 50 Pa to 100 Pa per meter for the coldest day [5].

Paper [55] proposes generic designing method which is compromise between pumping costs and piping investment costs. If the maximum heat load occurs less than 200 hours per year, then high pressure drops (>200 Pa/m) of short duration can be allowed. This means that smaller pipes diameters can be installed which demand higher flow velocities and higher pumping power for small period.

Authors of [55] also carried out analysis which compares network dimensioning for ULTDH and LTDH networks. It has been shown that ULTDH network demands larger DN values for main distribution lines, while house connections stay the same (DN 20), as shown in Figure 37.

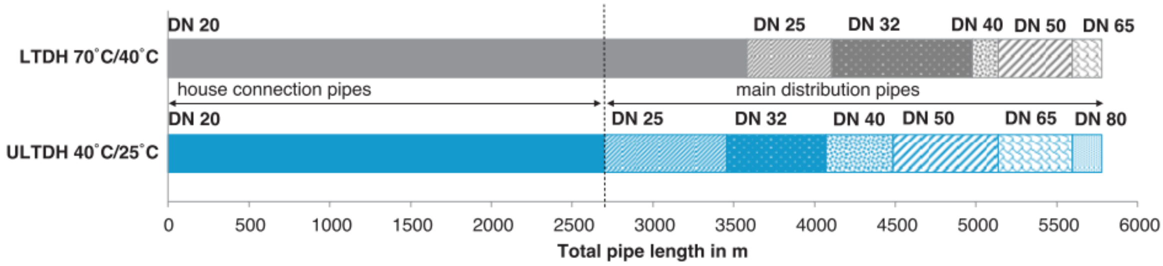

Figure 37 Different pipe size for LTDH and ULTDH network [55]

The paper also proposed specific network construction costs in €/m, ranging from 100-300 €/m for DN 20, up to 200-600 €/m for DN 125. The range depends on the production technology and the pipe type (flexible or rigid), as shown in Figure 38.

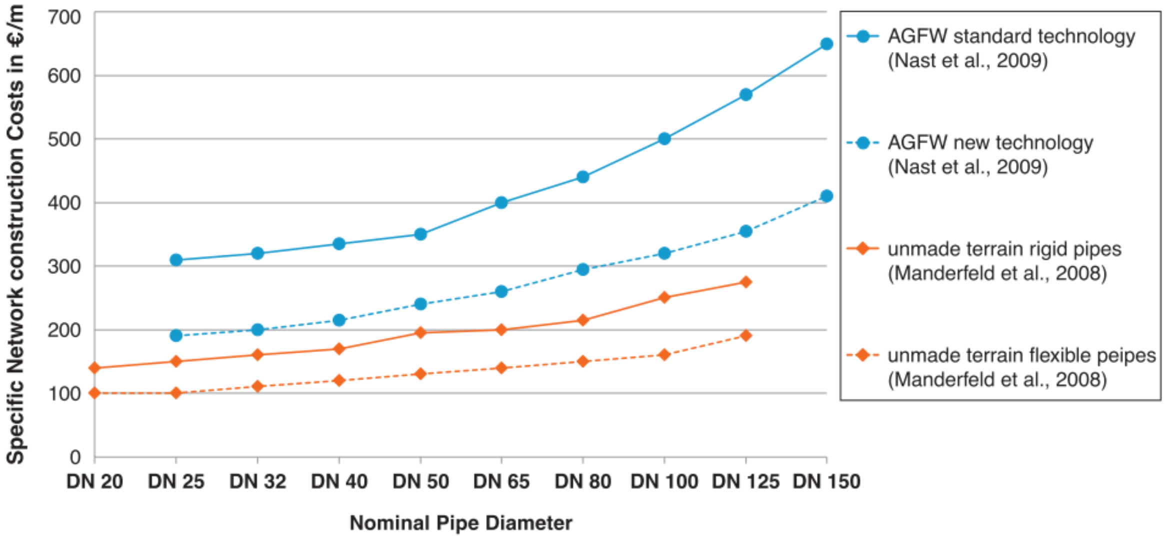

Figure 38 Specific network construction cost for different pipe sizes [55]

It has been shown that discounted network cost is little higher for ULTDH system (40/25°C) than for LTDH (70/40°C). The first being 117 k€/a, while the latter equal to 110 k€/a. However, total system costs were lower for ULTDH, equal to 415 k€/a for ULTDH and 444 k€/a for LTDH.

6.2 NTDH networks

6.2.1 NTDH network temperatures

Review paper from 2018 proposed temperature of a warm pipe around 12-20°C and the cold one around 8-16°C [3]. Due to this, NTDH can cover both heating and cooling demand of the final customer. In a case of a heating demand, the circulation pump of the building withdraws water from the warm line, uses it in a heat pump to reach temperatures suitable for space heating and domestic hot water and then discharges the cooled water to the cold line. In the case of a cooling demand, the system works in the other direction. It takes water from the cold line, heats it up and discharges it in a warm pipe. Due to this, the control of the system is rather complex and should be treated with care. It is important to notice that booster heating devices are needed both for space heating and domestic hot water production. NTDH network is used as heat pump source (in evaporator) for heating and DHW or heat pump sink (condenser) for cooling. In case of low temperature in the grid, cooling can be used directly, thus increasing efficiency of the system. This paper suggest definition of NTDH: "system for distributing cold water in a temperature range between 10°C and 25°C to end-users' substations where it is used to produce, also simultaneously, hot and cold water at different temperatures and for different purposes (space heating, cooling, DHW production) via heat pumps and chillers".

According to [3], generalised NTDH network is divided in primary and secondary circuit to avoid direct heat exchange between heat source and end-users, as shown in Figure 39. This is effective if using sea water, groundwater or similar source with chemical properties which could be challenging to distribute through the network. The paper also proposes three types of customers, each with different thermal load type. The first uses thermal network for cooling purposes, i.e. substation outlet temperature is smaller than the inlet. The second one uses NTDH network for heating, i.e. inlet temperature is higher that outlet temperature of the substation. Finally, the third customer has equal temperature of substation inlet and outlet, which means that it is using NTDH network for both heating and cooling purposes, in equal shares. Furthermore, the secondary circuit in NTDH grid can have optional pre-heating, e.g. during winter season when thermal source temperature is too low. The authors are comparing NTDH network with large-scale system level water-loop heat pump.

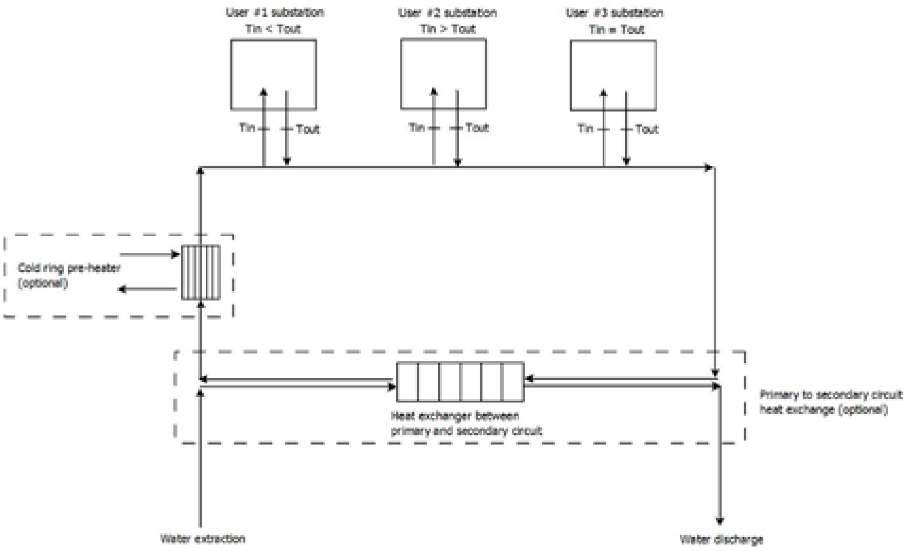

Figure 39 general overview of NTDH network with various final customers

In this case, it is assumed that heating and cooling loads are in equilibrium. If this is not the case, it is necessary to integrate the loop with a heat rejecter (i.e. cooling tower or geothermal heat exchanger), heat supplier (i.e. boiler or geothermal heat exchanger) or energy storage. Important aspect to be considered is number of final customers. The higher the number of simultaneous requests for heat and cold the greater the possibility to limit the temperature variation of cold ring water.

6.2.2 NTDH network thermal losses

According to paper [3], thermal losses of NTDH are evidently smaller than in other LTDH and ULTDH networks. For the network operating at 10°C, they are about 2% of the supplied energy. This is substantially lower when comparing to 60°C and 90°C DH temperature regimes which have losses of 19% and 25% respectively. Additional advantage is that NTDH networks require lower piping insulation, which additionally reduces investment costs. In case of NTDH network temperature levels which are similar to ground, thermal insulation can even be avoided. Reduced thermal losses is one of the most important aspects of using NTDH networks. This enables reduction of operational costs and enables savings which could be used for additional investments needed in the grid.

6.2.3 NTDH network pressure levels

According to Buffa et al [56], pressure losses in high temperature DH networks are relatively low, compared to thermal losses. Ratio of electricity consumption for circulation pumps and delivered heat is around 0.5%, while thermal losses are around 15% of the heat delivered. However, they emphasize that pressure losses are indirectly converted to internal heat gains of the network due to the friction-to-heat dissipation in pipes.

In NTDH networks pressure losses are much higher than in conventional DH networks, due to the low temperature differences which are around 10-15°C depending on the network topology [56]. Such low temperature difference demands high pipe flow velocities which results in increased specific pressure losses. To reduce specific pressure losses, larger pipe diameters should be installed. This issue is also apparent in ULTDH networks, however with smaller impact due to larger temperature differences between supply and return.

6.2.4 NTDH network dimensioning

As in other DH networks, pipeline design is defined according to the specific pressure losses, determined with flow velocity in the network. The pipeline diameter of the NTDH network is thus determined by total peak flowrate, which is computed in turn on the basis of total peak thermal/cooling demand and available temperature decrease/increase. NTDH network requires a higher flowrate in comparison with traditional district heating if the allowable temperature drop in the cold ring is under 10°C, i.e. the diameter of the pipe has to be bigger. However, it should be mentioned that NTDH can supply both heat and cold, thus reducing the investment cost in the network. However, since NTDH network can supply both heating and cooling following aspects should be considered

- If the balance between heating and cooling demand is higher, the required flow rate is lower, thus reducing operational pumping cost. In ideal case, final customers are exchanging thermal energy between themselves, while network serves only as energy reservoir at specific temperature.
- Heat production is partially carried out on-spot, in substation. This means that grid can have capacity lower than peak demand. In other words, capacity of the grid is equal to the peak demand of heat pump evaporator thermal load.

6.2.5 Bi-directional NTDH networks

Bi-directional thermal energy exchange between final customers and the network is the most important advantage of NTDH systems. It allows thermal energy recycling and minimizes external energy supplied to the network. However, not all NTDH networks are utilizing this possibility. Nevertheless, some studies are focusing solely on the possibility of bidirectional energy exchange in NTDH networks.

Authors of paper [57] have studied control of bi-directional NTDH grids by using agent-based control. The only heat and cold source used was a water coupled with a heat exchanger. The water heat exchanger is controlled to keep the warm line temperature between 12°C and 20°C and the cold line temperature between 8°C and 16°C. In previous research, free-floating temperature approach has been used. This means that NTDH network temperature is kept only between lower and higher limits, without considering system efficiency. It implies that temperature was not optimized, it only depended on the heating and cooling demands of the final customers. By using free-floating temperature, the grid is heated-up during summertime and cooled down during winter season, thus diminishing COP of booster heat pumps in substations. In other words, the grid is warm when it should be cold and is cold when it should be warm. Agent-based modelling and optimization of network temperatures enable lower electricity consumption due to higher COP values during winter and summer time.

When analysing bi-directional NTDH networks, the ratio of heating and cooling demand is crucial for system level planning and overall system efficiency. All authors agree with the following: higher the temporal overlap of heating and cooling demand, the greater system efficiency and lower overall system cost. However, perfect overlap of heating and cooling patterns presents ideal case which is hardly achievable in real life scenario. Due to this, authors are analysing the threshold value of heating and cooling demand overlap which could make NTDH systems better than other technical solutions.

Authors of [58] provided thermodynamic analysis of a bi-directional district heating and cooling system. They have developed diversity criterion to understand when the bidirectional system may be a more energy-efficient alternative to modern individual-building systems. They have shown that bidirectional NTDH network is more efficient if there is at least 1 unit of cooling energy per 5.7 units of simultaneous heating energy (or vice versa). They analysed the system where the plant guarantees delivery of water between 12 and 20°C and in net cooling mode, between 8 and 16°C. Furthermore, they concluded that bi-directional systems have higher exergy efficiency than unidirectional systems.

In another paper, authors are also comparing NTDH networks with individual HVAC systems [59]. They have shown that bi-directional NTDH concept provides a cost reduction of 42% and causes 56% less CO_2 emissions compared to individual HVAC systems, network investment for NTDH represents small share in the total annual cost of such systems, as shown in Figure 40. NTDH also have higher exergy efficiency (34%) than individual system solutions (30.2%). In their case study, warm pipe is around 10°C higher than the cold pipe, while both pipes are at the temperature relatively close to the surrounding, around 5-30°C, thus minimizing thermal losses. They concluded that bi-directional networks are excellent for networks with similar heating and cooling demands. In that case, network can be used for demand balancing. Interestingly, the study has shown that utilization of all available waste heat sometimes is not profitable since it raises network temperature and diminishes cooling capacity of the network. It has been shown that cooling towers are economically feasible option since they increase flexibility of the system.

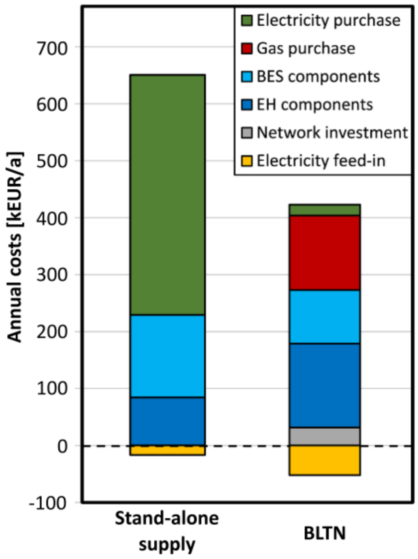

Figure 40 Discounted system cost comparison for individual HVAC and bi-directional NTDH systems

In paper [2], authors have studies the importance of heating and cooling demand balancing in bi-directional NTDH networks. The paper introduces quantification of simultaneousness of district heating and cooling demand, called demand overlap coefficient (DOC). It has been shown that the higher DOC the higher exergy efficiency of the system. Moreover, district energy systems with bi-directional NTDH networks have lower specific supply costs than a state-of-the-art reference system if the district DOC exceeds 0.45. The better economic and thermodynamic performance of systems with large district DOC is a result of the larger potential for balancing demands in the districts. Figure 41 shows how heating and cooling demand overlapping influences the system efficiency and cost. As expected, the higher demand overlap coefficient the better is the system COP and specific cost. Furthermore, it can be noticed that networks with higher cooling demand (R<0) the better system COP. Of course, the reason behind is much lower temperature lift between cold NTHD pipe and cooling demand temperature which increases chiller's efficiency.

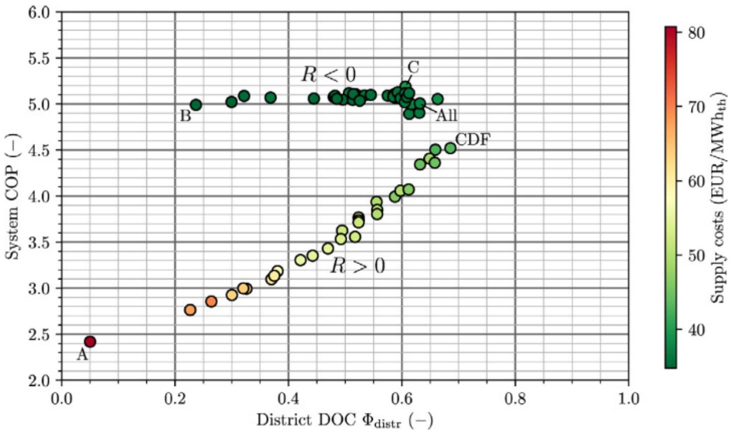

Figure 41 The impact of heating and cooling simultaneousness (DOC) and heating-cooling ratio (R)

6.2.6 NTDH as reservoir network

All NTDH networks discussed so far have "traditional" topology which includes two pipes: warm and cold pipe. It should be mentioned that NTDH networks usually does not include terms such as supply and return pipe, since network serves both for heating and cooling. Some researchers go even one step further to reduce network investment cost. Authors of [60] propose new network topology which includes only one pipe, so called reservoir network which enables simultaneous heating and cooling, as shown in Figure 42.

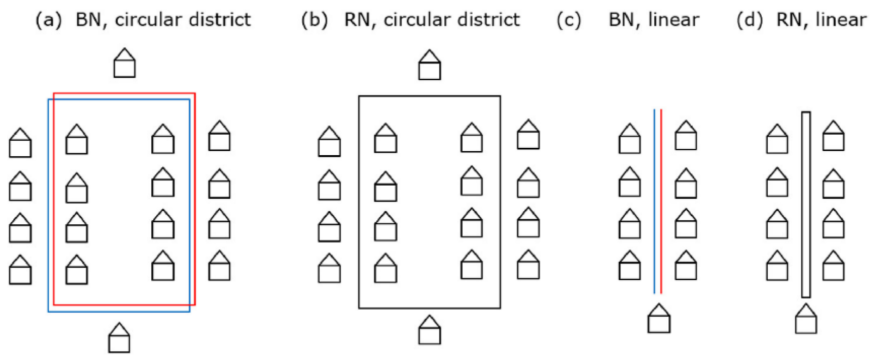

Figure 42 Overview of "traditional" two-pipe and one-pipe "reservoir" NTDH network topologies [60]

Although energy consumption is relatively same for reservoir networks, energy consumption of circulation pumps greatly depends on network control and pipe diameter. By using flow rate controller, the difference is relatively low, below 1%. However, if there is no flow control, the circulation pump energy consumption can be higher than 48% as shown in Figure 43.

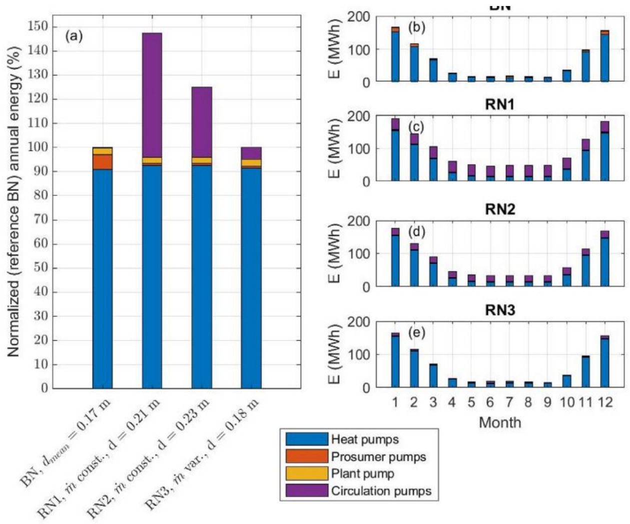

Figure 43 Pumping power consumption for different NTDH topologies and system controls

The biggest advantage of reservoir network is following. Reservoir network needs only 50% of the pipe length. For this reason, it is economically feasible to increase pipe diameter. An increase in diameter of up to 95% of the reservoir network compared to the two-pipe NTDH can be accepted while still maintaining an economic advantage. For the reservoir network with variable reservoir mass flow rate, a slight increase in pipe diameter by 6% over the BN average diameter leads to the most economical solution.

6.2.7 Other issues related to NTDH networks

Physical and chemical water properties of the NTDH network are crucial issue, especially when thermal source is circulating directly in the network [3]. For this reason, secondary and primary circuits in NTDH networks should be used. High levels of hardness and/or contaminant concentration may result in a high risk of clogging and/or damage to the pipeline components, like valves or heat exchangers. Depending on the particular application, a filtration-separation system may be added to the plant. Sea water presents major issue since materials should be chosen with care to avoid corrosion and galvanic currents.

One of the remaining challenges in bidirectional networks is managing complicated hydraulics, and strategic questions, such as how well this bidirectional system translates to different locations and different energy load profile [58]. Similar issues have been observed in other papers. Bi-directional networks have specific control challenges such as pump-to-pump interaction [60]. The problem occurs especially in case of prosumers of different sizes – large prosumers affect mass flow through small circulate pumps of other prosumers. Sometimes reverse flow can even occur. Furthermore, decreased mass flow may cause freezing damage in heat pumps. However, increase of mass flow can lead to cavitation in in circulation pumps. For this issue, booster pumps can be used.

7 End-user substations

Substations are crucial part of ULTDH and NTDH networks since they provide temperature boost for space heating and domestic hot water production. Unlike traditional DH networks which have only heat exchangers in end-user substations, ULTDH and NTDH network substation need to integrate temperature boosting devices due to insufficient temperature levels in a network.

ULTDH and NTDH are usually coupled with well-insulated buildings with low-temperature space heating demand, such as floor heating. Although space heating temperature regimes could be relatively low, less than 40°C, as shown in Figure 44, domestic hot water production needs high temperature levels. These temperature regimes are relatively high, around 60-65°C, and are the main challenge for successful development of ULTDH and NTDH networks. It should be mentioned that DHW temperature regimes cannot be reduced with building renovation. High temperatures are needed to prevent *Legionella* growth, as explained in detail in Section 7.1.

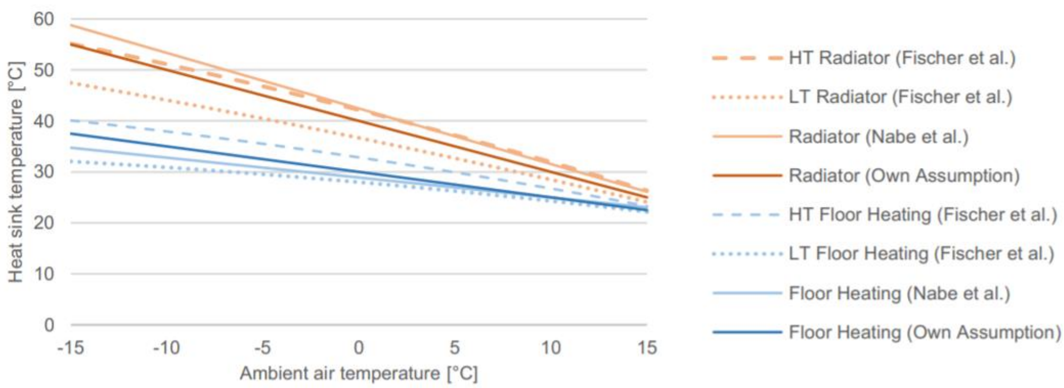

Figure 44 Different space heating temperature regimes [61]

7.1 Legionella

Legionella is group of gram-negative bacteria that grows in water and humid environment. Factors that influence its growth are water temperature, dimension and age of hot water system, hydraulic structure of a system, materials and construction, stagnation of the water in the system, scaling and the particles in hot water and the presence of commensal microbial flora (biofilm). Most influential factor of them all is the water temperature. The most suitable temperature range for growth of this bacteria is between 30 and 45°C. But studies have shown that in almost 73% of the cases there is no growth of *Legionella* because of short dwell time of the water in the system even with temperatures that promotes growth of it (that is the reason why installations are limited to 3 litres with no circulation). Figure 45 shows percentage where most of *Legionella* can be found in the system [42]. The study collected samples from different locations of a DHW system. The percentage next to each system segment shows the ratio of samples that have shown presence of *Legionella* (K100-indication). The most critical parts are where cold and mixed water can be found but that percentage decreases as water temperature in other segment increases [42]. Location in the system is directly correlated with temperature level. Figure 46 shows *Legionella* growth/decay as function of temperature. Lukewarm water is the best temperature regime for bacteria growth and must be avoided at all costs.

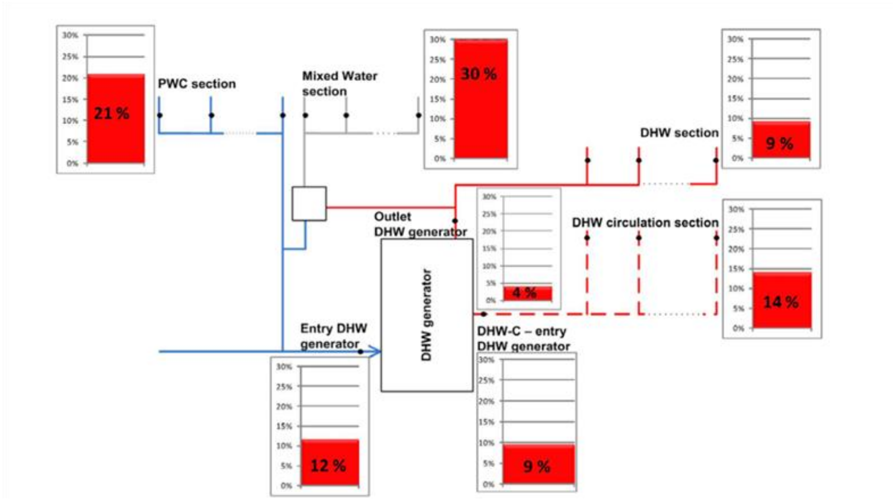

Figure 45 - Summary of central systematic and partly central contamination (K100-indications); PWC-portable water (cold); DHW-domestic hot water; blue lines-portable water, red lines-domestic hot water, grey lines-mixed water [42]

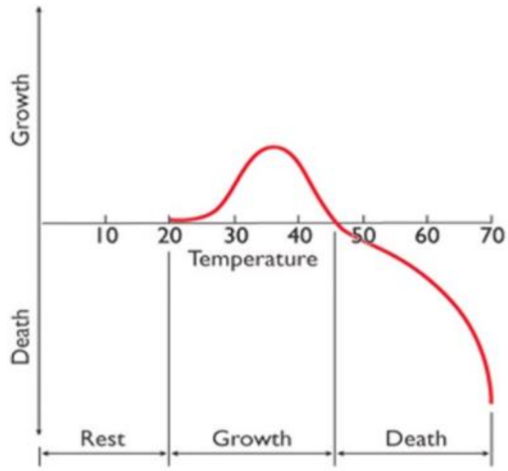

Figure 46 - Legionella growth/decay rates as function of temperature [41]

Main goal of DHW preparation system design is to reduce *Legionella* growth while keeping temperatures as low as possible. Most of the EU countries follow European guidelines EN 806-1:2000, EN 806-2:2005 and EN 1717:2011 when it comes to determining lowest temperature of DHW installations without *Legionella* growth. These guidelines suggest that temperature for portable cold water (PWC) should not exceed 25°C, and that temperature of DHW should not be less than 60°C 30 seconds after fully opening of tap. They also give some design recommendations as well as procedure od lowering risk of scalding [41]. However, every country can change these guidelines to suit their needs the best.

To reduce temperatures of DHW, and thus reduce heat booster unit operational cost, different *Legionella* treatments in system can be integrated. Bacteria growth can be diminished or even prevented. Basically, two approaches could be used. The first one includes alternative designs of DHW production system, while the second one involved different sterilisation methods. It must be noted that most of sterilization methods are allowed for a limited period because they can cause contamination [42].

7.1.1 *Alternative design*

Paper [62] provides general overview of various DHW preparation approaches to eliminate bacteria growth issues. General guidelines are following. Copper pipes have been shown to perform better than PEX pipes, and systems with instantaneous heaters have been found to be less contaminated than those with storage tanks. Vertical tanks have been shown to be more vulnerable to *Legionella* than horizontal ones. Alternative DHW system designs are listed below.

Decentralized substations

Decentralizes substation minimize volume of the DHW system. They are ideal for multi-storey buildings which would otherwise need large volume of the DHW system. End-users can regulate both temperature and heat demand, thus increasing flexibility. Furthermore, there is no need for circulation circle.

Micro heat pump

Heat booster unit which enables local temperature elevation. Heat pump source can be both DH supply and return. The location of the micro heat pump in the building is important issue which should be analysed in detail.

Electric heating element

Electric heating element much simpler solution that heat pump, however the efficiency does not go as high as heat pump, thus increasing operational costs. The electric heating element can be either integrated within storage tank or fitted separately. It can be used to boost DH temperature or prepare DHW directly.

Electric heat tracing

Electric heat tracing is wound around the DHW supply pipe and heats the DHW water when necessary. It is flexible solution since it can heat up a whole water volume or just a part of it. It does not require circulation pipe or a heat storage tank and is relatively simple to integrate into the system. However, like the previous technical solution, it has much lower efficiency than a heat pump.

7.1.2 *Sterilisation methods*

Sterilization methods can be divided in three types: thermal, chemical and physical treatment [42], [62].

Thermal treatment

Legionella can be killed rapidly at high temperatures. Thermal treatment means that the whole system needs to be treated at the same time with the raise of a temperature to more than 60°C at faucet. This method is used as a shorth term treatment for the bacteria outbreak, and it can be combined with other methods such as chemical for long term effect. World Health Organisation recommends a heat shock of 70°C for 30 min which needs to be repeated twice during the 72 hours period. When storage tank is used temperature should be lifted to 70-80°C and kept in that range for 72 hours to eliminate all bacteria in the tank [41].

Chemical treatment

Chemical treatment involves rinsing the piping system with chemical biocides to eliminate Legionella. It is widely spread treatment of systems which include ionization, oxidizing agents and non-oxidizing agents. To achieve high effectiveness of a treatment chemicals, need to be dosed precisely, but after the process finishes system needs to be thoroughly flushed to remove erosive and toxic chemicals. Ionization uses two different ionized metals (copper and silver electrode) to disrupt permeability of bacteria's cell walls. Oxidizing disinfectants are most widely used. Some of them are chlorine, chlorine dioxide, ozone, monochloramine and hydrogen peroxide [41]. Photocatalysis is a new water treatment technique for hot water systems [62]. The method used is to activate a solid catalyst such as titanium dioxide (TiO2) using sunlight and produce oxidants to kill bacteria. UV sterilization kills bacteria using UV light while filtration membrane retains bacteria because of its fabric structure with a lot of microscope pores (minerals in water can freely pass through) [41]. State-ot-the-art DHW treatment include oxidization which allows DHW temperature to be around 48°C (pilot project in Sweden). This system reduces both bacteria and biofilm on which bacteria grows. This method significantly reduces heat needed for DHW preparation.

Physical treatment

Physical treatment mainly refers to filtration which prevent the microorganisms from getting into the protected site by using membrane filter. Filtration is very effective, but the short lifetime of the filter is one of its most important limitations. Operation costs of filtration are much higher than any other method since the filter has to be replaced regularly. Another limitation is retrograde contamination. The filter can easily lose its efficacy by coming into contact with contaminated sources.

7.2 ULTDH substations

Ultra-low temperature district heating networks have temperature regimes (up to 35-55°C) which are suitable for low-temperature space heating, such as floor heating. However, they are too low for domestic hot water production. Due to this, ULTDH substation always include direct heat exchanger for space heating purposes and booster heater unit to provide temperature regimes which are suitable for prevent *Legionella* bacteria occurrence in the DHW system of the building.

Development of ULTDH substations is often topic of research and there are numerous reports dealing with the analysis of the most suitable ULTDH substations. In the following paragraphs, the most common practices and research outcomes are presented.

Study [63] modelled various proposals for district heating systems with different supply temperatures for two different building topologies. The paper proposes two solutions for ULTDH. The first proposed solution includes electric micro tank which can be easily installed in a building with existing IHEU. The tank is heated up to 60°C with electric heater which is immersed in the tank. The water from the tank is mixed with water from the heat exchanger. The micro tank system can be applied in both single-family houses and multi-storey buildings with instantaneous heat exchanger units. Figure 47 shows the implementation of the electric booster unit for different building types. In case of single-family house

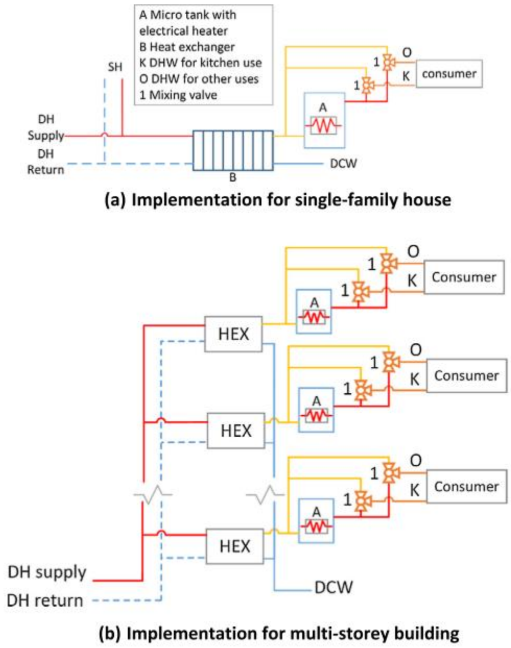

Figure 47 Electric heating booster implementation for single-family and multi-storey building [63]

The second solution is micro heat pump, which is convenient for single-family houses. Heat pumps uses supply of DH both as a heat source and a heat sink. This enables high COP, especially when compared to electrical heater solution. It is important to mention that tank is located on primary side, thus preventing any issues with bacteria growth. Figure 48 shows booster heat pump in combination with hot water tank on the primary side. This is often used DHW system also proposed in [50].

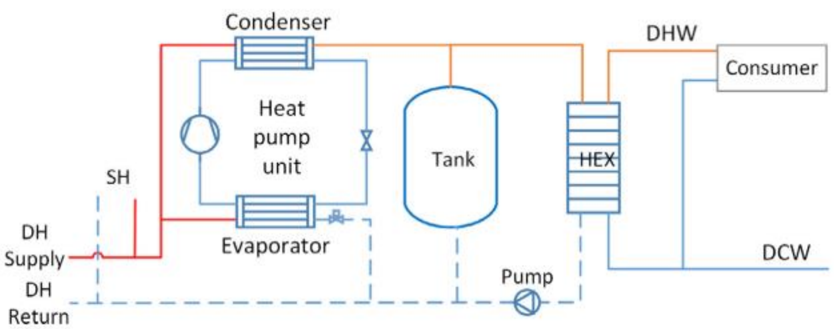

Figure 48 Heat pump booster unit in combination with tank on the primary side [63]

During substation development process, it is important to consider domestic hot water circulation losses [5]. They occur in DHW pipes, which results in heat demand with high mean temperature. Some solutions reheat the DHWC by mixing with DHW in stratified tanks, which requires the DHW to exceed the temperature levels required to avoid the bacteria growth.

Besides tank location, DHW booster heat pump also can be installed in the primary or the secondary side of the system. When DH is used for evaporator heat source, return temperature could be too low for direct heat exchange. Control of the return temperature is crucial for optimisation of both central heating plant and network and final customers. New substations sometimes have two booster units for matching of the demand of multifamily buildings. Such booster units are usually single-stage HPs [5].

Tommen et al found that a heat pump on the primary side of the hot tap water heat exchanger, is superior in terms of COP and exergy efficiency at almost all temperature configurations of low temperature DH [6]. Both approaches are shown in Figure 49. Booster HP integration on the primary side is usually combined with stratified tank on the primary side. According to [6], there are basically two main approaches for booster heat pump and stratified water tank positioning in a DHW system: i) the water has to be preheated to temperature where bacteria growth is avoided in order to be stored and ii) heated water cannot be stored after heating.

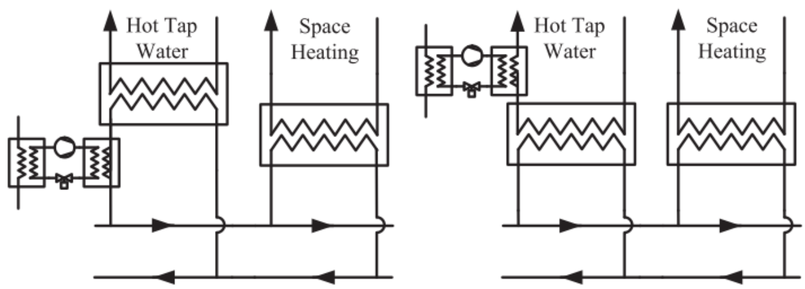

Figure 49 Booster heat pump positioning in a DHW preparation system [5]

Similarly to papers [6] and [63], [64] explores theoretical implications of different substations for DHW preparation through utilisation of electrical heaters and heat pumps. Analysed DH network is 45/25°C, with the supply temperature high enough to supply space heating demand. Three boosting substations have been proposed: i) electrical heater, ii) heat pump with secondary side tank and iii) heat pump and primary side tank and. Two heat pumps refrigerants have been considered, R134a and R744. In the first configuration, the required hot water temperature is obtained by supplementary electric heating between the district heating and the hot water tank. This solution has 89% system energy efficiency, however only 16% exergy efficiency with the total cost of 870 €/year and the highest CO_2 emissions of 1.4 Mg/y. The highest heat pump COP, equal to 9.6, is obtained for R134a refrigerant, preheating and primary side tank. The cost of such solution is 740 €/y with only 1.1 Mg of CO_2 per year. Obtained solutions have been compared with conventional DH systems with 80/40°C and 65/55°C temperature regimes, with similar total yearly costs.

In other paper, Meesenburg et al compare three ULTDH concepts with LTDH systems by using levelized cost of heat (LCOH), socio-economic NPV and seasonal COP (SCOP) [4]. The analysis was carried out for different boundary conditions of plot ratio, specific heat demand and different booster unit configurations. They have shown that LTDH is better from the economic point of view, however ULTDH could be feasible for higher values of linear heat density and lower investment cost of the booster units. The paper studies ULTDH with 40/25°C temperature regime with three different DHW booster unit configurations, as shown in Figure 50. All of them are utilizing heat exchangers for space heating the only difference is DHW preparation system. The first configuration is using DH forward temperature as the HP heat source and heat sink. Substation and booster HP were implemented at building level. The advantage of this configuration is a high booster HP COP of 5.23. Second configuration is using air-source booster HP to supply DHW to the building. Due to this, COP is lower than for the first configuration and in range 2.9-3.3. These two configurations are also including DHW storage tank with 60°C of inflow temperature to prevent bacteria growth. The third configuration does not include thermal storage tank since it uses micro booster units at each apartment. Heat source is DH supply network. Due to the smaller volume of the piping, DHW temperatures are assumed to be lower, around 54°C, resulting in the highest COP, around 6.7. To secure bacteria-free environment, DHW temperatures are increased once-twice per week. According to the manufacturer, this presents relatively small energy consumption, equal to 1% of the total consumption. Due to this, it can be neglected.

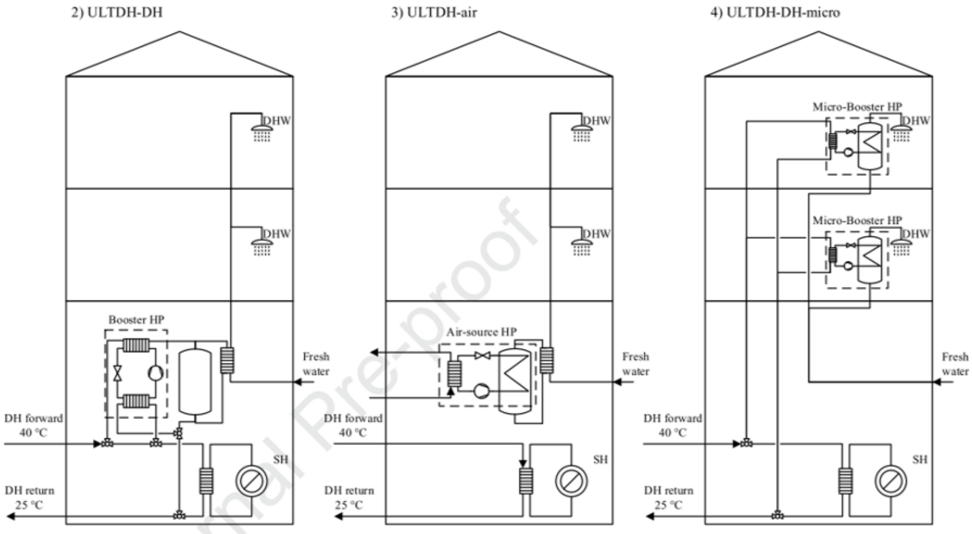

Figure 50 Different ULTDH substations for DHW production [4]

Paper [65] also compares five different substations for DHW preparation in ULTDH networks by using energy and economic performances.

Substation 1: DHW is stored in the storage tank and used directly. The DHW is preheated by the district heating and further heated by the immersion heater. To meet the hygiene requirement of avoiding Legionella, water in the tank is kept above 60°C.

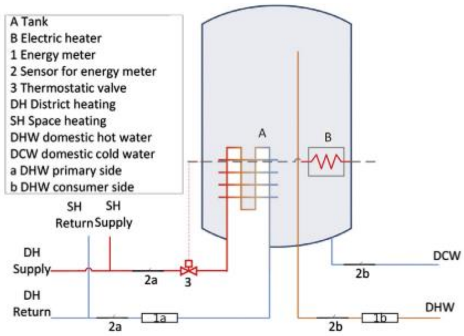

Figure 51 ULTDH substation based on immersion heater [65]

Substation 2: has a heat exchanger after the storage tank, and the district heating water is stored in the tank. The DHW can be heated instantaneously by the heat exchanger, which reduces the risk of Legionella. The set-point temperature of the immersion heater in substation #2 was 55°C to assure the DHW could achieve 45-50°C.

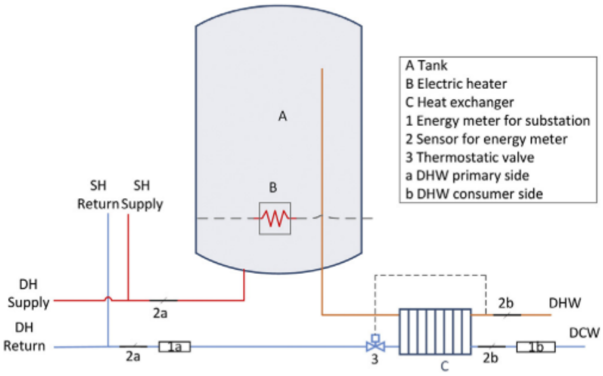

Figure 52 ULTDH substation based on district heating storage tank [65]

Substation 3: micro heat pump and a storage tank are installed before the heat exchanger. Such application has been tested and proved to have a good exergy performance for heat supply [13]. One stream of the district heating supply is used as the heat source for the heat pump. The set-point temperature of the tank was 55°C

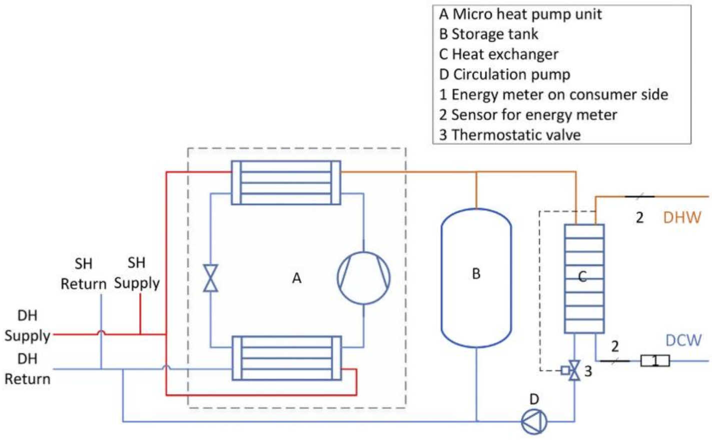

Figure 53 ULTDH substation based on heat pump [65]

Substation 4: DHW is preheated by district heating through a heat exchanger. It is assumed that temperature is high enough for taking the shower, while electrical heater is installed for DHW flow to kitchen taps.

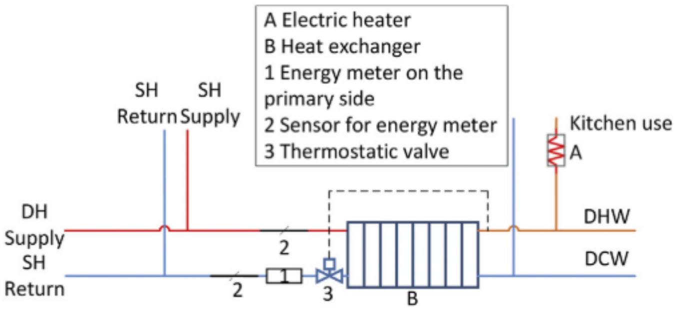

Figure 54 ULTDH substation based on electrical heaters on kitchen taps [65]

Substation 5: has the same layout as substation #4, except that an electric heater was used to heat up the total DHW flow

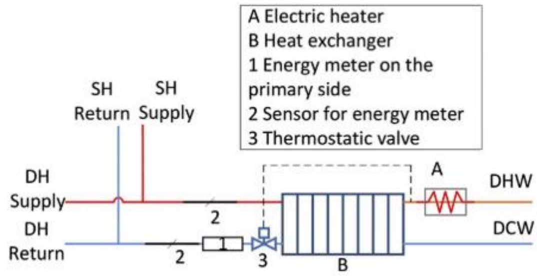

Figure 55 ULTDH substation based on electrical heaters on kitchen taps [65]

Comparing the measurements and model results of the five substations, substation #4 and #5 with an in-line heater as supplementary heating device had better energy and economy performances than the other substations.

Paper [66] analyses ULTDH network, by using parametric study. DH supply temperature was in range between 15-45°C with 5°C step, while temperature difference was 5, 10 and 15°C respectively. The substation model consisted of thermal storage tank and a booster heat pump which utilizes DH supply as the heat source. However, supply space heating temperature for the buildings was relatively high, higher than 45°C, thus space heating could not be covered by direct heat exchangers. The economic analysis shows that the system is already competitive with individual gas boilers provided that a local low-temperature heat source can be recovered with minor marginal costs.

Zühlsdorf et al seek to obtain optimal zeotropic mixture to increase performance of booster heat pump in ULTDH system (40/25°C) [48]. The booster substation uses forward temperature of DH system both as source and sink to reach 60°C for thermal storage tank which feeds DHW. Space heating regimes is 35/25°C, thus covered with direct heat exchanger. It was concluded that the mixtures 50% Propylene/50% Butane and 50% R1234yf/50% R1233zd(E) could considerably improve the thermodynamic performance of the overall heat supply system while being economically competitive to pure fluid. The increase in COP was found to be 31% for a required minimum superheating of5 K for the mixtures and 47% in case the required superheating can be reduced to 0 K. The best resulting COP was equal to 9.

7.3 NTDH substations

Neutral temperature district heating substations must be capable of providing temperature boost both for domestic hot water and space heating. The most common technology used is water-to-water booster heat pump in different configurations. Besides space heating and domestic hot water, NTDH networks can also supply space cooling and substations should also be designed in that manner. Space cooling can be covered directly via heat exchanger from cold pipe or by using booster heat pump and NTDH network as a heat sink.

Paper [3] proposes general NTDH network substation configuration for multipurpose booster heat pump which can operate in four different working conditions, depending on the valves open-close positions:

- Heating purpose, where S3 is used as evaporator (cold ring heat source) and S1 as condenser (space heating heat sink).
- Cold water production (chiller), where S1 is now evaporator and S3 operates as condenser

- DHW production, where working principle is similar to heating, but this time S2 is used as a condenser. S3 is once again evaporator
- Cold water production and condensation heat recovery for DHW where S1 operates as evaporator and S2 as condenser. In this mode, there is no heat delivery to the network.
- In addition, substation can include cold and/or hot storage water tank, in case of simultaneous thermal and cooling needs. If the cold ring temperature is low enough it can bypass multi-purpose heat pump and go directly to the cold-water heat exchanger. Furthermore, it is possible to heat or cool water flow to the NTDH network

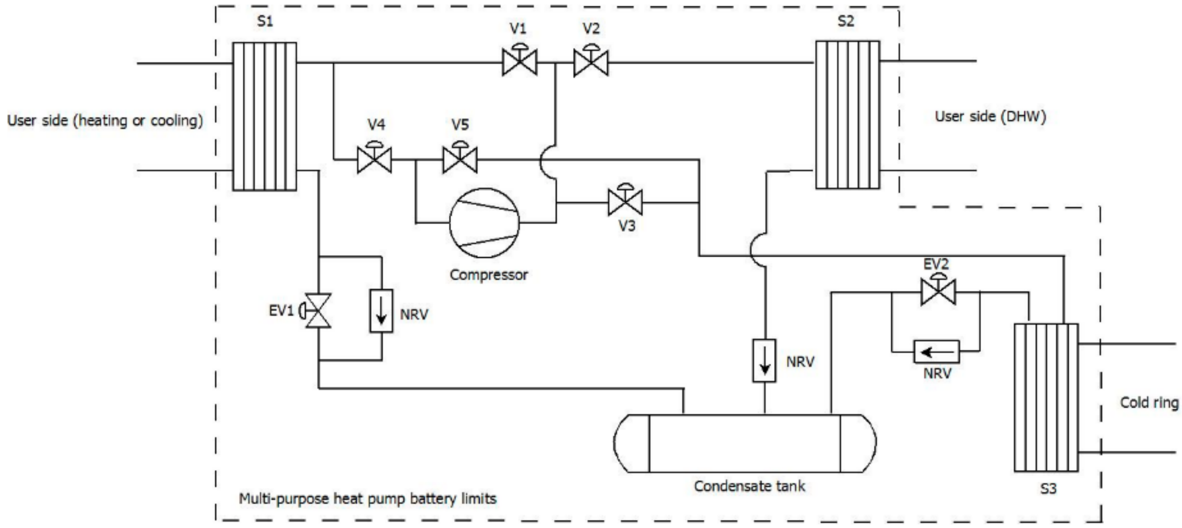

Figure 56 NTDH substation proposal [3]

NTDH substations are more complex and bigger than in traditional DH systems. First, they require booster technology, usually a heat pump. Secondly, due to low temperature regimes, temperature drop across heat exchanger is relatively low which requires high heat exchange surface area for the same level of heat demand. Thirdly, these systems usually need cold and/or hot water thermal storage. All of this can become crucial issue since additional space in the building should be reserved. This is quite problematic for existing buildings which are connecting to NTDH network.

Buffa et al [56] provided overview of best practice examples for prosumers in thermal networks an proposed NTDH substation shown in Figure 57. Three solutions are shown. Substation A is the simplest one where water-to-water booster heat pump is connected to the thermal network to provide heating and cooling. Two 3-way diverter valves are used to enable free-cooling via heat exchanger. This solution also includes back-up unit which could represent redundant thermal source after building refurbishment and connection to the NTDH network. Substation B uses redundant heat exchanger which is placed between thermal network and booster heat pump. It is also used as safety measure for booster heat pump from fouling risks. Additional heat exchanger results in temperature difference increase and reduced COP of the heat pump. In some cases, this heat exchanger could be optional, however this depends on local regulation and practices. Substation C is the most complex solution and involved two diverter 3-way valves on the primary loop. This enables to reject separately hot water (in active or free-cooling mode) in the warm pipeline and cold water (in heating mode) in the cold pipeline, what avoids thermal mixing within the network so that the exergy content of the DHC transfer fluid is not lost.

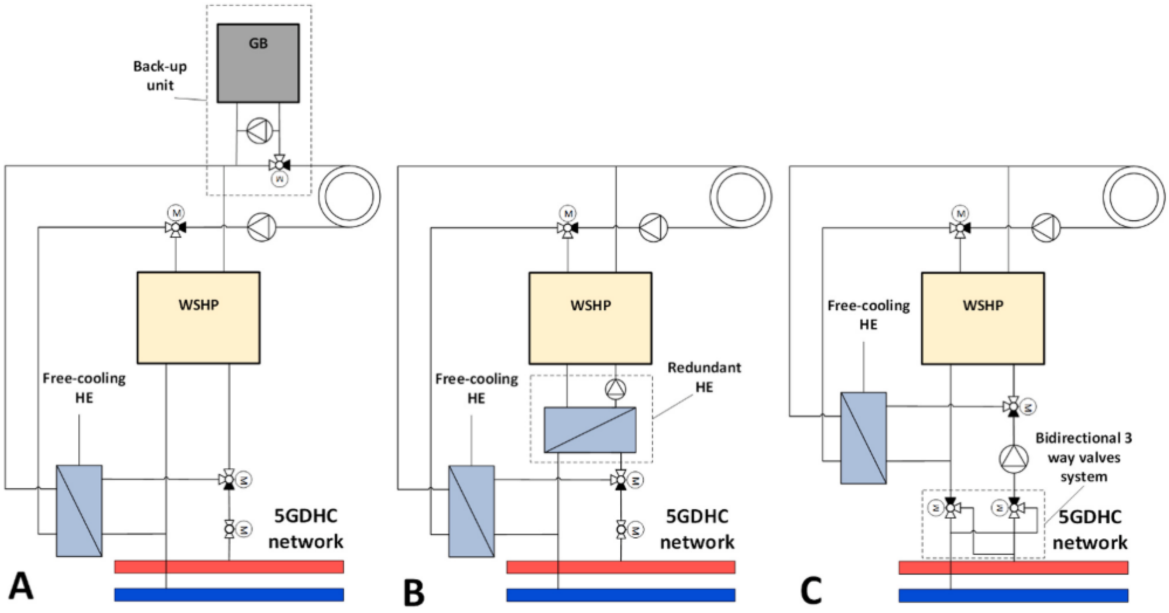

Figure 57 Proposal of NTDH substation by Buffa et al [56]

Figure 58 shows NTDH substation configurations in Mijnwater NTDH system [67]. In Case A, thermal network is used as a heat source for booster heat pump to boost the temperature for building thermal demand. In Case B, when the thermal network supply temperature is higher than building return temperature, part of the heat load can be directly covered by the network and heat pump covers only partial building load. If thermal network temperature is higher than the building's required supply temperature, the thermal load if distributed directly from the network, as shown in Case C. If the return to the network needs to be cooled to be lower than return temperature from the building, the building return flow is both fed to the HP evaporator and condenser. In Case D, when higher temperatures in network is allowed, booster heat pump can be fully by-passed and thermal load is directly covered by the thermal network only via heat exchanger.

Additional details on the NTDH substations can be found in D4.1. - Configuration and sizing of packaged substations and other deliverables dedicated to WP4 (Technologies for low temperature RES and WH harvesting).

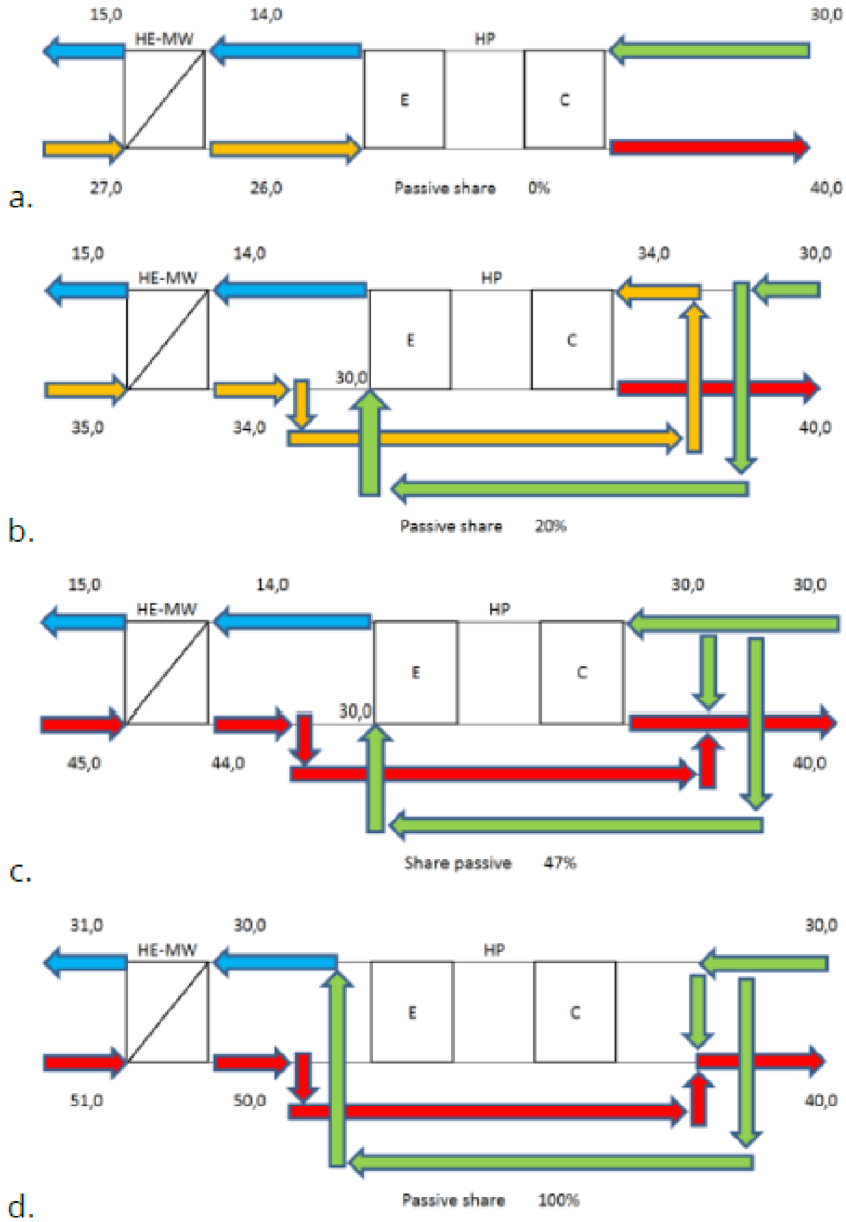

Figure 58 Mijnwater's NTDH substation [67]

7.3.1 NTDH Substation control and metering

Periodical wireless meter reading provides continuous measurement of energy consumption [3]. This is crucial for efficient payment system. Data mining makes it possible to optimize matching of energy demand and production at substation and network level. The metering should also be able to measure thermal energy injected to the grid by the end-users. This will enable implementation of a smart and bidirectional energy grid. Bi-directional metering needs sophisticated smart metering network and an efficient control and regulation system, including novel business models

8 Overview of existing next generation DHC networks

For this deliverable, 124 existing district heating systems have been analysed with respect to thermal source type and temperature regimes. The database [68] is publicly available on Zenodo platform, on this **link**.

Overview of thermal sources used in NTDH networks is shown in Figure 59. Shallow geothermal, i.e. ground and ground water, is the most commonly used. However, temperature regimes of the network allow large-scale utilisation of waste heat sources, which is also evident in the figure. Around 20% of the studied existing systems are utilising waste heat source. Besides shallow geothermal, solar is the most frequently used renewable energy source.

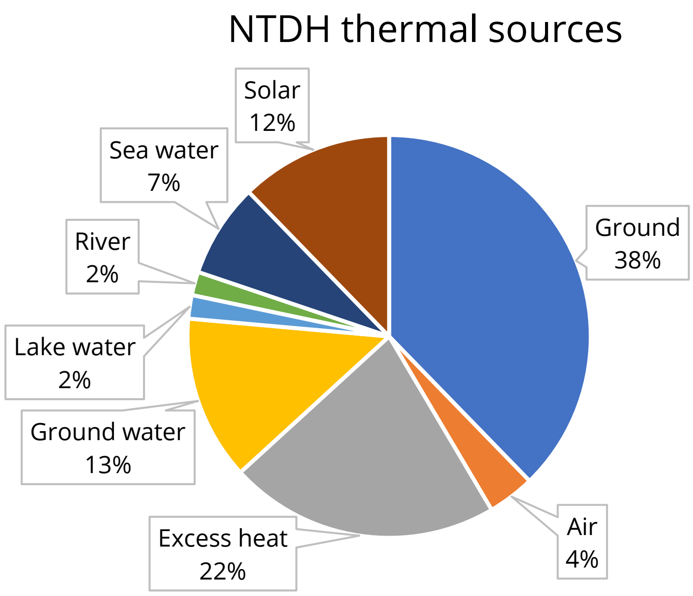

Figure 59 Overview of thermal sources in existing NTDH networks

Figure 60 shows which thermal sources are the most often coupled with ground. Most commonly, ground is used as the only thermal source in the NTDH networks. In 25% of the analysed systems, ground is coupled with excess heat. Next most favourable coupling thermal source is solar (13%) or solar combined with excess heat (7%). On the other hand, Figure 61 shows the most common thermal sources coupled with ground water. In most of the cases (86%), ground water is the only thermal source used.

During the analysis, only few ULTDH networks have been identified. The most probable reason is that are usually defined as LTDH network with simple DHW boosting devices. Nevertheless, Figure 62 shows the most used thermal sources. ULTDH networks are mostly based on solar thermal, as expected for such temperature regimes.

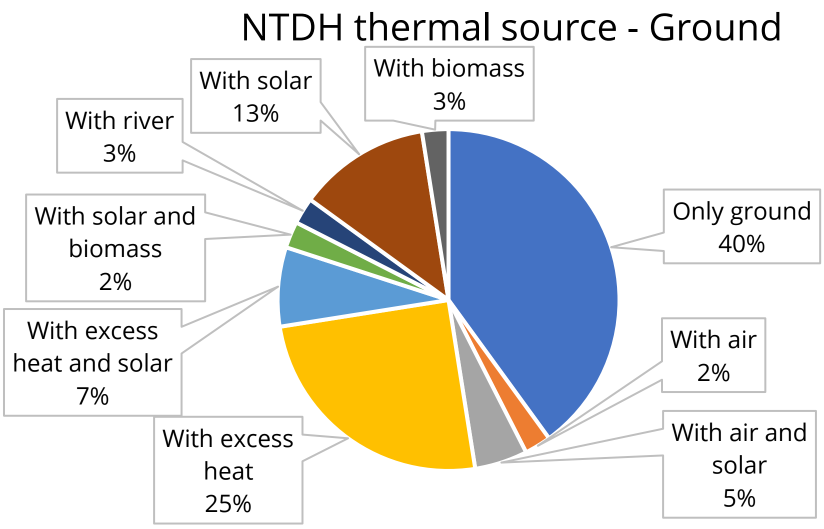

Figure 60 Overview of thermal sources coupled with ground in existing NTDH networks

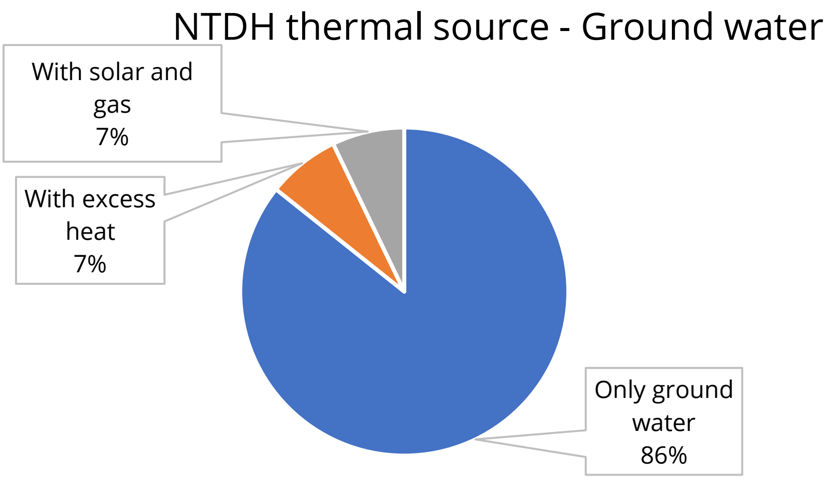

Figure 61 Overview of thermal sources coupled with ground water in existing NTDH networks

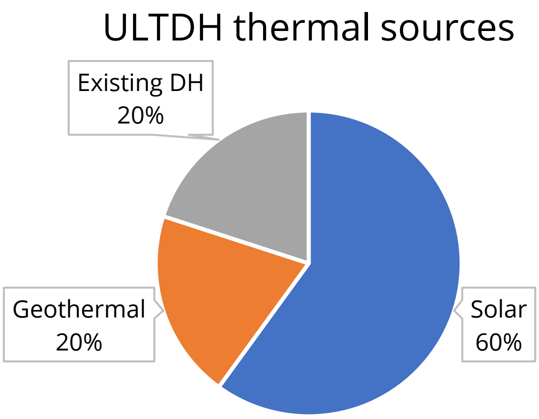

Figure 62 Overview of thermal sources in existing ULTDH networks

Overview of thermal sources used in LTDH networks is shown in Figure 63. Although these networks are not the topic of this deliverable, they are also analysed to show crucial differences between traditional LTDH and ULTDH/NTDH networks. First of all, it can be noticed that, in most cases (36%), LTDH networks are connected to existing high-temperature networks via shunt or heat exchanger. Excess heat is also dominantly used in these networks (21%) together with ground (16%) solar (11%) and biomass (7%).

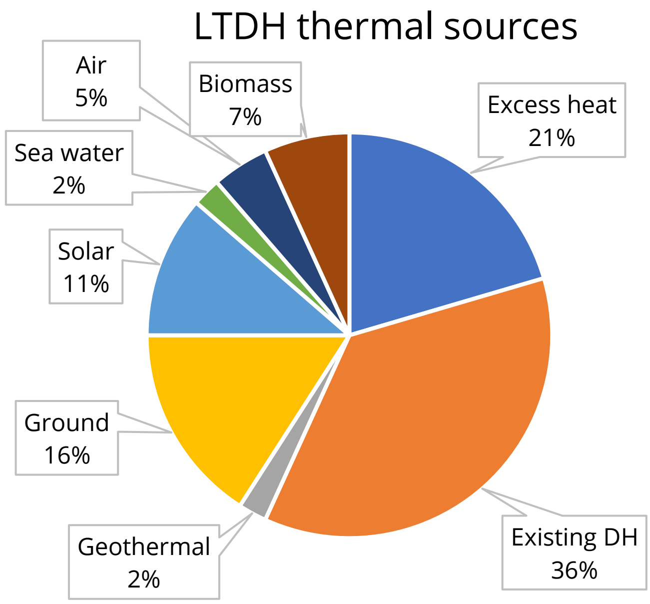

Figure 63 Overview of thermal sources in existing LTDH networks

Figure 64 shows overview of temperature regimes throughout the network, starting from the thermal source, supply pipe network, final user supply temperature, final user return temperature and finally return pipe of the network. The temperature level overview is shown for LTDH and NTDH networks. Firstly, it should be noticed that in LTDH networks, the highest temperature usually occurs at the thermal source or at the supply pipe of the network, depending on if a heat pump is utilised or not. Then, the temperature level is gradually decreased to the temperature regimes at the final user and return pipe of the network. On the other hand, temperature levels in NTDH networks are the lowest at the thermal source location and usually identical to the ones in the network. In other words, utilisation of booster heat pump at the thermal source is seldom used. In NTDH networks, temperature boosting is carried at the end-user substation level, as evident from the diagram. It should be noticed that the end-user temperatures are similar in both networks. Final demand consists of domestic hot water and space heating. It should be mentioned that space cooling is not shown in this diagram, but it is evident that some NTDH networks can even cover space cooling demand directly via heat exchangers.

Figure 65 shows temperature differences between supply and return in the networks. It is noticeable that temperature differences are much higher in LTDH networks (between 15-40°C), while temperature difference in NTDH networks is usually below 10°C due to extremely low temperature levels in supply and return pipe. Of course, this result in lower thermal losses of the grid. However, it could present an issue due to higher water velocities in the pipes to maintain the same level of thermal capacity. Consequently, this could lead to higher pressure losses or larger pipes resulting in higher operational or investment cost. Nevertheless, cost-benefits of each system should be analysed in detail while considering all boundary conditions.

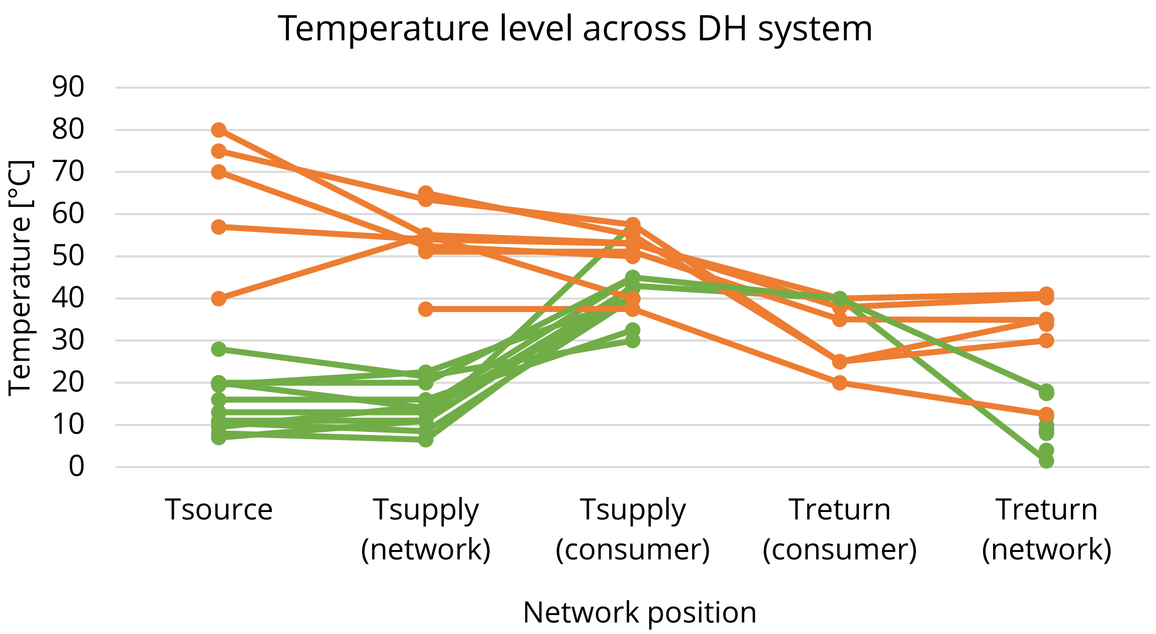

Figure 64 Temperature levels across DH system: green – NTDH, orange – LTDH

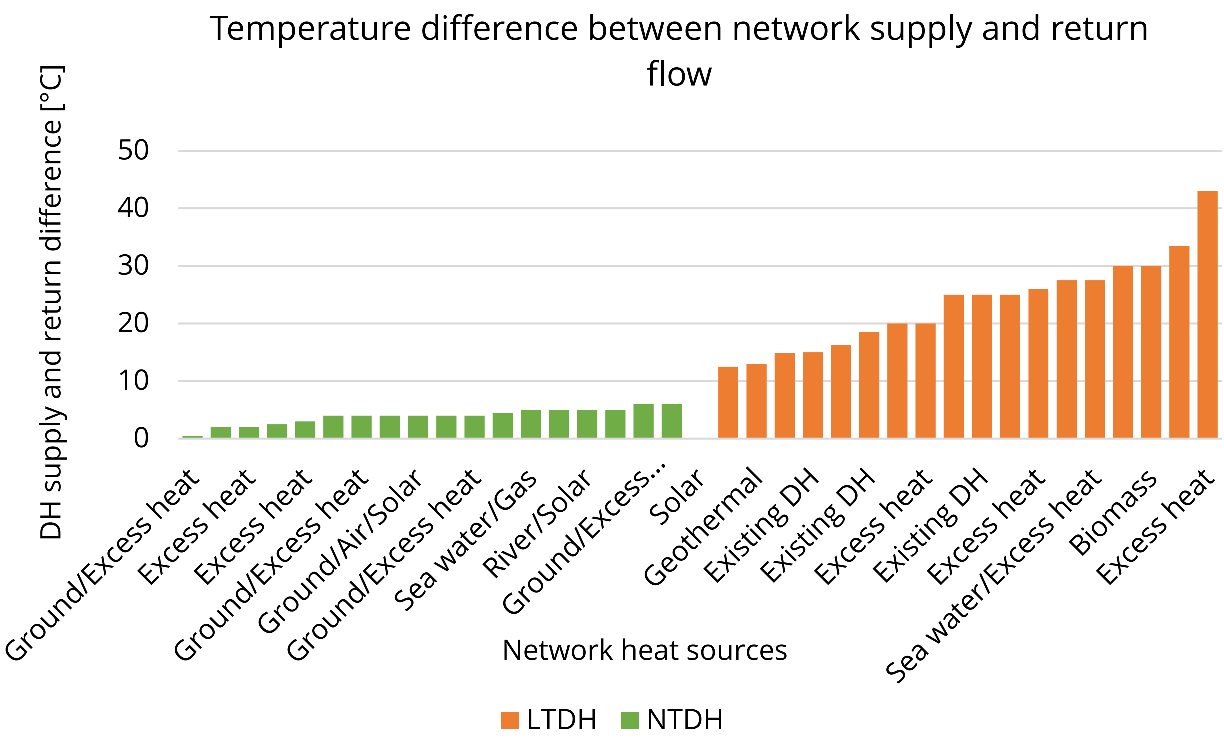

Figure 65 DH network supply and return temperature for different systems

9 System components database

In this section, different system components are analysed and discussed by using SWOT analyses. Then, different combinations of system components integration have been proposed, while considering best practice examples and carried out literature review.

9.1 District heating and cooling system overview

District heating and cooling system has different components, as illustrated in Figure 66. Thermal supply constitutes of the thermal source, coupled with supply technology and thermal storage, thermal network, and end-user substation.

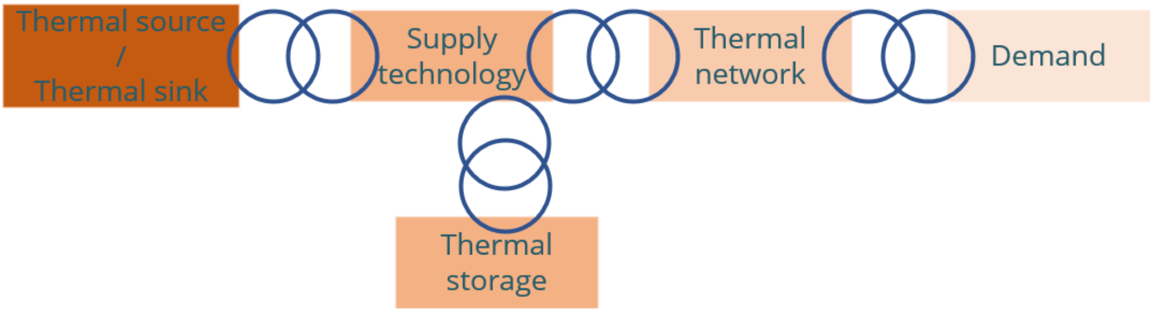

Figure 66 Overview of the DHC system

In this section, different types of end-user substations, thermal networks and thermal sources are shown. These system components can be combined in numerous different ways. In this document, the most common combinations are shown while focusing on ultra-low temperature (ULTDH) and neutral temperature (NTDH) district heating system. Main characteristics of such networks, and comparison with traditional low-temperature (LTDH) systems are shown in Table 6.

Table 6 Main characteristics of ULTDH and NTDH systems

LTDH system	ULTDH system	NTDH system
Temperature regimes around 55-60°C	Temperature regimes around 35-45°C	Temperature regimes around 15-25°C
Thermal losses relatively high (~20%)	Thermal losses relatively low (~15%)	Thermal losses are minimal (~10%)
RES and urban WH must be boosted via HP before thermal network	RES and urban WH are usually boosted via HP before thermal network	RES and urban WH can be directly injected in the thermal network without booster heat pump
No need for boosting technologies in end-user substations	Need for DHW temperature boosting in end-user substations	Need for SH and DHW temperature boosting in end-user substations
Simultaneous heating and cooling not possible	Simultaneous heating and cooling not possible	Simultaneous heating and cooling possible

9.2 End-user substations

End-user substation is component which is usually located in the building of the final user. Substation is used to connect primary (thermal network) and secondary (building) thermal circuit. End-user substations are used to cover space heating (SH), domestic hot water (DHW) and space cooling (SC) demand. The type of end-user substation is directly related to temperature regimes in the thermal network. Due to this, in this analysis three substation types are defined: LTDH, ULTDH and NTDH substations. The main characteristics of ULTDH and NTDH substations are shown in Table 7, which shows main characteristics of ULTDH and NTDH substations and comparison with "traditional" LTDH substations. Additional details on end-user substations can be found in deliverables D4.1 - Configuration and sizing of Package Substations and D4.2 - Prefabricated skids.

Table 7 Main characteristics of ULTDH and NTDH substations

LTDH substations	ULTDH substations	NTDH substations
Space heating and domestics hot water demand can be covered directly without temperature boosting Substations use traditional technologies and concepts Relatively simple design and operation Investment relatively small Bi-directional energy exchange with thermal network is not possible	Space heating can be covered directly by using direct heat exchanger, while domestic hot water demand should be covered via booster unit or additional heater Substations must use boosting technology such as electrical heater (simple solution) or booster heat pump (more com) Substation design more complex since it includes DHW booster technology Investment is increased due to booster technology Bi-directional energy exchange with thermal network is possible but limited	Both space heating and domestic hot water demand cannot be covered directly due to low temperature regimes in the thermal network. Boosting technology, such as heat pump is needed Substations are usually based on water-water heat pumps with relatively high COP due to small temperature differences between heat source and heat sink Substations are relatively complex, resulting in high investment. Operation is relatively complex and thermal network operator usually must be responsible and is owner of the equipment Low operational cost due to high COP of heat pump Possible to cover cooling demand Bi-directional energy exchange with thermal network is possible

9.2.1 LTDH substations (no booster)

Two LTDH substations are presented in this section, based on instantaneous heat exchanger unit (IHEU) and the other one based on district heating storage unit. For each solution, simple scheme is shown, including SWOT analysis.

LTDH substation – instantaneous heat exchanger unit

This LTDH substation is based on instantaneous heat exchanger unit. It is highly efficient and compact heat exchanger capable of providing domestic hot water on-demand. The SWOT analysis for this substation is shown in Table 8 while substation scheme is shown in Figure 67.

Table 8 SWOT analysis, LTDH substation – instantaneous heat exchanger unit

Strengths - Low-space consuming - Cost-effective
Weaknesses - DHW production on demand (no TES available)
Opportunities - Easily upgradeable
Threats - System flexibility is reduced

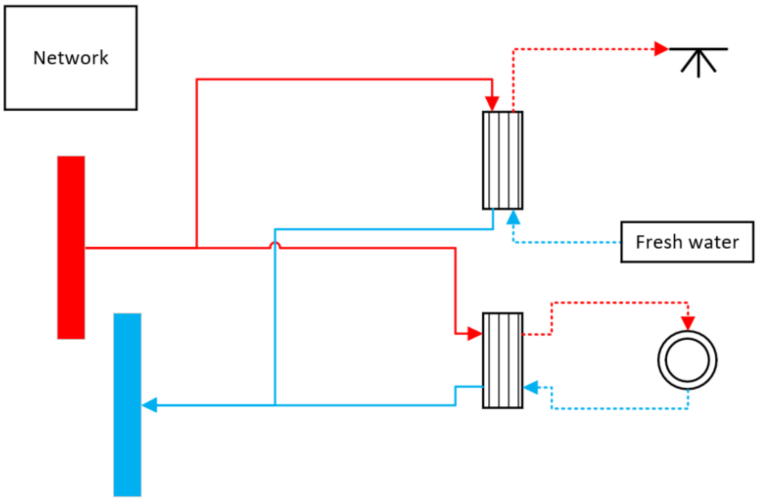

Figure 67 LTDH substation – Instantaneous heat exchanger unit

LTDH substation – District heating storage unit

Second LTDH substation is based on district heating storage unit. Due to water stagnation, temperature regimes must be higher that with IHEU. This solution demands higher volume for installation of district heating storage tank. Besides thermal storage unit, heat exchangers are needed domestic hot water and space heating demand. Table 9 shows SWOT analysis for this substation, while Figure 68 displays simplified schematics of this solution.

Table 9 SWOT analysis, LTDH substation – District heating storage unit

Strengths - Increased flexibility (TES available on-site)
Weaknesses - TES investment needed - Additional space is needed in the building
Opportunities - Easily replaceable with different space-demanding solution (booster heat pump)
Threats - Higher temperature is needed due to stagnated water (Legionella risk)

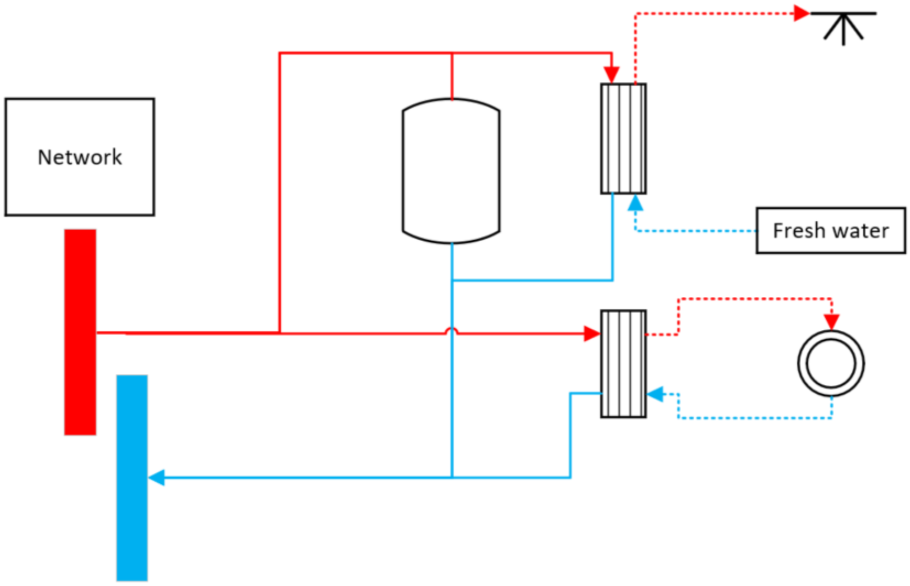

Figure 68 LTDH substation – District heating storage unit

9.2.2 ULTDH substations

Four different ULTDH substation concepts are analysed in this section, with integrated DHW booster technology. The first solution is based on booster heat pump combined with district heating storage unit. Second solution utilizes micro booster heat pumps. Third and fourth solution are using additional booster technology such as air-water heat pump or a boiler unit.

ULTDH substation – booster heat pump and district heating storage unit

This substation is based on booster heat pump combined with district heating storage unit. Thermal network supply line is used both as a heat source and a heat sink for a heat pump. Hot water is feeding the district heating storage unit and/or DHW heat exchanger. Since the temperature regime of the network is suitable for space heating demand, no boosting is needed. Table 10 shows SWOT analysis while Figure 69 displays schematics for this ULTDH substation.

Table 10 SWOT analysis, ULTDH substation – booster heat pump and district heating storage unit

Strengths - Single heat pump per building - Flexible and central DHW production - Reduced cost (BHP economy of scale) **W**eaknesses - Space demanding (building substation) - Lower booster heat pump COP due to higher temperature in TES needed **O**pportunities - Easily replaceable with different technology - Flexible production could utilise low electricity tariffs **T**hreats - Water stagnation (high temperature needed) - DH network reduction influences BHP COP

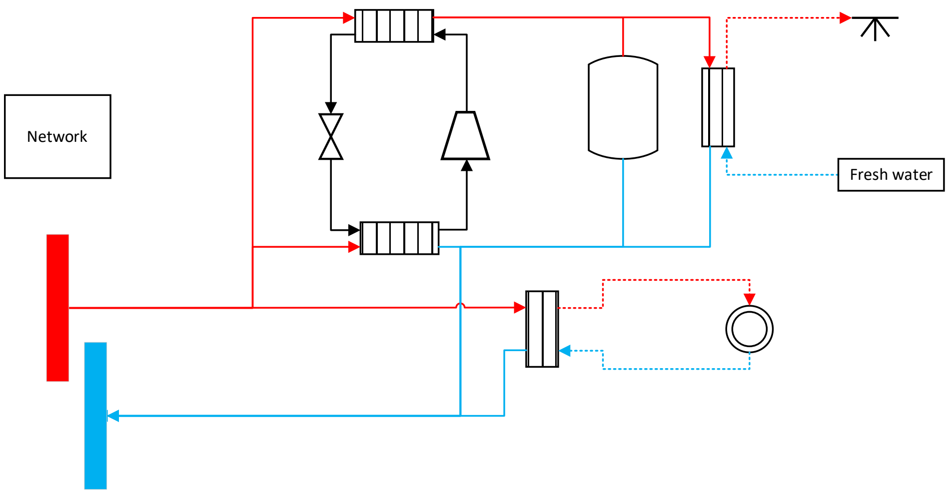

Figure 69 ULTDH substation – booster heat pump (supply split to evaporator and condenser) and district heating storage unit

However, different configuration is also possible, as shown in Figure 70, where supply from the thermal network is used only as a heat source for booster heat pump.

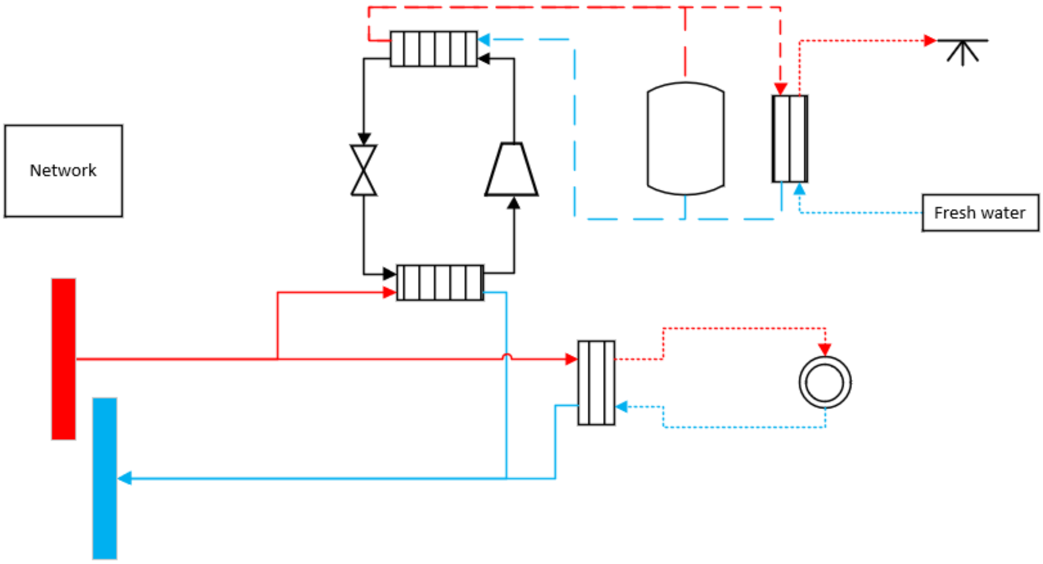

Figure 70 ULTDH substation – booster heat pump (supply only as heat source) and district heating storage unit

ULTDH substation – micro booster heat pumps

The substation also utilizes thermal network supply pipe as a heat source, however there is no central heat pump in the substation. On the contrary, every apartment building has its own micro booster heat pump which enables DHW production on-demand. This means there is little-to-no water stagnation in the system and temperatures can be kept relatively low (around 55°C), thus resulting in relatively high COP. Thermal network temperature regime is sufficient for space heating production, thus only heat exchanger is needed. Table 11 shows SWOT analysis, while Figure 71 displays substation scheme.

Table 11 SWOT analysis, ULTDH substation – booster heat pump and district heating storage unit

Strengths - Low temperature lift, due to low water stagnation, results in high COP - Low-space consumption
Weaknesses - Every apartment needs booster heat pump - Investment cost intensive
Opportunities - Low operational cost and low vulnerability to electricity tariffs
Threats - Difficult to replace

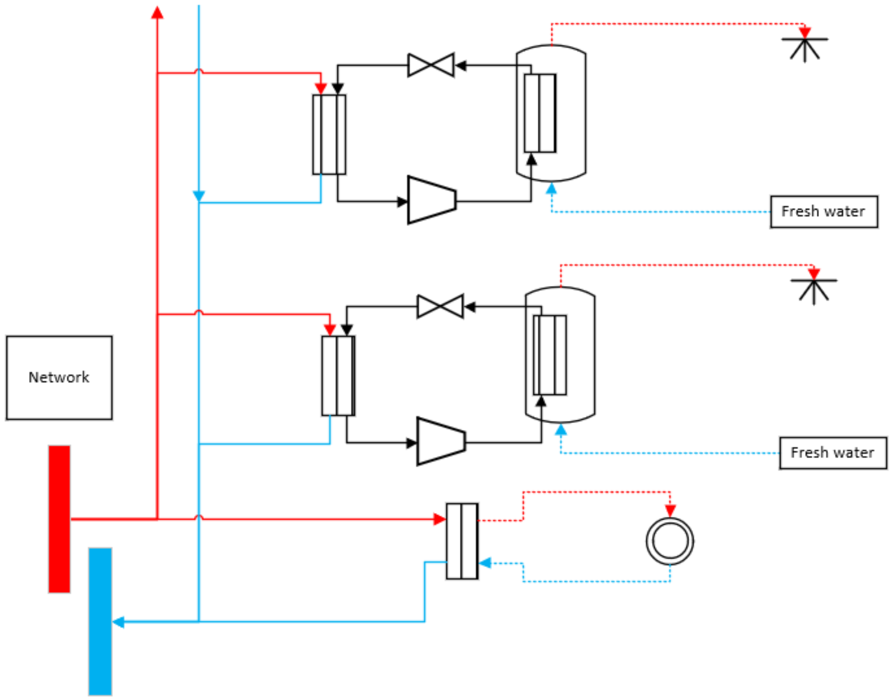

Figure 71 ULTDH substation – micro booster heat pumps

ULTDH substation – other booster technology (e.g. air heat pump)

This substation is using ULTDH network only for covering space heating demand. Since thermal network temperatures are sufficient, only heat exchanger is needed. However, for domestic hot water production additional locally installed technology should be used, such as ais-source heat pump. Table 12 shows SWOT analysis of this ULTDH substation and Figure 72 illustrates substation scheme.

Table 12 SWOT analysis, ULTDH substation – other booster technology (e.g. air heat pump)

Strengths - Simpler system planning - Utilisation of well-established technologies **W**eaknesses - Thermal network is not utilised as a heat source (lower system COP) - DH connection and additional supply technology is needed (high investment) **O**pportunities - Booster technology could also serve as a back-up technology if DH network is under retrofit e.g. **T**hreats - Operational cost depends on the booster heat source (on the other hand DH temperature regimes are guaranteed)

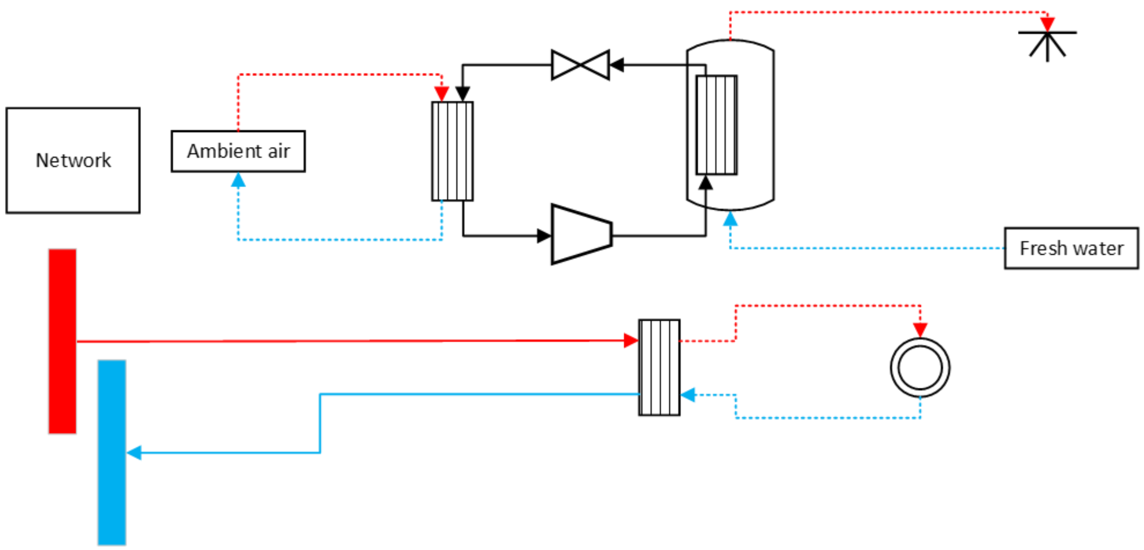

Figure 72 ULTDH substation – other booster technology (e.g. air heat pump)

ULTDH substation – other booster technology (e.g. boiler)

Like the previous one, this substation is also additional booster technology to cover domestic hot water demand. In this case, the booster technology is a boiler which can use electrical energy, natural gas or biomass. Table 1 shows SWOT analysis, while Figure 73 illustrates substation overview.

Table 13 SWOT analysis, ULTDH substation – other booster technology (e.g. boiler)

Strengths - Simpler system planning - Utilisation of well-established technologies - Local energy tariffs could be utilised (e.g. if biomass is locally available)
Weaknesses - Thermal network is not utilised as a heat source (lower system COP) - DH connection and additional supply technology is needed (high investment)
Opportunities - Booster technology could also serve as a back-up technology if DH network is under retrofit e.g. - Easily replaceable with other technology
Threats - Operational costs depend on the energy tariffs of the used fuel (e.g. natural gas)

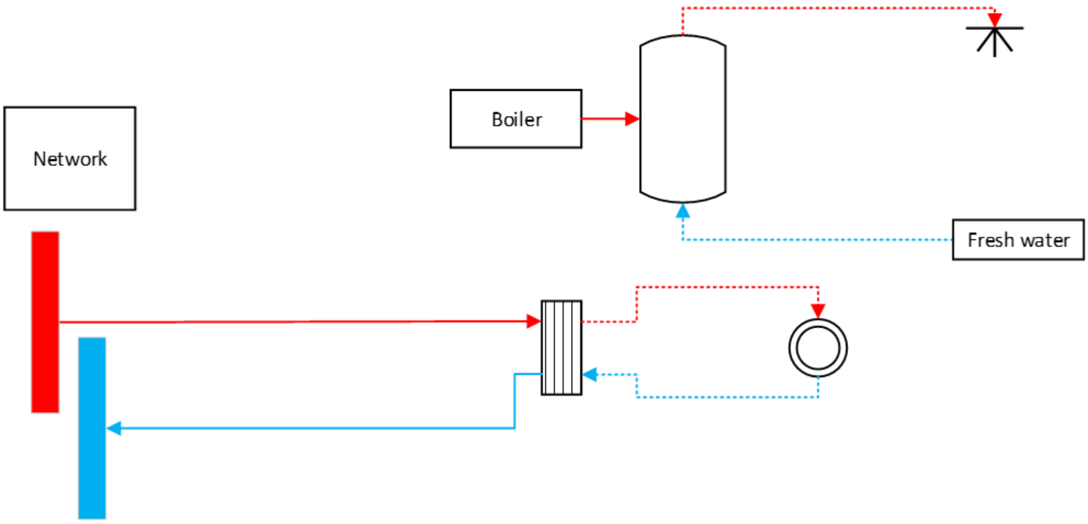

Figure 73 ULTDH substation – other booster technology (e.g. boiler)

9.2.3 NTDH substations

NTDH substations are connected to the thermal networks with temperature regimes around 25°C. Since these temperatures are not suitable for covering space heating and domestic hot water demand directly, booster technologies should be used. For this purpose, booster heat pump-based substations are proposed. Furthermore, since temperature regimes are relatively low, space cooling demand can also be covered.

NTDH substation – BHP for DHW and SH, SC directly

In this NTDH substation, booster heat pump is using thermal network warm pipe as heat source to provide space heating and domestic hot water. Two buffer tanks are used to increase flexibility of the system and secure temperature stability. Furthermore, space cooling is directly covered by using cold pipe of the NTDH network. It is important to mention that temperature regimes of the cold pipe should be around 10°C to be suitable for direct cooling. Table 14 shows SWOT analysis of the proposed substation, while Figure 74 provides overview of the substation schematics.

Table 14 SWOT analysis, NTDH substation – BHP for DHW and SH, SC directly

Strengths - Single BHP for DHW and SH - Space cooling directly **W**eaknesses - Low temperature of return needed for direct space cooling - Return temperature must be low enough to cover direct cooling **O**pportunities - Simultaneous heating and cooling is possible (however rarely used) - Could be upgraded from existing ULTDH **T**hreats - Booster heat pump COP could be reduced due to network temperature constraint

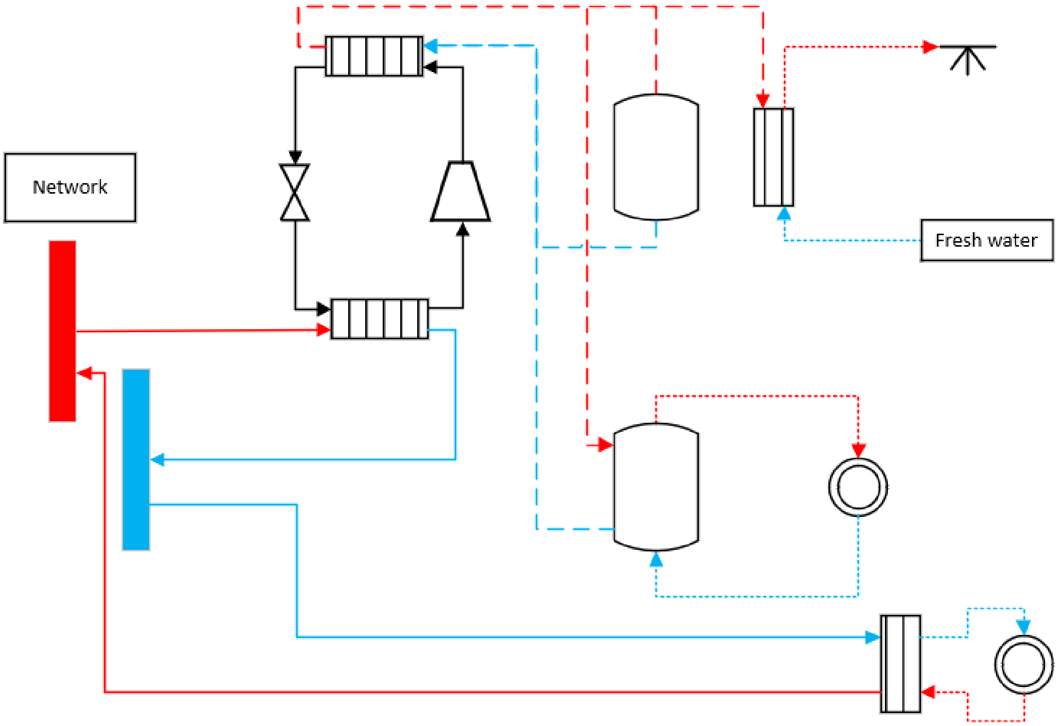

Figure 74 NTDH substation – BHP for DHW and SH, SC directly

NTDH substation – BHP for DHW and SH, SC as heat source for DHW BHP

This substation is also based on the booster heat pump. Heat pump is used to cover both space heating and domestic hot water demand. However, heat source (evaporator side) changes depending on the heating and cooling mode of the substation. In the heating mode (when space heating is needed), heat source is warm pipe of the thermal network. In the cooling mode (when space cooling is needed), heat source is return flow from the cooling system. This means that booster heat pump is used both for cooling and DHW production simultaneously. Table 15 shows SWOT analysis of such NTDH substation, while Figure 75 and Figure 76 illustrate substation schematics during heating and cooling modes.

Table 15 SWOT analysis, NTDH substation – BHP for DHW and SH, SC as heat source for DHW BHP

Strengths - Heat recycling on-site - Building-level system COP relatively high - Only one BHP needed
Weaknesses - Space cooling possible only with DHW production - DHW BHP performance reduced since heat source is on lower temperature than network
Opportunities - Space cooling system could be easily upgraded with additional BHP if needed
Threats - DHW and SC demand should be simultaneous and balanced

<u>*Heating mode*</u>

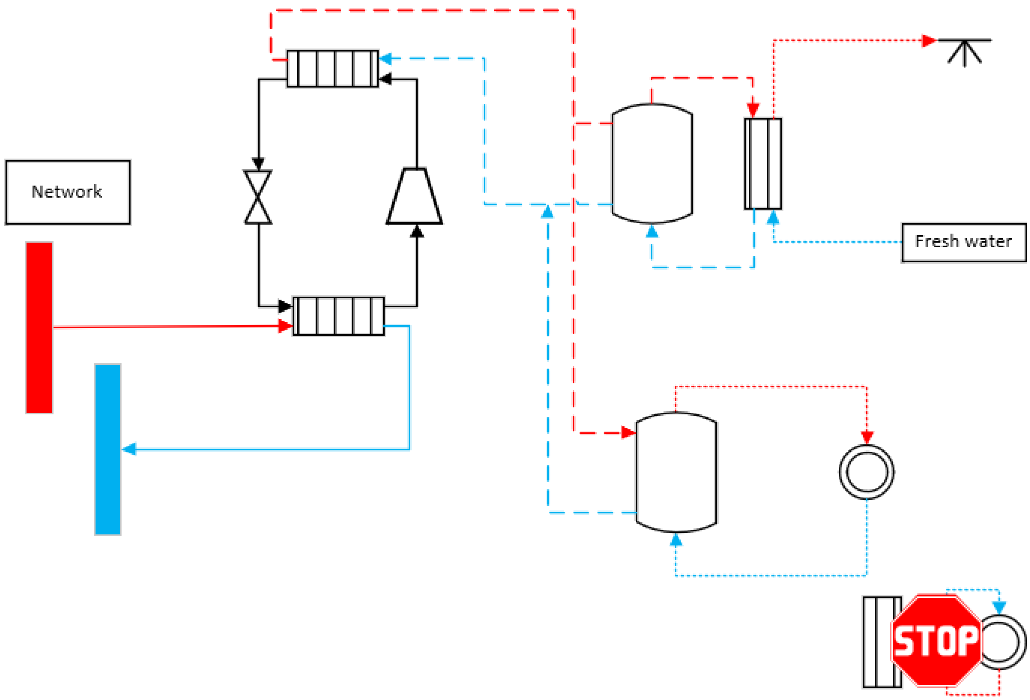

Figure 75 NTDH substation – BHP for DHW and SH, SC as heat source for DHW BHP (heating mode)

<u>*Cooling mode*</u>

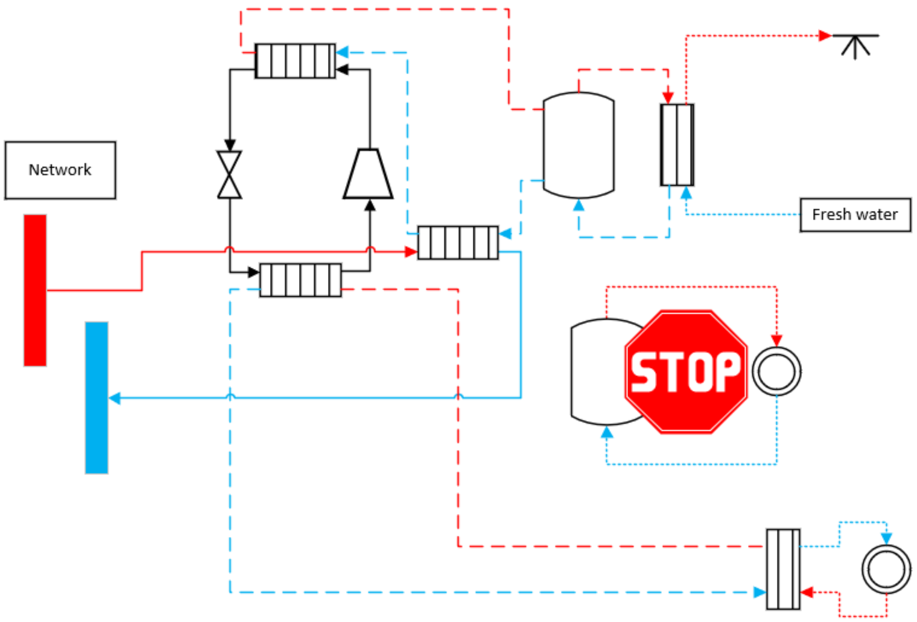

Figure 76 NTDH substation – BHP for DHW and SH, SC as heat source for DHW BHP (cooling mode)

NTDH substation – reversible heat pump for SH/DHW and SC

This NTDH substation on reversible heat pump which provides space heating and domestic hot water during heating mode and space cooling during cooling mode. In this configuration, it is not possible to cover domestic hot water and space cooling simultaneously. During heating mode warm pipe is used both as heat sink and heat source to provide SH and DHW. During cooling mode network is used as heat sink, increasing its temperature from cold to warm pipe temperature. Heat source is return from space cooling system. Table 16 shows SWOT analysis of this NTDH substation, while Figure 77 and Figure 78 illustrate substation schematics during heating and cooling mode.

Table 16 SWOT analysis, NTDH substation – reversible heat pump for SH/DHW and SC

Strengths - High COP both for heating and cooling - Network serves as heat sink and heat source **W**eaknesses - Not possible cover heating and cooling simultaneously - Reversible heat pump needed **O**pportunities - TES could be added in order to increase flexibility **T**hreats - DHW operation is needed throughout the whole year, this could represent an issue

Heating mode

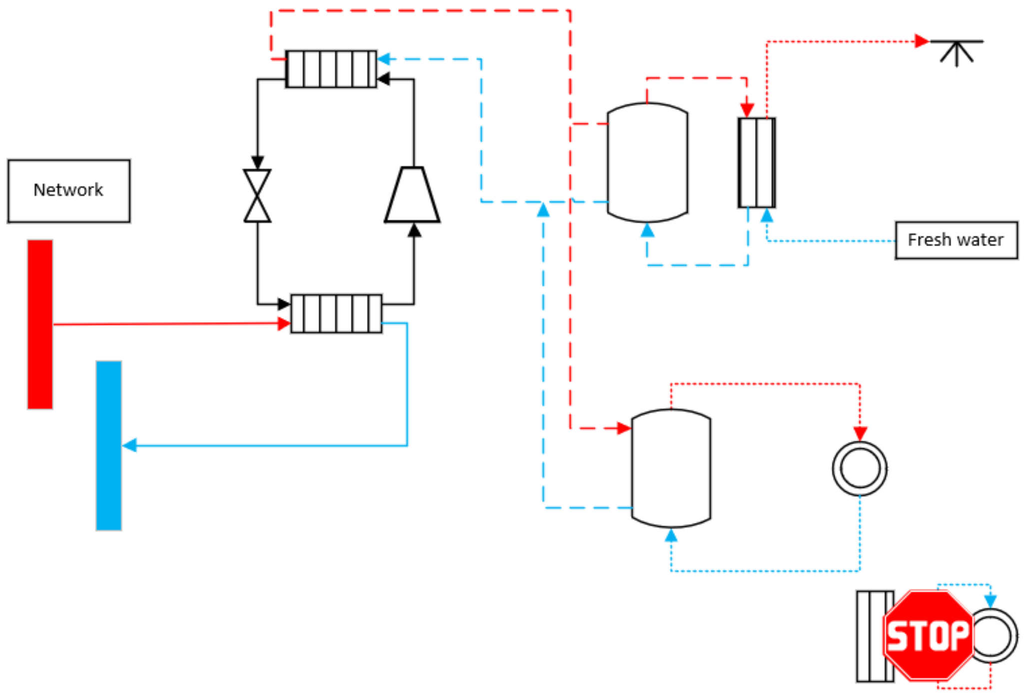

Figure 77 NTDH substation – reversible heat pump for SH/DHW and SC (heating mode)

Cooling mode

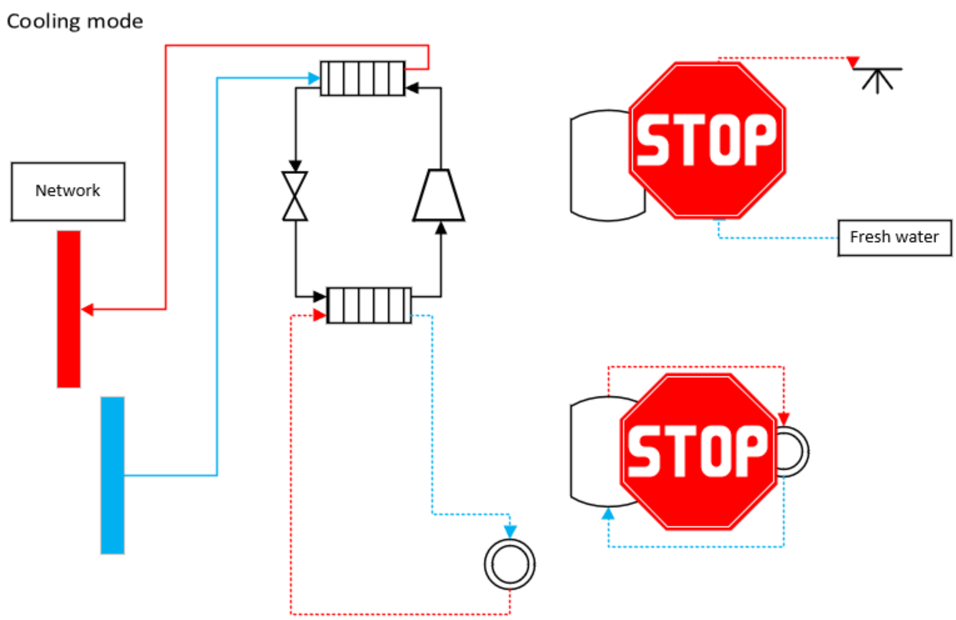

Figure 78 NTDH substation – reversible heat pump for SH/DHW and SC (cooling mode)

NTDH substation – booster heat pump for SH/DHW and heat pump for SC

This substation includes two booster heat pumps, thus separating heating and cooling demands. One booster heat pump utilizes warm pipe for heating purposes, while the second one uses cold pipe of the network for cooling demand. Table 17 shows SWOT analysis of this substation, while Figure 79 shows schematics of the substation.

Table 17 SWOT analysis, NTDH substation – reversible heat pump for SH/DHW and SC

Strengths - The most flexible NTDH substation - High COP for both BHPs **W**eaknesses - High investment cost - Additional space requirements **O**pportunities - Suitable for large facilities with different simultaneous demands - High level of bidirectionality in the network **T**hreats - No on-site recuperation - High O&M costs (2 BHPs)

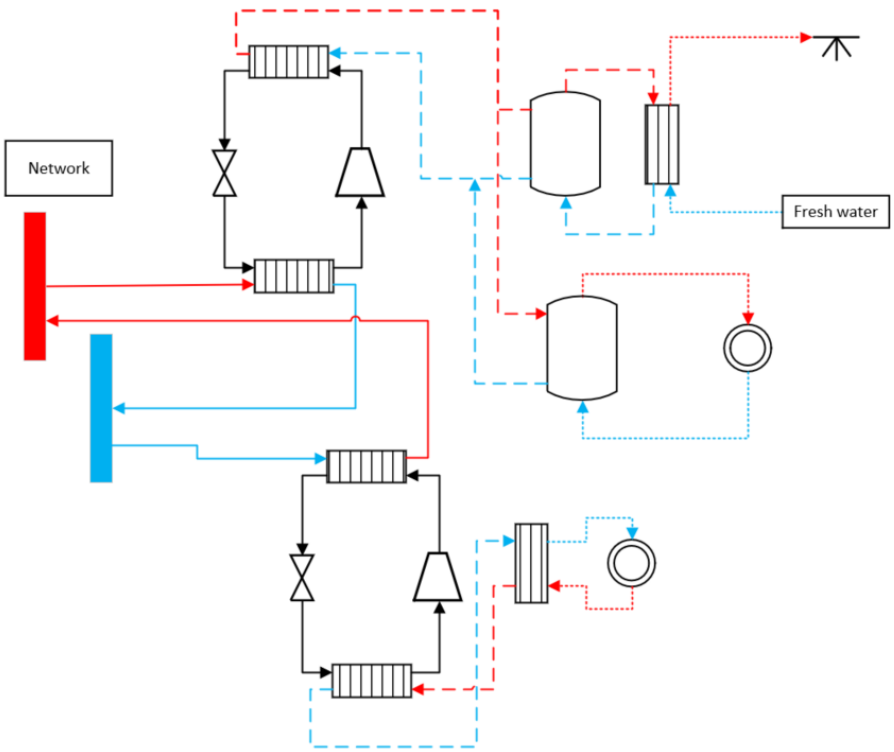

Figure 79 NTDH substation – booster heat pump for SH/DHW and heat pump for SC

9.3 Thermal network types

In this section, different thermal network topologies are shown. Table 18 shows crucial differences between traditional LTDH and ULTDH and NTDH networks.

Table 18 Main characteristics of ULTDH and NTDH thermal networks

LTDH network	ULTDH networks	NTDH networks
Supply temperature 55-70°C Return temperature 30-40°C Temperature difference relatively high 25-30°C High temperature difference enables smaller pipe diameters for the same level of peak capacity Pressure losses relatively low due to small water velocity needed in the grid Higher insulation class needed due to relatively high temperature regimes to reduce thermal losses Circulation pumps can be centralised since flow direction does not change	Supply temperature 35-55°C Return temperature 30-40°C Temperature difference relatively low 15-20°C Relatively small temperature difference usually results in larger pipe diameters for the same level of peak capacity Pressure losses could be increased due to increased water velocity needed in the grid Insulation class could be reduced due to relatively low temperature regimes Circulation pumps can be centralised since flow direction does not change Pipes can be made from polymeric materials	Supply temperature 20-35°C Return temperature 10-20°C Temperature difference very low, around 10-15°C Small temperature difference usually results in large pipe diameters for the same level of peak capacity Pressure losses are increased due to increased water velocity needed in the grid (increased running cost) Cost benefit between pumping costs and piping investment must be considered Pipe insulation usually is not needed due to low temperature regimes Circulation pumps should be decentralised since flow direction changes Pipes can be made from polymeric materials Both ground and the network could be used as the thermal storage Thermal networks could be used for cooling purposes

9.3.1 Thermal networks

Thermal network – 2-pipe "traditional" network

Thermal networks usually consist of only two pipes. In traditional networks they are usually referred as supply and return pipe. However, in NTDH networks both could serve as supply since heating and cooling can be provided with the same network simultaneously. This is the reason they are called warm and cold pipe in case of NTDH networks. Mayor drawbacks and advantages of such topology is shown in Table 19, while schematic overview is shown in Figure 80.

Table 19 SWOT analysis, Thermal network – 2-pipe "traditional" network

Strengths - Only two pipes - Simple operation and regulation **W**eaknesses - Issues for networks with different users (different temperature regimes) - Cooling possible only with NTDH networks, or if there is no DHW during summer **O**pportunities - Temperature regime reduction is relatively easy, if follows building refurbishment trends **T**hreats - Potentially high thermal losses

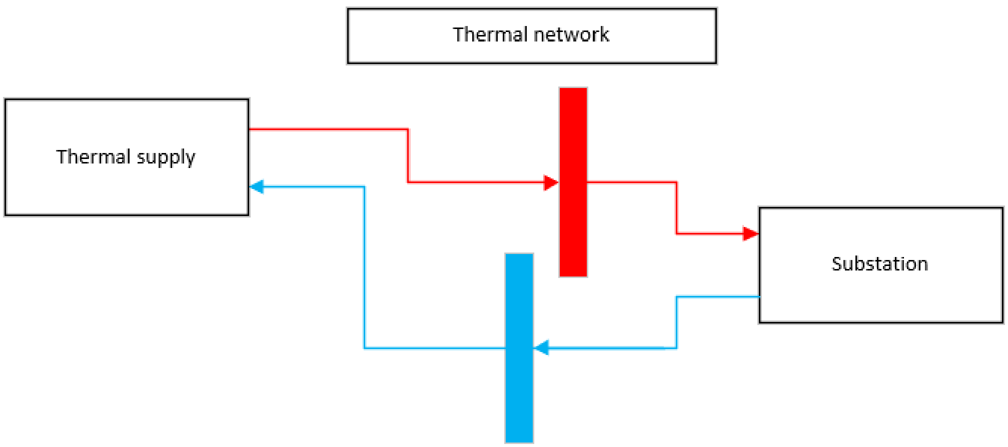

Figure 80 Thermal network – 2-pipe "traditional" network

However, additional pipe could be added thus making 3-pipe system. Such systems have two supply lines with different diameters. During summer operation, only one pipe is used in periods of low demand, thus minimizing thermal losses in the network.

Thermal network – 4-pipe network for SH/SC and DHW

Second option is using 4-pipe network – two supply pipes and 2 return pipes. One pair is used for heating (during winter season) or cooling (during summer season), while the second pair is used for domestic hot water demand throughout the year. Due to this, heating and cooling modes are possible. It is important to mention that this topology should be used when thermal demands have different temperature regimes, thus reducing overall thermal losses in the network. Nevertheless, cost benefit of such investment should be carried out beforehand.

Table 20 shows SWOT analysis of 4-pipe configuration while Figure 81 and Figure 82 illustrate possible heating and cooling modes of the network.

Table 20 SWOT analysis, Thermal network – 4-pipe network for SH/SC and DHW

Strengths - Flexible, SH and DHW are - Reduced thermal losses - Heating and cooling modes possible **W**eaknesses - Increased investment - Pressure losses issues if heating and cooling demands are not appropriately planned **O**pportunities - System upgrade is relatively easy since DHW is separated **T**hreats - System operation could be challenging - Network refurbishment could be costly

Heating mode

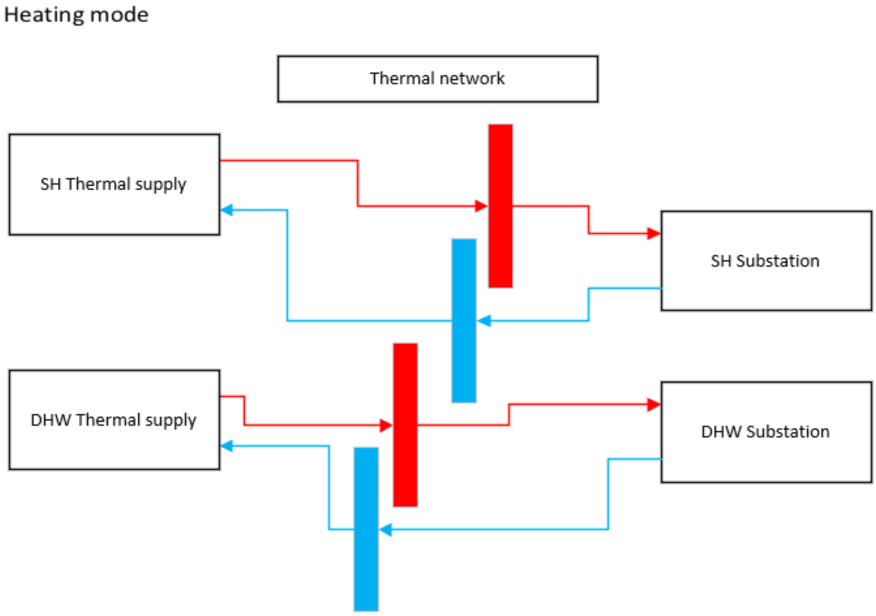

Figure 81 Thermal network – 4-pipe network for SH/SC and DHW (heating mode)

Cooling mode

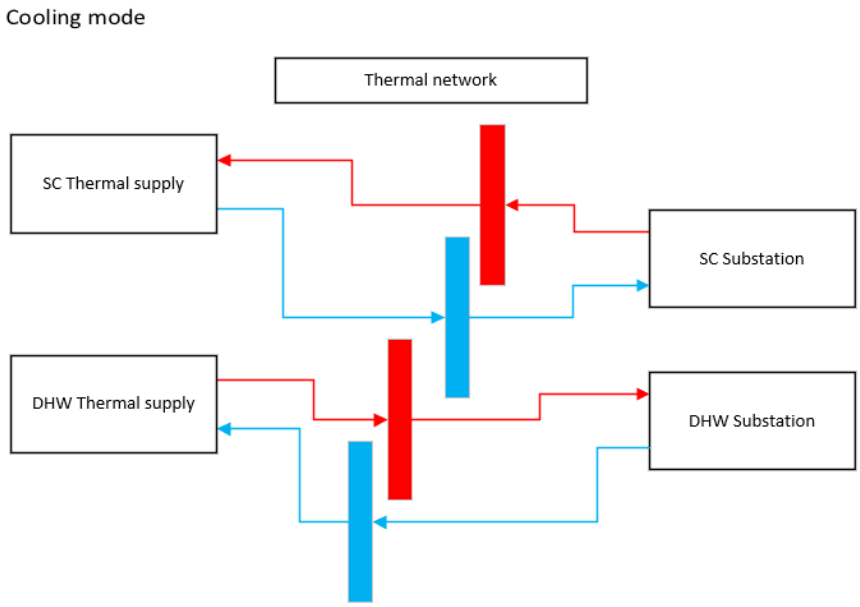

Figure 82 Thermal network – 4-pipe network for SH/SC and DHW (cooling mode)

Thermal network – 6-pipe network for SH, SC and DHW

The most complex network topology includes 6 pipe which enables provision of space heating, space cooling and domestic hot water simultaneously. This should be reserved for systems with specific heating and cooling needs, while the total length of the network should be kept as short as possible due to high investment costs. Table 21 shows SWOT analysis of such network topology while Figure 83 illustrates network schematics.

Table 21 SWOT analysis, Thermal network – 6-pipe network for SH, SC and DHW

Strengths - The most flexible network - Booster units can be optimised for each thermal demand **W**eaknesses - High investment - Spacing in the ground needed **O**pportunities - Suitable for all users, network expansion is relatively easy **T**hreats - Refurbishment could be expensive

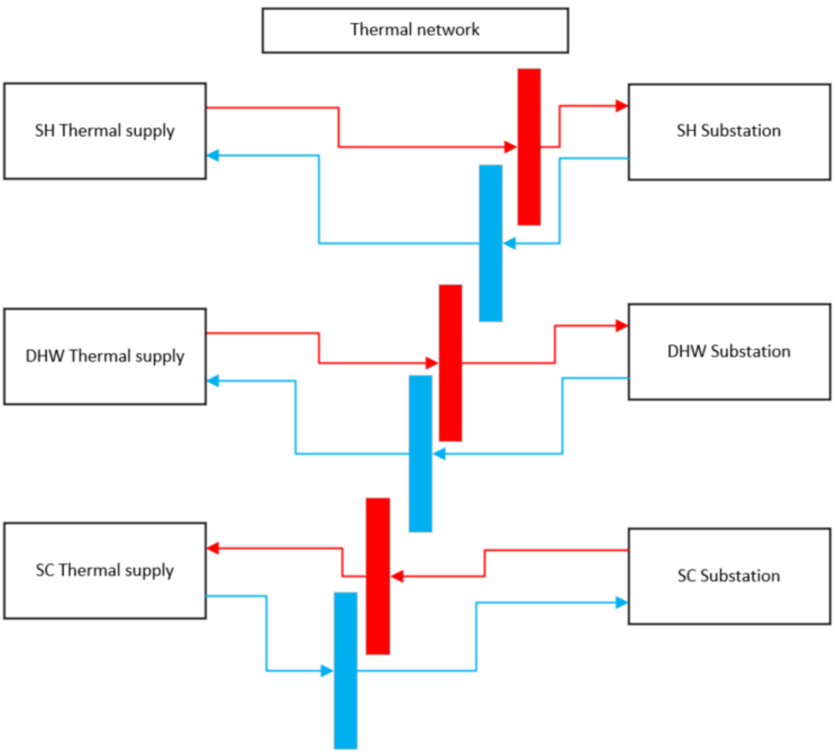

Figure 83 Thermal network – 6-pipe network for SH, SC and DHW

Thermal network – 1-pipe network for SH, SC and DHW (reservoir network) – *research phase*

Final network topology consists of only single pipe. It is also called "reservoir" network. It should be mentioned that such network is still in research phase. The idea is that all final customers are using the same pipe on the specified temperature, thus covering simultaneously space heating, space cooling and domestic hot water demand. However, the total cooling and heating thermal energy demand should be relatively balanced, while system operator should only secure stable temperature of the network. Although its design is relatively simple, its operation is relatively complex since all final customers act as prosumers. Table 22 show SWOT analysis of the 1-pipe network while Figure 84 provides the simplified scheme.

Table 22 SWOT analysis, 1-pipe network for SH, SC and DHW (reservoir network)

Strengths - Reduced investment - Suitable for all thermal users - High prosumer capabilities **W**eaknesses - Pressure issues (prosumers) - Grid operation is relatively complex, grid operator is „balancing" thermal needs - All users need booster units - The network is in research phase **O**pportunities - User-grid interaction is increased - If users are balanced, there is little-to-no energy supply needed **T**hreats - The grid is still only in research phase - Users should be relatively balanced

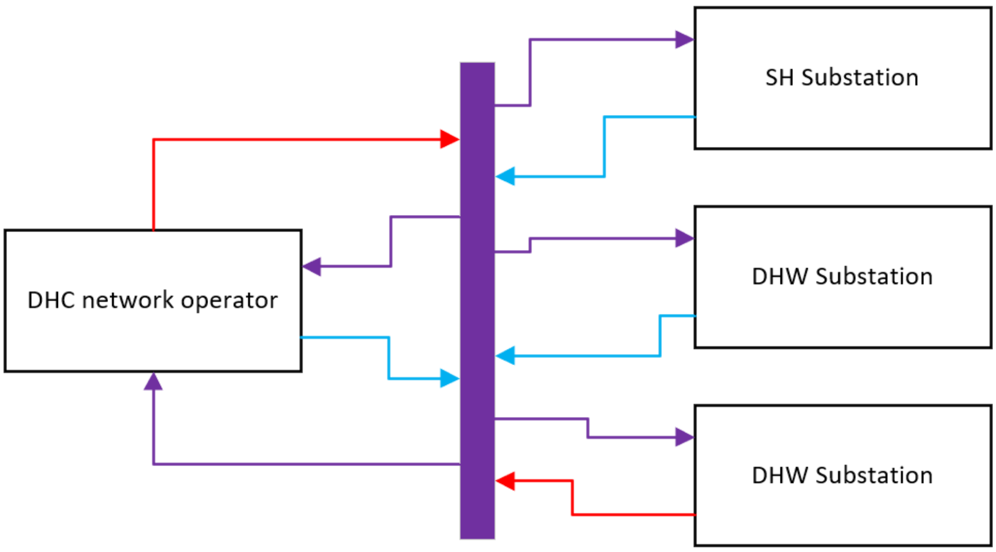

Figure 84 Thermal network – 1-pipe network for SH, SC and DHW (reservoir network)

9.3.2 Thermal sub-networks

District heating and cooling systems can have several subsystems which have different temperature regimes correlating connected final customers. In that case, we are talking about thermal sub-networks. In this section, two different approaches are presented.

Thermal sub-network – traditional DH system serves as a heat source for LTDH/ULTDH/NTDH network

Thermal sub-networks are usually part of a larger DH network. They can be hydraulically separated via heat exchanger or a shunt connection. In that case, high temperature DH networks serves as a heat source for thermal sub-network which has reduced temperature regimes. Table 23 shows SWOT and Figure 85 illustrated thermal subnetwork connection.

Table 23 SWOT analysis, Thermal sub-network – traditional DH system serves as a heat source for LTDH/ULTDH/NTDH network

Strengths - High temperature DH networks are almost always available - Heat supply is possible without booster units between the networks
Weaknesses - Temperature regimes should be carefully selected - Networks should operate simultaneously
Opportunities - Several subnetworks can be developed and expanded at the same time, depending on the available thermal network capacity
Threats - Shunt connections are relatively complex and could cause pressure issues in the grids

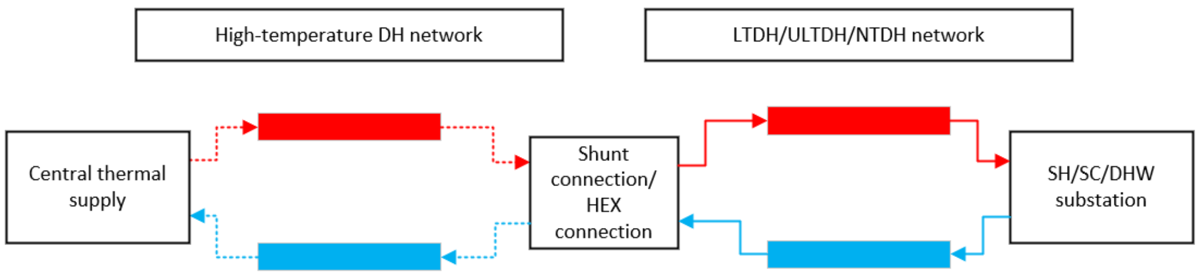

Figure 85 Thermal sub-network – traditional DH system serves as a heat source for LTDH/ULTDH/NTDH network

Besides heat exchanger and shunt connection, return pipe of high temperature DH network could serve as the supply pipe to the thermal sub-network customers.

Thermal sub-network – NTDH serves as a heat source for LTDH/ULTDH network

Different approach can also be used, where NTDH network serves as a heat source for ULTDH or LTDH networks. In this case, booster heat pump should be used where NTDH network serves as a heat source and ULTDH/LTDH network serves as a heat sink. In this way, overall thermal losses are minimized while different customers (with different temperature regimes) are simultaneously supplied. Table 24 shows SWOT analysis of such sub-network while Figure 86 illustrates network scheme.

Table 24 SWOT analysis, Thermal sub-network – NTDH serves as a heat source for LTDH/ULTDH network

Strengths - Reduced thermal losses for ULTDH/LTDH customers - No booster substations needed for LTDH network - Higher COP for BHP in ULTDH networks
Weaknesses - Planning of the network is challenging - Thermal networks must be balanced - Central BHP must be carefully selected - Operation of the grid is challenging
Opportunities - Simultaneous user expansion for NTDH and LTDH/ULTDH users
Threats - Grid expansion could be a challenge since network capacities must be aligned

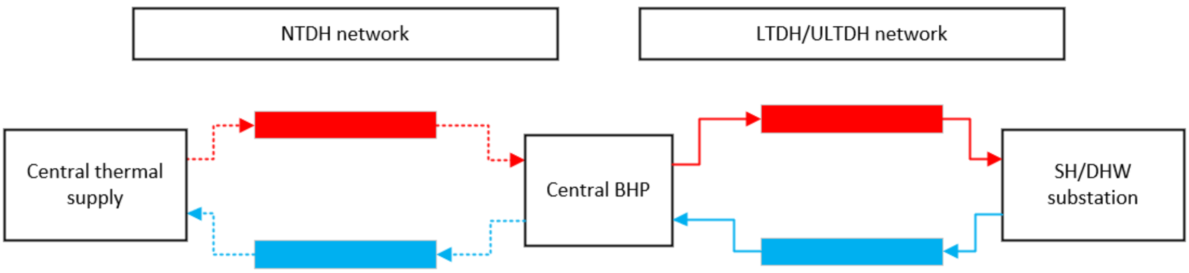

Figure 86 Thermal sub-network – NTDH serves as a heat source for LTDH/ULTDH network

9.3.3 Circulation pump configurations

Besides network piping topology, circulation pump configurations should also be mentioned. In traditional networks, circulation pumps are located in a central pumping station, since water flow direction does not change. In NTDH networks pumping must be decentralised since water flow direction changes in different network sections. This is crucial since some customers can operate as prosumers and establish bidirectional energy exchange with the thermal network. As a result, water flow direction must be reversed. For this reason, NTDH networks circulation pumps are decentralised which increases pressure control complexity and should be considered during predesign phase.

9.3.4 Thermal sources and connection configurations

Thermal sources used in the thermal networks can be divided in renewable and waste heat sources. Overview of possible thermal sources in shown in Table 25, while focusing on the temperature regimes, theoretical potential, and their temporal variations throughout the seasons. Besides renewable thermal sources, the focus was put on urban waste heat sources. Finally, the table also proposed how to connect different thermal source to ULTDH and NTDH networks.

Three thermal source connection configurations are considered. The first one is heat exchanger-based configuration shown in Figure 87. It is used when temperature regimes of the thermal source are dominantly higher than those in the thermal network. It is usually used for high-temperature industrial waste heat sources. However, if the thermal network temperature regimes are suitable, it can be used for low-temperature renewable energy sources such as water bodies or shallow geothermal.

The second configuration is heat-pump based connection shown in Figure 88, where temperature boosting is needed to satisfy temperature regimes of the network. This configuration must be used for integration of low-temperature sources to ULTDH networks. However, heat pump sometimes also has to be used in combination with NTDH networks since temperature difference between thermal source and thermal network are minimal.

The third configuration is combination of heat exchanger and heat pump connected in a series, shown in Figure 89. Waste heat is firstly utilised in the heat exchanger, while the rest of the waste heat is used in the booster heat pump unit to increase efficiency of waste heat utilisation.

It should be mentioned that thermal sources can be also used as thermal sinks for cooling purposes. In that case, the heat transfer direction is reversed, and thermal network is releasing the heat to the thermal sink.

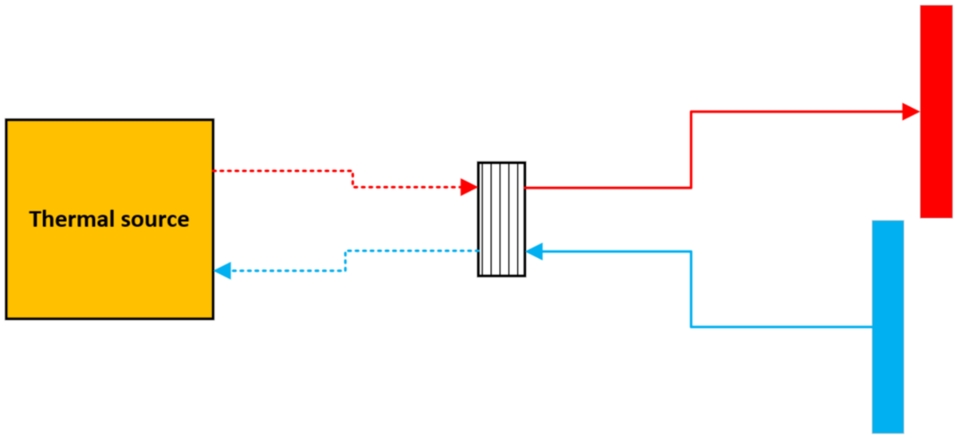

Figure 87 Thermal source connection – heat exchanger configuration

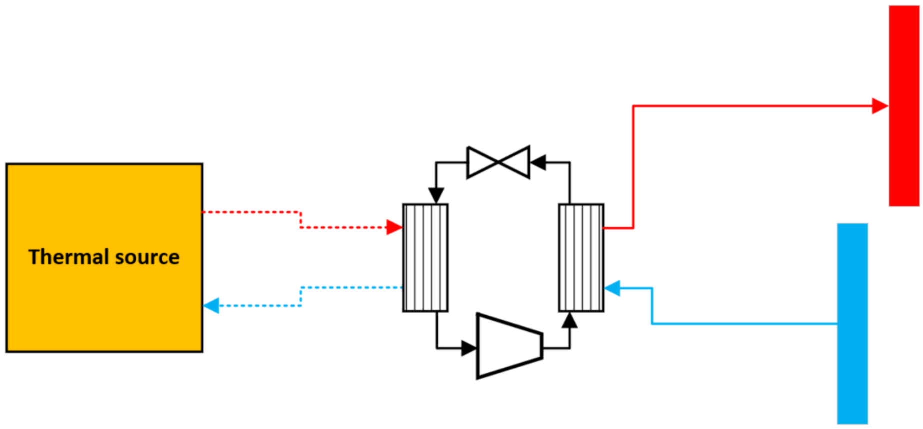

Figure 88 Thermal source connection – heat pump configuration

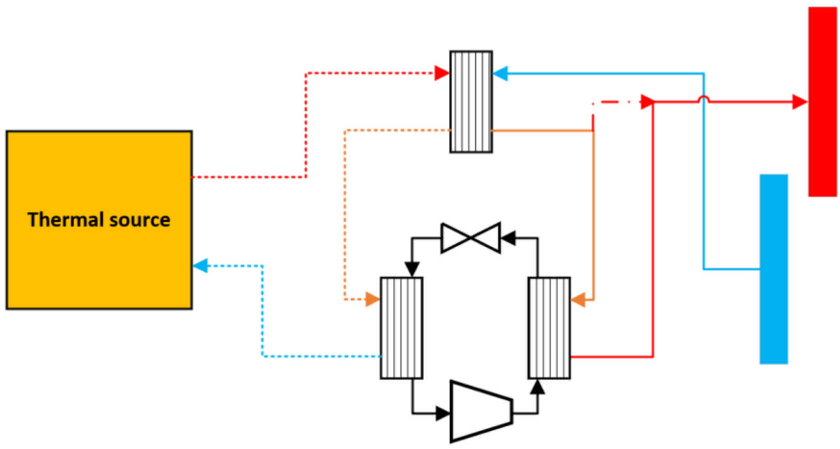

Figure 89 Thermal source connection – heat exchanger and heat pump configuration

Table 25 Thermal sources and sinks overview

Thermal source/sink	Temperature [°C]	Temperature distribution	Source Capacity	Source connection scheme
Air	- 5 - 35	The change of temperature is seasonal, reaching highest during the summer period	Infinite, but temperature change should be taken into account in case of higher capacities	ULTDH – HP NTDH – HEX/HP
Sea	10 - 25	The change of temperature is seasonal, reaching highest during the summer period	Infinite but the impact on environment should be considered. Local temperature increase should be considered.	ULTDH - HP NTDH – HEX/HP
Lake	5 - 30	The change of temperature is seasonal, reaching highest during the summer period	Depends on the lake size. The impact on environment should be considered. Local temperature increase should be considered.	ULTDH - HP NTDH – HEX/HP
Aquifer/ ATES	~12 (5 – 30, operation temperature regime)	During winter period it is used for heating and the temperature drops, while in the summer period it can be used for cooling and its temperature rises.	30 - 40 kWh/m^3 Limited because biological conditions must be respected.	ULTDH –HP NTDH –HEX/HP
Ground /BTES	~12 (30 – 55, operation temperature regime)	During winter period it is used for heating and the temperature drops, while in the summer period it can be used for cooling and its temperature rises.	15 - 30 kWh/m^3 Limited because biological conditions must be respected	ULTDH - HP NTDH – HEX/HP

Thermal source/sink	Temperature [°C]	Temperature distribution	Source Capacity	Source connection scheme
Industry	30 - 900	The source temperature is constant with very small changes during the year.	Iron & Steel Industry – 170 TWh/a Mineral industry – 70 TWh/a Paper industry – 20 TWh/a Food & drink industry – 15 TWh/a	ULTDH - HEX/HP NTDH – HEX
Supermarket	50 - 120	The change of temperature is seasonal, reaching highest during the summer period	~500 kWh/m^2 Depends on the location and operating conditions	ULTDH - HP NTDH – HEX
Shopping mall	40 - 90	The change of temperature is seasonal, reaching highest during the summer period	30-350 kWh/m^2 Depends on the location and operating conditions	ULTDH - HP NTDH – HEX/HP
Data centre	30 - 60	The change of temperature is seasonal, reaching highest during the summer period	Traditional: 430-861 W/m^2; new generation: 6 458-10 764 W/m^2 Depends on the location and operating conditions	ULTDH - HEX/HP NTDH – HEX/HP
Wastewater treatment plant	15 - 40	The source temperature is constant with slight changes during the observed period.	Depending on WWTP flow capacity Depends on the location and operating conditions	ULTDH - HP NTDH – HEX/HP

Thermal source/sink	Temperature [°C]	Temperature distribution	Source Capacity	Source connection scheme
Metro station	25 - 50	The change of temperature is seasonal, reaching highest during the summer period	Depends on the location and operating conditions	ULTDH - HEX/HP NTDH – HEX
Power substation	30 - 70	The change of temperature is seasonal, reaching highest during the summer period	0.2 to 2% of the nominal substation load	ULTDH - HEX/HP NTDH – HEX/HP

10 Economical, energetic and environmental analysis of ULTDH and NTDH networks

In this analysis a short overview is given of neutral temperature district heating (NTDH), ultra-low temperature district heating (ULTDH), and low temperature district heating (LTDH) systems, as well as their main components. Also, it shows the techno-economical calculation to assess the cost and benefits of these systems. Future district heating systems are expected to supply lower temperatures to increase system efficiency and enable exploitation of renewable heat sources. To answer whether it is beneficial to lower district heating temperatures below the level where it is still possible to supply domestic hot water directly, the economic feasibility ULTDH and NTDH concepts have been analysed and compared to LTDH systems. The possibility of SC was also considered during the analysis.

For this purpose, building plot ratio, space heating share were varied together with different system topologies. The different solutions were compared based on levelized cost of heat, primary energy factor, and carbon emission factor. This analysis showed that NTDH and ULTDH are suitable for relatively high space heating shares and high plot ratios, which are characteristic for urban areas with high energy effective buildings.

The modelling used in this analysis is based on the paper [4]. The method has been upgraded to calculate CO_2 emissions and primary energy factor (PEF) as shown in master thesis [69].

The used model is publicly available on Zenodo platform, on this **link**.

10.1 Methods and approach overview

To examine the economic viability of the scenarios, a comparison based on Levelized Cost of Energy (LCOE), Capital Expenditures (CAPEX), and Operational Expenditures (OPEX) was proposed.

Levelized cost of energy (LCOE) is a parameter that is used to assess the cost of total annual heat demand. It is calculated as a ratio of total discounted cost (CAPEX and OPEX) and total annual thermal demand. The value of LCOE is important when it comes to comparing energy systems that use different energy sources and technologies

Parameter	Label	Unit	Equation
Levelized cost of heat	$LCOE$	€/MWh	$LCOE = \frac{CAPEX + OPEX}{\dot{Q}_{tot}}$

Capital expenditures (CAPEX) can be calculated by multiplying the capital recovery factor (CRF) with an investment cost of a certain element of a network (e.g., central heat pump, central heat exchanger, network cost, etc.). The capital recovery factor is used to calculate the present value of a series of equal annual cash payments which for the needs of this paper equals CAPEX. The value n represents the lifetime (in years) of a certain part of a system, while the value i represents the discount rate.

Parameter	Label	Unit	Equation
Capital expenditures	$CAPEX$	€	$CAPEX = CRF * I = \frac{i * (1+i)^n}{(1+i)^n - 1} * I$

Operating expenditures of a system (e.g., district heating network) can be calculated as a sum of operational and management costs (O&M) and electricity and/or gas consumption costs. These costs are ongoing throughout the year and can be calculated daily, weekly basis, or simply annual basis. O&M costs include inventory costs, repairs, overhauls, electricity (E_i), and/or gas (G_i) costs of all parts of the network, pay checks for employees, etc.

Parameter	Label	Unit	Equation
Operating expenditures	$OPEX$	€	$OPEX = \sum_{i=1}^{N} O\&M_i + E_i + G_i$

Plot ratio is the ratio of the total (floor) area of buildings in a district/site to the total district/site area. If Plot ratio is 0.2 it represents areas of low population with a small buildings' density. If plot ratios is equal to 2 it represents areas with high population with many buildings.

Parameter	Label	Unit	Equation
Plot ratio	ϵ	-	$\epsilon = \frac{A_{buildings}}{A_{district}}$

Space heating share is ratio of space heating demand and total thermal demand. For example, a space heating share of 0.8 means that 80% of the total specific annual heat demand is required for heating. The lower the space heating share is, the buildings are more energy efficient. SH share of 0.1 represents almost energy-neutral buildings.

Parameter	Label	Unit	Equation
Space heating share	s_H	-	$s_H = \frac{SH\ demand}{SH\ demand + DHW\ demand}$

Primary energy factor (PEF or f_{prim}) indicates how much primary energy is used to generate a unit of electricity or a unit of useable thermal energy. The value of $f_{prim,scenario}$ can be calculated for each scenario that differs from others in energy consumption. First, total electricity or gas consumption was converted to primary energy. The result was then divided with total annual heat demand to calculate the $f_{prim,scenario}$ of each scenario. Scenarios with higher electricity consumption have higher primary energy factors. Results have shown that every low and ultra-low temperature district heating case has a lower primary energy factor than primary energy factor for individual gas boiler heating which factor has a value of 1,205.

Parameter	Label	Unit	Equation
Primary energy factor (scenario)	$f_{prim,\, scenario}$	-	$f_{prim,\, scenario} = \frac{(\dot{W}_{tot}\ or\ \dot{T}_{tot}) * f_{prim}}{\dot{Q}_{tot}}$

Carbon emission factor (CEF or f_{CO_2}) indicates how much CO_2 gasses were emitted into the atmosphere to generate a unit of electricity or a unit of useable thermal energy. The value of $f_{CO_2,scenario}$ can be calculated for each scenario that differs from others in energy consumption. First, total electricity or gas consumption was converted to the equivalent amount of carbon dioxide emissions. The result was then divided with total annual heat demand to calculate the CEF of each scenario.

Parameter	Label	Unit	Equation
Carbon emission factor	$f_{CO_2,\, scenario}$	-	$f_{CO_2,\, scenario} = \frac{(\dot{W}_{tot}\ or\ \dot{G}_{tot}) * f_{CO_2}}{\dot{Q}_{tot}}$

10.2 Overview of analysed ULTDH, NTDH and LTDH systems

Table 26 shows all scenarios and their characteristics regarding network type, heat source, utilization unit of central heat source, DHW (domestic hot water), SH (space heating), and SC (space cooling) substations in the building. Source temperatures for groundwater were 12°C – 7°C. Excess heat cases had 40°C, 30°C, and 20°C supply temperature which were cooled to 10°C in the central unit. Air was considered as an infinite heat source that does not change the temperature in the heat pump. DHW temperature is always needed to be raised to 60°C, from 20°C portable water. Detailed network temperatures are shown in Table 26.

Table 26 Overview of proposed ULTDH, LTDH, and NTDH system topologies

System topology name	Central source	Central unit	$T_{central,source,in}$ [°C]	$T_{central,source,out}$ [°C]	$T_{central,sink,in}$ [°C]	$T_{central,sink,out}$ [°C]	Network	SH unit	DHW unit	Cooling unit
LTDH_ASHP	Air	HP	Hour air temp.	Hour air temp.	Hour LTDH return temp.	Hour LTDH supply temp.	LTDH	HEX	HEX	-
LTDH_GWHP	Ground water	HP	12	7	Hour LTDH return temp.	Hour LTDH supply temp.	LTDH	HEX	HEX	-
LTDH_EH1HP	Excess heat	HP	40	10	Hour LTDH return temp.	Hour LTDH supply temp.	LTDH	HEX	HEX	-
LTDH_EH2HP	Excess heat	HP	30	10	Hour LTDH return temp.	Hour LTDH supply temp.	LTDH	HEX	HEX	-
LTDH_EH3HP	Excess heat	HP	20	10	Hour LTDH return temp.	Hour LTDH supply temp.	LTDH	HEX	HEX	-
ULTDH_Booster_ASHP	Air	HP	Hour air temp.	Hour air temp.	Hour ULTDH return temp.	Hour ULTDH supply temp.	ULTDH	HEX	HP building	-
ULTDH_Booster_GWHP	Ground water	HP	12	7	Hour ULTDH return temp.	Hour ULTDH supply temp.	ULTDH	HEX	HP building	-
ULTDH_Booster_EH1HEX	Excess heat	HEX	40	10	Hour ULTDH return temp.	Hour ULTDH supply temp.	ULTDH	HEX	HP building	-
ULTDH_Booster_EH2HP	Excess heat	HP	30	10	Hour ULTDH return temp.	Hour ULTDH supply temp.	ULTDH	HEX	HP building	-
ULTDH_Booster_EH3HP	Excess heat	HP	20	10	Hour ULTDH return temp.	Hour ULTDH supply temp.	ULTDH	HEX	HP building	-
ULTDH_Micro_ASHP	Air	HP	Hour air temp.	Hour air temp.	Hour ULTDH return temp.	Hour ULTDH supply temp.	ULTDH	HEX	HP apartm ent	-
ULTDH_Micro_GWHP	Ground water	HP	12	7	Hour ULTDH return temp.	Hour ULTDH supply temp.	ULTDH	HEX	HP apartm ent	-

System topology name	Central source	Central unit	$T_{central,source,in}$ [°C]	$T_{central,source,out}$ [°C]	$T_{central,sink,in}$ [°C]	$T_{central,sink,out}$ [°C]	Network	SH unit	DHW unit	Cooling unit
ULTDH_Micro_EH1HEX	Excess heat	HEX	40	10	Hour ULTDH return temp.	Hour ULTDH supply temp.	ULTDH	HEX	HP apartment	-
ULTDH_Micro_EH2HP	Excess heat	HP	30	10	Hour ULTDH return temp.	Hour ULTDH supply temp.	ULTDH	HEX	HP apartment	-
ULTDH_Micro_EH3HP	Excess heat	HP	20	10	Hour ULTDH return temp.	Hour ULTDH supply temp.	ULTDH	HEX	HP apartment	-
ULTDH_Air_ASHP	Air	HP	Hour air temp.	Hour air temp.	Hour ULTDH return temp.	Hour ULTDH supply temp.	ULTDH	HEX	ASHP building	-
ULTDH_Air_GWHP	Ground water	HP	12	7	Hour ULTDH return temp.	Hour ULTDH supply temp.	ULTDH	HEX	ASHP building	-
ULTDH_Air_EH1HEX	Excess heat	HEX	40	10	Hour ULTDH return temp.	Hour ULTDH supply temp.	ULTDH	HEX	ASHP building	-
ULTDH_Air_EH2HP	Excess heat	HP	30	10	Hour ULTDH return temp.	Hour ULTDH supply temp.	ULTDH	HEX	ASHP building	-
ULTDH_Air_EH3HP	Excess heat	HP	20	10	Hour ULTDH return temp.	Hour ULTDH supply temp.	ULTDH	HEX	ASHP building	-
NTDH_Booster_ASHP	Air	HP	Hour air temp.	Hour air temp.	Hour NTDH return temp.	Hour NTDH supply temp.	NTDH	HP	HP building	-
NTDH_Booster_GWHP	Ground water	HP	12	7	Hour NTDH return temp.	Hour NTDH supply temp.	NTDH	HP	HP building	-
NTDH_Booster_EH1BHP	Excess heat	HP	40	10	Hour NTDH return temp.	Hour NTDH supply temp.	NTDH	HP	HP building	-
NTDH_Booster_EH1HEX	Excess heat	HEX	40	10	Hour NTDH return temp.	Hour NTDH supply temp.	NTDH	HP	HP building	-
NTDH_Booster_EH2BHP	Excess heat	HP	30	10	Hour NTDH return temp.	Hour NTDH supply temp.	NTDH	HP	HP building	-

System topology name	Central source	Central unit	$T_{central,source,in}$ [°C]	$T_{central,source,out}$ [°C]	$T_{central,sink,in}$ [°C]	$T_{central,sink,out}$ [°C]	Network	SH unit	DHW unit	Cooling unit
NTDH_Booster_EH3HEX	Excess heat	HEX	30	10	Hour NTDH return temp.	Hour NTDH supply temp.	NTDH	HP	HP building	-
NTDH_Booster_EH3	Excess heat	HP	20	10	Hour NTDH return temp.	Hour NTDH supply temp.	NTDH	HP	HP building	-
NTDH_Booster_ASHP_cooling	Air	HP	Hour air temp.	Hour air temp.	Hour NTDH return temp.	Hour NTDH supply temp.	NTDH	HP	HP building	HEX building
NTDH_Booster_GWHP_cooling	Ground water	HP	12	7	Hour NTDH return temp.	Hour NTDH supply temp.	NTDH	HP	HP building	HEX building
NTDH_Booster_EH1BHP_cooling	Excess heat	HP	40	10	Hour NTDH return temp.	Hour NTDH supply temp.	NTDH	HP	HP building	HEX building
NTDH_Booster_EH1HEX_cooling	Excess heat	HEX	40	10	Hour NTDH return temp.	Hour NTDH supply temp.	NTDH	HP	HP building	HEX building
NTDH_Booster_EH2BHP_cooling	Excess heat	HP	30	10	Hour NTDH return temp.	Hour NTDH supply temp.	NTDH	HP	HP building	HEX building
NTDH_Booster_EH2HEX_cooling	Excess heat	HEX	30	10	Hour NTDH return temp.	Hour NTDH supply temp.	NTDH	HP	HP building	HEX building
NTDH_Booster_EH3_cooling	Excess heat	HP	20	10	Hour NTDH return temp.	Hour NTDH supply temp.	NTDH	HP	HP building	HEX building
Individual_ASHP	-	-	-	-	-	-	-	ASHP	ASHP	-
Individual_GB	-	-	-	-	-	-	-	GB	GB	-

Figure 90 shows system topology based on the LTDH network. Temperature regimes are 60/30°C while end-user substation is based on the heat exchangers. Central unit is always heat pump, connected to various thermal sources, depending on the defined topology.

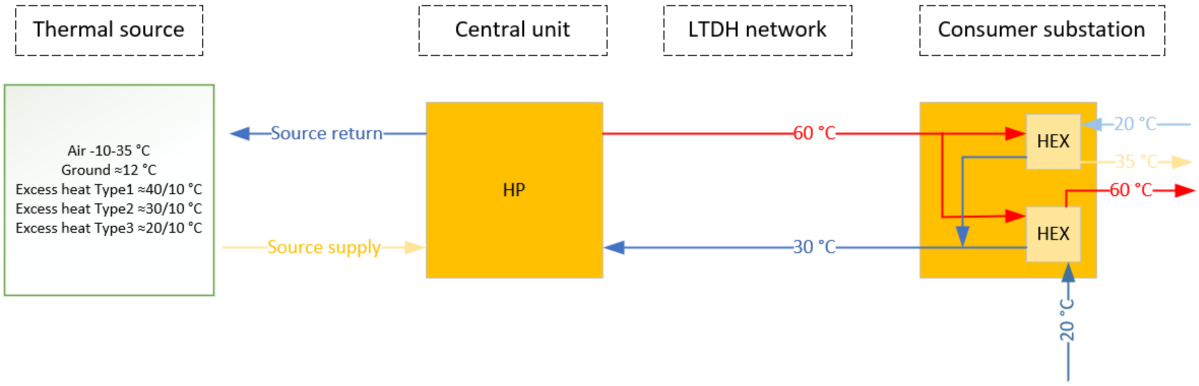

Figure 90 LTDH network-based system with district heating storage unit substation

Figure 91, Figure 92 and Figure 93 show ULTDH network-based systems with various end-user substation designs. Central unit is heat pump or heat exchanger, depending on the thermal source type.

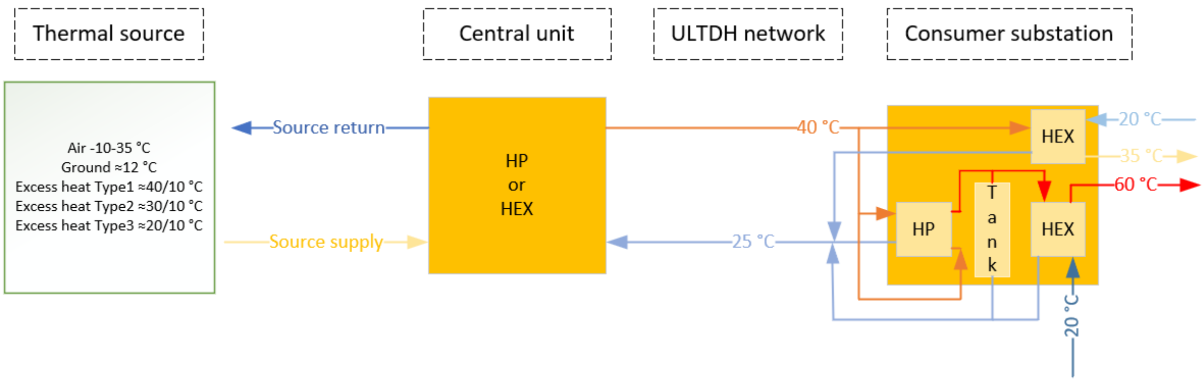

Figure 91 ULTDH network-based system with booster heat pump substation

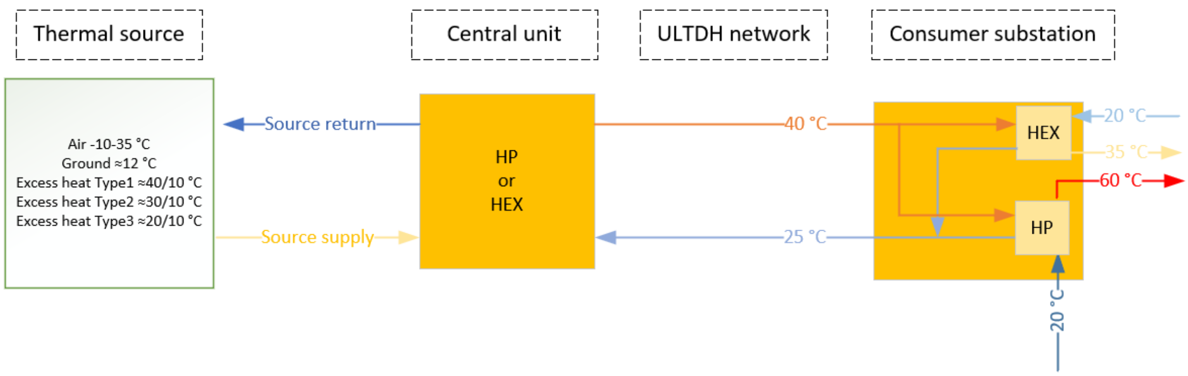

Figure 92 ULTDH network-based system with micro booster heat pump substation

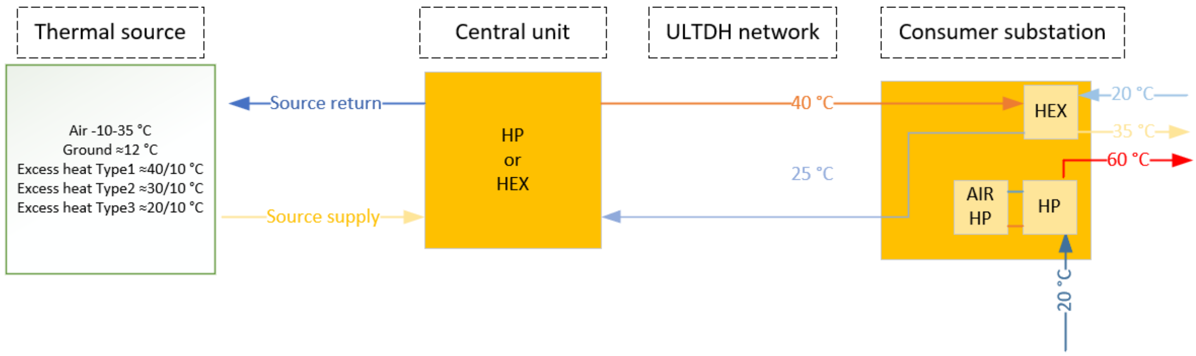

Figure 93 ULTDH network-based system with air-source heat pump substation

Finally, Figure 94 shows NTDH network-based system which is based on booster heat pump substation. Besides space heating and domestic hot water, the system can provide space cooling from cold pipe via heat exchanger.

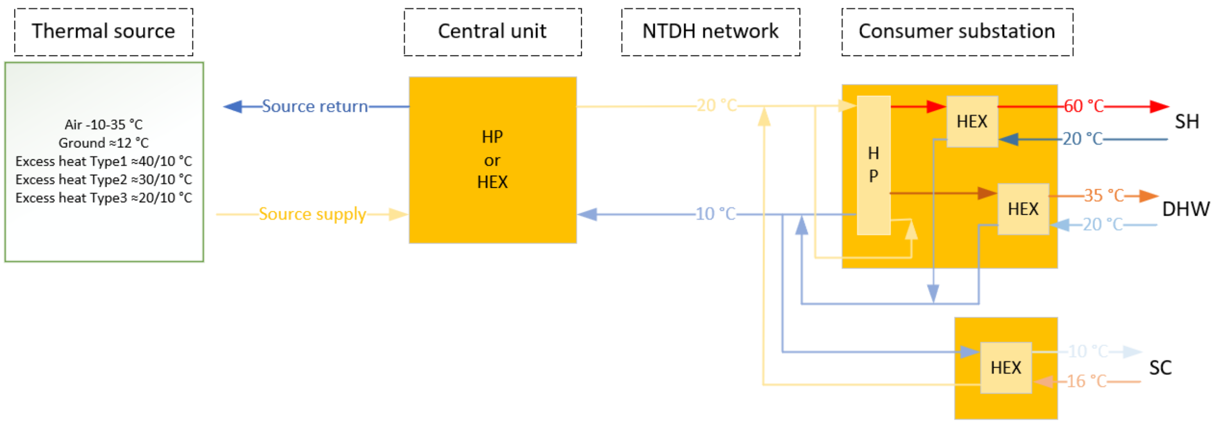

Figure 94 NTDH network-based system

10.3 Economic analysis

Table 27 shows for which scenarios SH share and Plot ratio the analysis of LCOE and LCOE structure was performed.

Table 27 LCOE scenarios analysis

Space Heating share	Plot ratio
0.1	0.2 (Rural areas)
0.1	2 (Urban areas)
0.45	1
0.8	0.2
0.8	2

Figure 95 shows the LCOE for SH share 0.1 and Plot ratio 0.2, i.e. for rural areas with sparse population and high energy efficiency. The figure shows that the LCOE is high for most of the proposed solutions, the highest amount of LCOE is when using ULTDH in which heat pumps are used for the central station which uses for source groundwater or air, while the micro heat pumps are used in each apartment for the preparation of hot domestic water and heat exchanger for heating. The highest LCOE is for ULTDH_Micro_GWHP. The reason for the high LCOE in the case of using ULTDH in this scenario is that there will be increased investment costs (CAPEX) in central and decentralized units, but there will also be an increase in operating costs (OPEX) of the central unit. The LCOE for ULTDH_Micro_GWHP is 410 €/MWh. The most favourable option in this scenario proved to be the independent use of a gas boiler, Individual_GB, which in turn will have an adverse environmental impact, which will be shown in the next chapter. This option makes cost-effective the absence of central unit costs and central unit operating costs. The LCOE for Individual_GB is 60 €/MWh.

Figure 96 shows the LCOE distribution for SH share 0.1 and Plot ratio 2, which characterizes urban areas with high energy efficiency. In this scenario, the most expensive option was ULTDH systems in which heat pumps are used in the central units. The most unfavourable system is ULTDH_Micro_ASHP and ULTDH_Micro_GWHP. In the decentralized units, micro heat pumps are used in each apartment to prepare hot water, and heat exchangers are used for heating. In these systems, the investment (CAPEX) and operating (OPEX) costs of decentralized units, i.e. micro heat pumps, are high. The LCOE for the ULTDH_Micro_ASHP and ULTDH_Micro_GWHP is 202 €/MWh. LTDH systems, especially LTDH systems based on waste heat recovery, prove to be the most favourable option in this scenario. The most favourable LTDH system proved to be a system that has waste heat in the central unit. The waste heat source temperature is 40°C. In these systems, a heat pump is installed in the central unit to raise the temperature level to suitable for integration into the DH network, while in the decentralized units heat exchangers are used for both heating and domestic hot water preparation. The LCOE for this option is 47 €/MWh.

Figure 97 shows the LCOE for SH share 0.8 and Plot ratio 0.2, which represents rural areas with low energy efficiency (cities with older buildings). The Figure shows that the most unfavourable solutions in this scenario are ULTDH systems with micro heat pumps, especially ULTDH_Micro_ASHP. Micro heat pumps in these systems are used to prepare the domestic heat of water, while heat exchangers are used for heating, they are also decentralized units. As a rule, a heat pump is used in the central unit to raise the heat source temperature to a level suitable for integration into the DH network. The LCOE for this system is 105 €/MWh. The main cause of the high LCOE are high investment costs (CAPEX) in central and decentralized units, and their operating (OPEX) costs. The most favourable option in this scenario is NTDH with a neutral temperature regime, which is suitable for heating in winter, but also for cooling in summer. The NTDH network with the lowest LCOE is NTDH_Booster_EH2HEX_cooling. This system uses waste heat with a temperature of 30°C as a source. These systems in the central unit have a heat exchanger because the temperature of the source is higher than the temperature regime of the DH network, while in the decentralized unit they have a heat exchanger and a booster heat pump with a tank for domestic hot water. The LCOE for the most favourable option is 35 €/MWh. In this option, the highest cost in the LCOE structure is the investment costs (CAPEX) in the network.

Figure 98 shows the LCOE for SH share 0.8 and Plot ratio 2, which represent urban areas with low energy efficiency (cities with older buildings). LCOE analysis for this case found that the most inconvenient option is the individual use of air source heat pumps, Individual_ASHP. The reason lies in the fact that there is a high investment (CAPEX), but also operating (OPEX) costs of decentralized units, i.e. heat pump. The heat pump in this case is used for heating, but also the preparation of domestic hot water. The LCOE for this system option is 94 €/MWh. The most favourable option in this scenario is NTDH which utilizes a waste heat source of 30°C, NTDH_Booster_EH2HEX_cooling. In this case, a heat exchanger is used in the central unit, while in the decentralized unit a heat exchanger is used for heating, while a heat pump with a hot water tank is used to prepare the hot domestic water. The LCOE in this system option is 17 €/MWh, and the highest part of LCOE comes from investment costs (CAPEX) in the central and decentralized unit.

Figure 99 shows the LCOE for SH share 0.45 and Plot ratio 1 which represent semi-urban areas with medium energy efficiency, e.g., suburbs. Analysing Figure 99, it can be concluded that the most inconvenient option in this scenario is the use of the ULTDH network in combination with micro heat pumps, ULTDH_Micro_ASHP. Particularly unsuitable are systems that use heat pumps in the central units whose heat source is outside air. In decentralized units, such systems use heat exchangers for heating, while micro heat pumps are used to heat domestic hot water. The amount of LCOE for ULTDH with micro heat pumps is 147 €/MWh. In contrast, NTDH systems that utilize waste heat at a temperature level of 30°C have proven to be the most suitable option in this scenario, especially NTDH_Booster_EH2HEX_cooling. In the central unit, these systems have a heat exchanger since the temperature of the source is higher than the temperature of the DH network, and in the central unit, they use a booster heat pump for heating and preparation of domestic hot water. The LCOE for NTDH_Booster_EH2HEX_cooling is 51 €/MWh, most of this cost is coming from investment costs (CAPEX) in the network of this decentralized unit, i.e. booster heat pumps.

In general, it can be noticed that the most unfavourable option is the systems used in the central units as a source of outdoor air or groundwater to operate the heat pump, while in the decentralized units use micro heat pumps. It turned out that such systems have high investment costs (CAPEX) in central and decentralized units, but also high operating costs (OPEX) of these units. NTDH systems appear to be the most favourable option, especially systems that utilize waste heat in central systems using heat exchangers. In the decentralized unit, such systems use a booster heat pump to achieve a temperature suitable for heating and preparing domestic hot water.

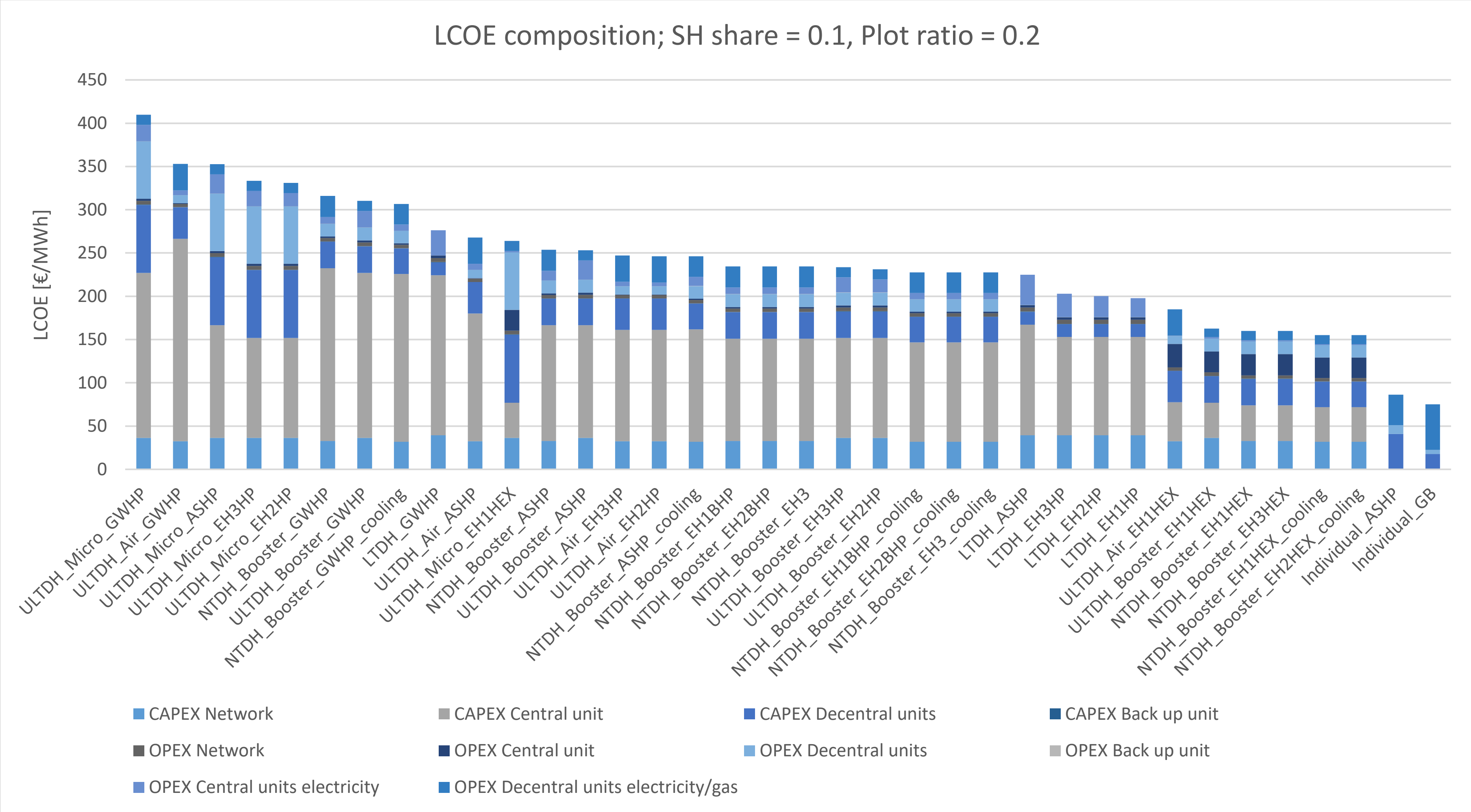

Figure 95 LCOE composition for NTDH, ULTDH, LTDH, SH share = 0.1, Plot ratio = 0.2

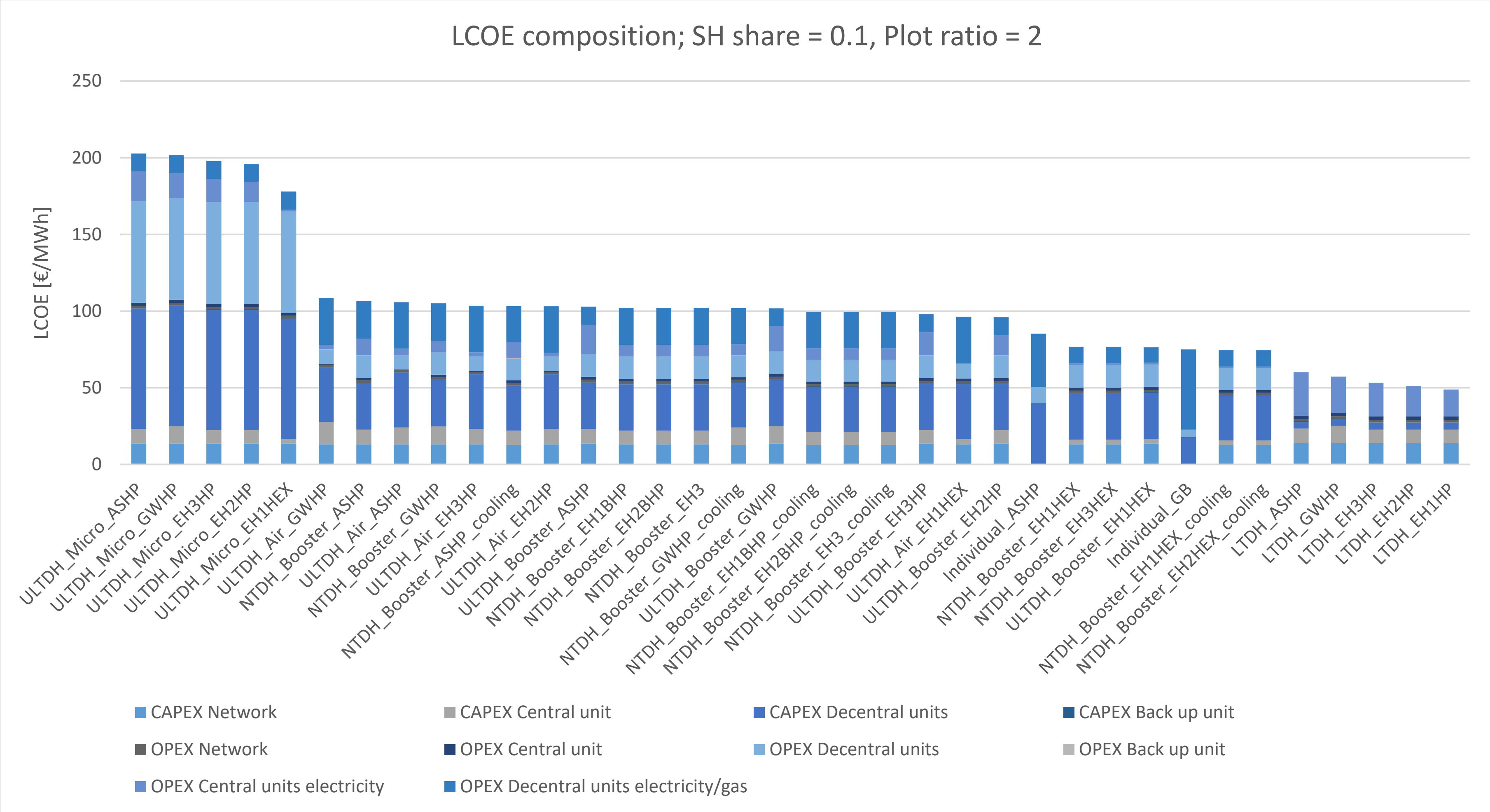

Figure 96 LCOE composition for NTDH, ULTDH, LTDH, SH share = 0.1, Plot ratio = 2

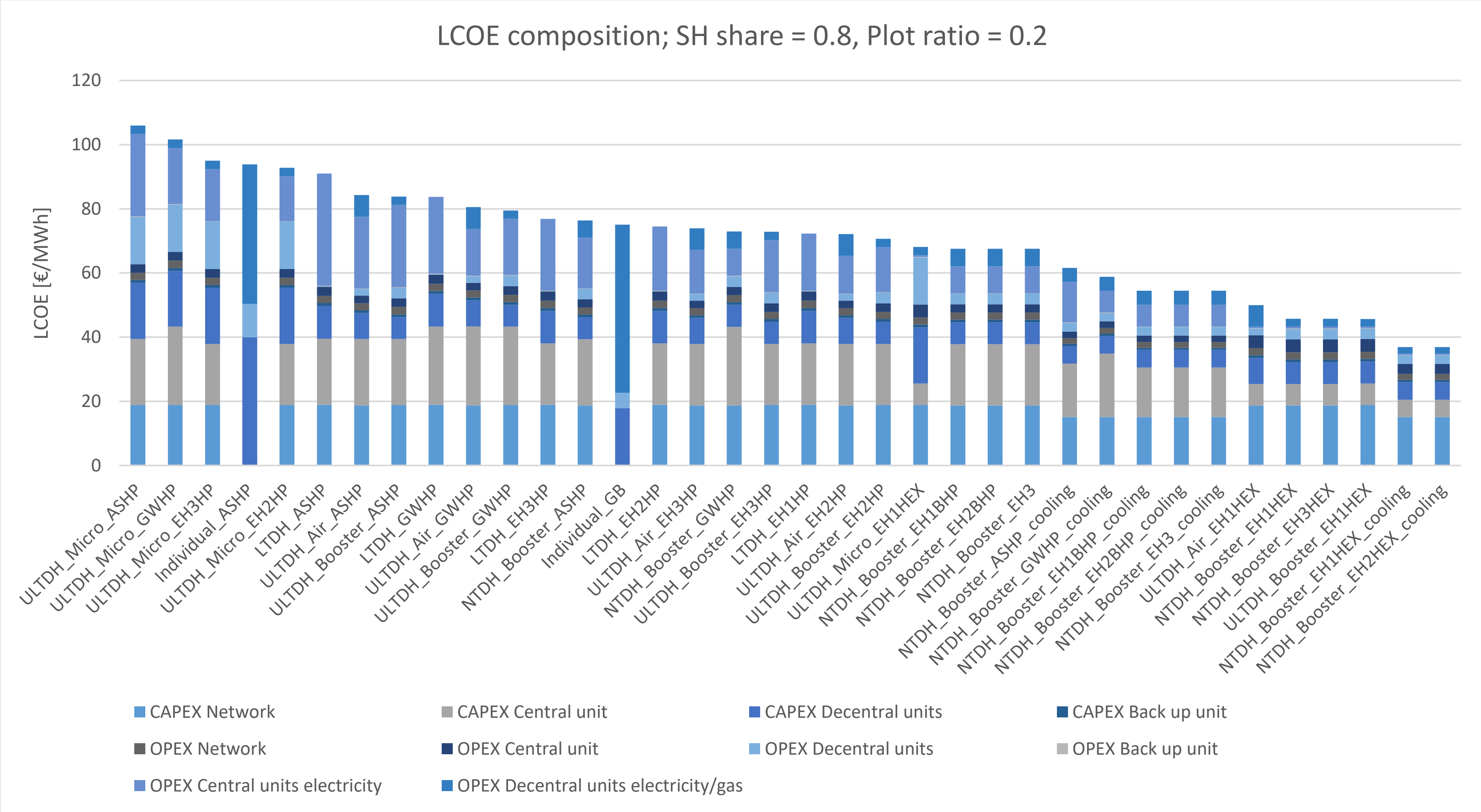

Figure 97 LCOE composition for NTDH, ULTDH, LTDH, SH share = 0.8, Plot ratio = 0.2

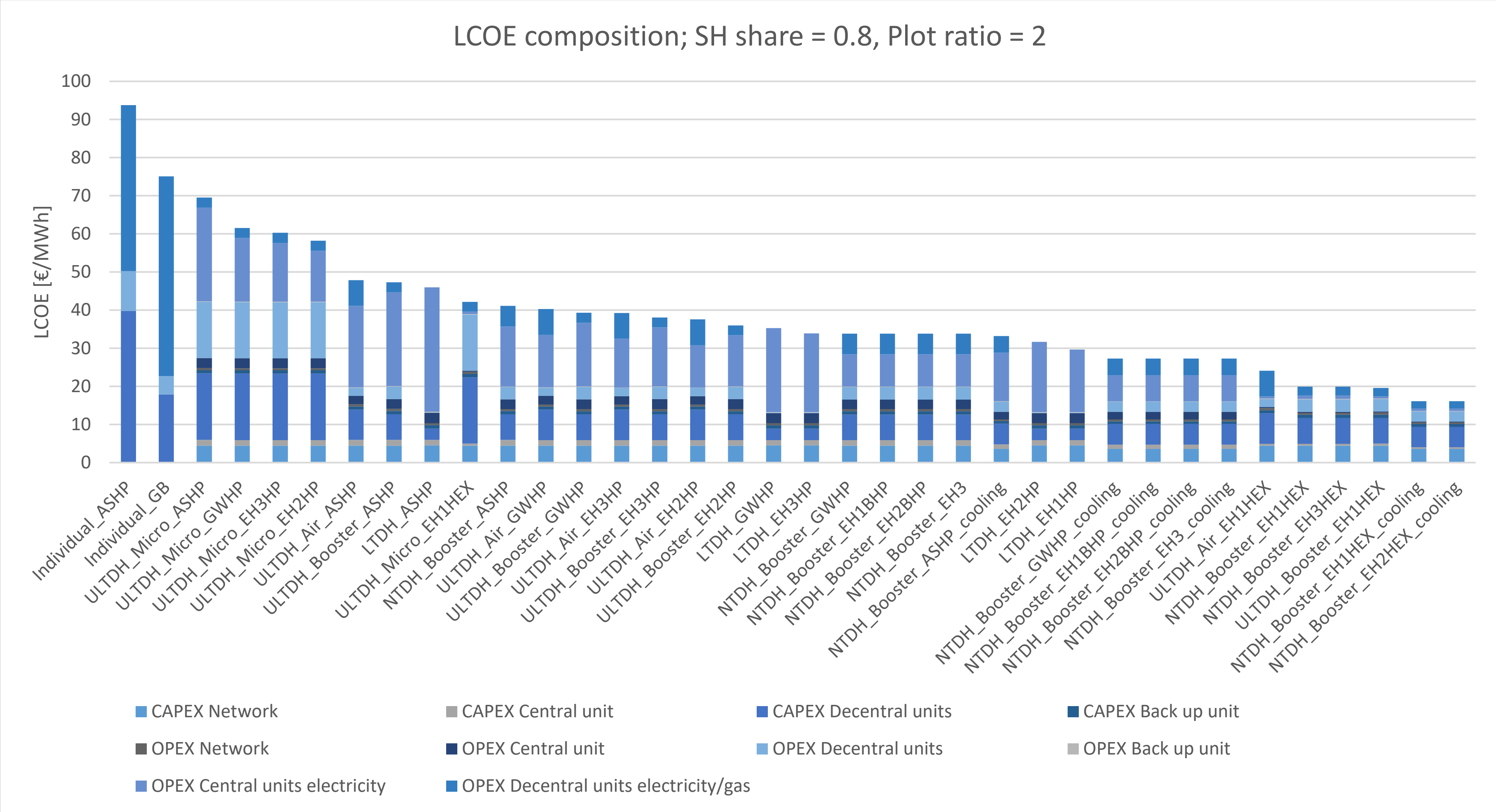

Figure 98 LCOE composition for NTDH, ULTDH, LTDH, SH share = 0.8, Plot ratio = 2

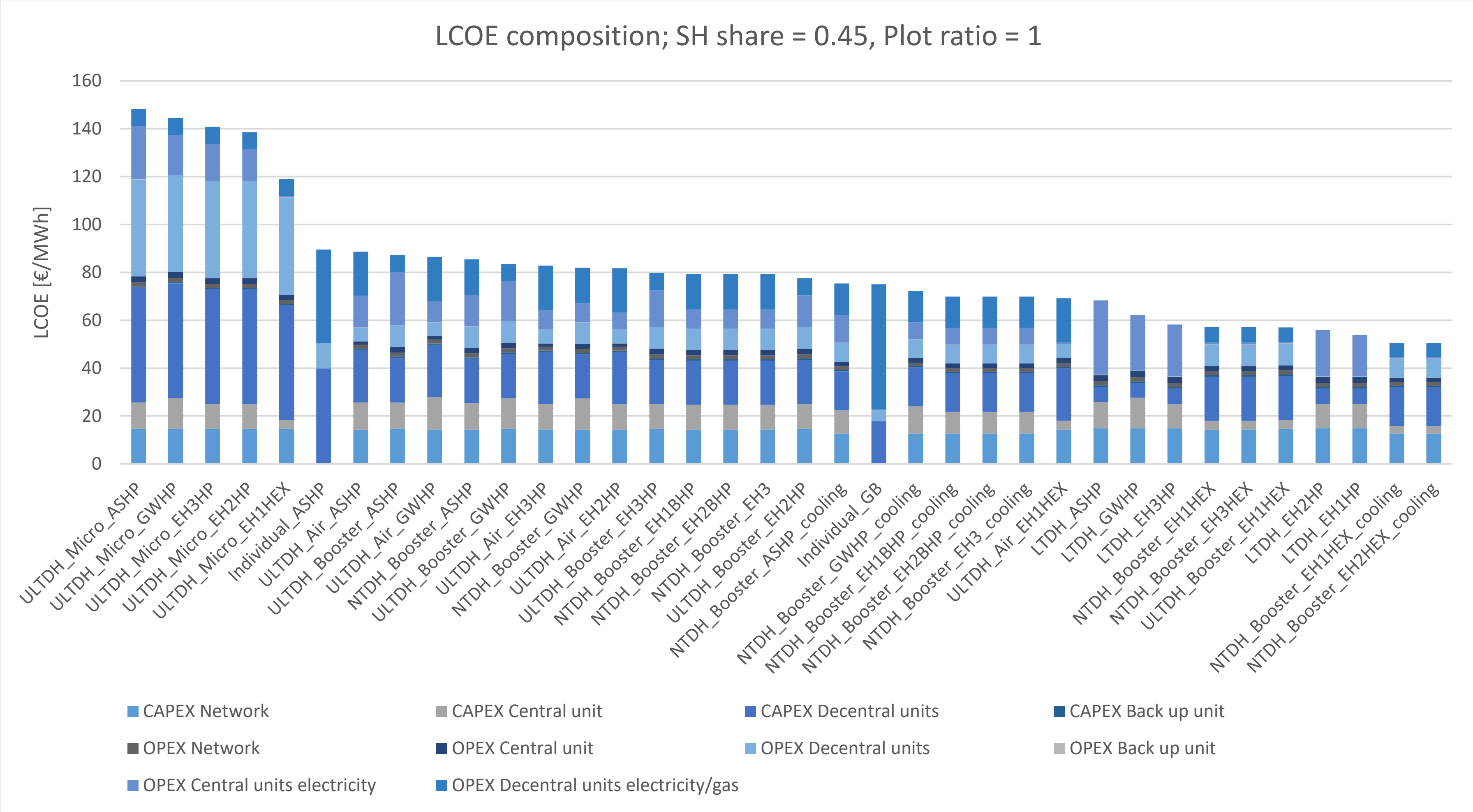

Figure 99 LCOE composition for NTDH, ULTDH, LTDH, SH share = 0.45, Plot ratio = 1

10.4 Energetic and environmental analysis

The PEF and CEF analysis were performed, as well as the LCOE analysis, for the different SH share and Plot ratio scenarios (see Table 26). Analysis of primary energy factor has been conducted for each district heating configuration (for different central sources) and each central heat source in different network configurations. The figures show how CEF monitors PEF, and it can be concluded that if we consume more primary energy, more CO_2 emissions are released into the atmosphere. All systems have lower CO_2 factors than individual gas boiler's CO_2 factor. As in previous analyses, each system configuration is evaluated for different central units. Also, each central unit is analysed for different system configurations.

Analysing Figure 100, Figure 101, Figure 102, Figure 103, and Figure 104, it can be concluded that the maximum amount of PEF and CEF for individual gas boilers will be 1.2, i.e. 0.23, which is in line with expectations since gas has a higher carbon emission factor than electricity. Systems that use a heat pump and heat exchangers are systems with a lower CEF because they use electricity that has a low carbon emission factor. Also, looking at the Figures, with an increase in SH share (if buildings are energy inefficient) there is an increase in PEF, and consequently CEF. Increasing the Plot ratio (from rural to urban areas) reduces the PEF, and thus the CEF. This means that systems with low SH share and high Plot ratio, an urban area with energy-efficient buildings, will be solutions with low PEF and CEF. Systems with a high SH share and a low Plot ratio, i.e. rural old settlements, will have a high PEF and CEF.

Figure 100 shows PEF and CEF for SH share 0.1 and Plot ratio 0.2, i.e. rural areas with high energy efficiency buildings, as already mentioned the most inconvenient solution is an individual gas boiler, followed by systems with heat pumps whose temperature lift between source and sink in the central unit is high. This requires a large amount of electricity to operate the system. The most unsuitable solution is LTDH_ASHP whose PEF is 0.69 and CEF 0.1. The most suitable solution in this scenario is NTDH systems that use low-temperature waste heat sources. The source of waste heat that is suitable for recovery, in this case, is at a temperature level of 40°C to 30°C.

Figure 101 shows PEF and CEF for SH share 0.1 and Plot ratio 2 which represent urban areas with new high energy efficiency buildings. As already mentioned, individual gas boilers prove to be the worst system, the next worst are those systems that use heat pumps in central sources whose source is outside air. The reason lies in the fact that heat pumps operate at higher temperature elevators, which means that higher electricity is required to operate the compressor, so this results in increased PEF and CEF. The worst system is LTDH_ASHP whose PEF is 0.56 and CEF 0.082. The best solution in this scenario is ULTDH_Booster_EH1HEX, which uses 40°C waste heat as a source in the central unit. For this reason, it is not necessary to use a heat pump in the central unit, but a heat exchanger, which results in low PEF and CEF, since only in the central unit there is electricity consumption due to the booster heat pump.

Figure 102 shows PEF and CEF for SH share 0.8 and Plot ratio 0.2, which represents rural areas with high energy efficiency buildings. Figure 102 shows that the worst system is an individual gas boiler, followed by heat pumps that use outdoor air as a source in the central unit to operate heat pumps. The most unsuitable such system is the LTDH_ASHP system whose PEF is 0.69 and CEF 0.101. The best system, in this case, are systems that use waste heat, the best characteristics were shown by the NTDH_Booster_EH2HEX_Cooling system. This system uses a 30°C heat exchanger in the central unit. The heat source is used to heat the DH network, and in the decentralized unit, the water used for heating and preparation of domestic hot water is heated using a booster heat pump. What makes this system stand out is the possibility of using a decentralized unit for cooling as well. The extremely low-temperature regime in the DH network, whose return is 10°C, and by installing a heat exchanger, also achieves a cooling effect. Low PEF and CEF are the results of using electricity only in the decentralized booster heat pump unit.

Figure 103 shows PEF and CEF for SH share 0.8 and Plot ratio 2, i.e. an urban area with low energy efficiency buildings. Individual gas boilers and systems that use heat pumps in the central unit whose heat source is outside air proved to be the most unsuitable systems with the highest amounts of PEF and CEF. The reason for the poorer results of such systems is explained in the sections above (see text about Figure). The most unsuitable system with the amount of PEF 0.65 and CEF 0.094 is LTDH_ASHP. The most suitable systems proved to be the NTDH and ULTDH systems which show low amounts of PEF and CEF. The reason for this lies in the fact that they use waste heat whose temperature class is above the DH network temperature, which enables the use of heat exchangers, thus reducing the use of electricity, which reduces the amount of PEF and CEF. The most suitable solution is NTDH_Booster_EH2HEX_cooling whose PEF is 0.037 and CEF 0.005. This system utilizes waste heat at a temperature of 30°C using a heat exchanger in the central unit, while the decentralized unit uses a booster heat pump to heat the heating water and domestic hot water. This system also enables the realization of the cooling effect (see the section above).

Figure 104 shows PEF and CEF for SH share 0.45 and Plot ratio 1, i.e. a semi-urban area with medium energy efficiency buildings representing the suburbs. Individual gas boilers and systems that use heat pumps in the central unit whose heat source is outside air proved to be the most unsuitable systems with the highest amounts of PEF and CEF. The reason for the poorer results of such systems is explained in the sections above (see text about Figure). The most unsuitable system with PEF 0.62 and CEF 0.090 is LTDH_ASHP. The most suitable systems proved to be the NTDH and ULTDH systems which show low amounts of PEF and CEF. The reason for this lies in the fact that they use waste heat whose temperature class is above the DH network temperature, which enables the use of heat exchangers, thus reducing the use of electricity, which reduces the amount of PEF and CEF. The most suitable solution is NTDH_Booster_EH2HEX_cooling whose PEF is 0.088 and CEF 0.012. This system utilizes waste heat at a temperature of 30°C using a heat exchanger in the central unit, while the decentralized unit uses a booster heat pump to heat the heating water and domestic hot water. This system also enables the realization of the cooling effect (see text about Figure 102).

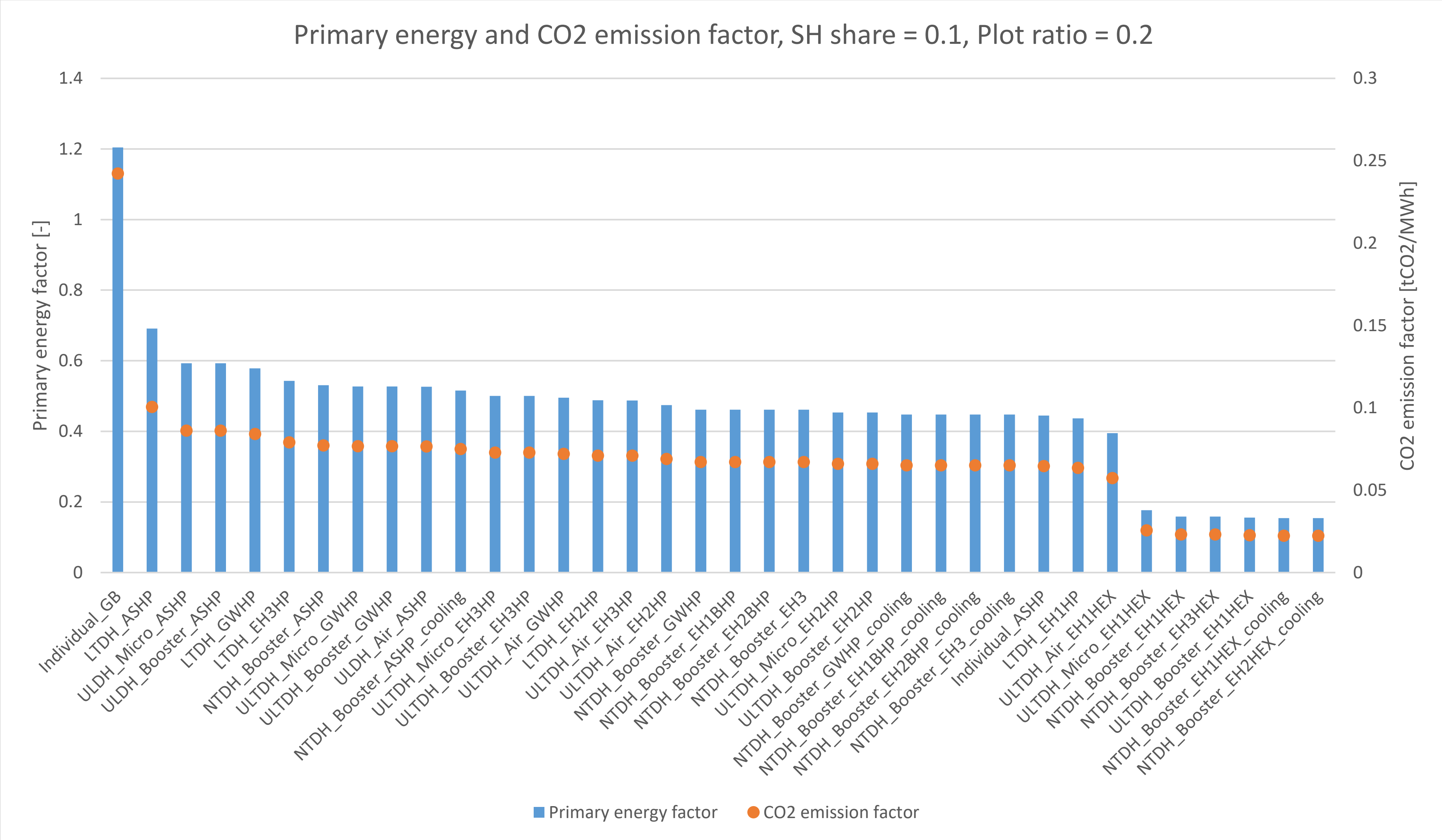

Figure 100 Primary energy and CO2 emission factor for NTDH, ULTDH, LTDH, SH share = 0.1, Plot ratio = 0.2

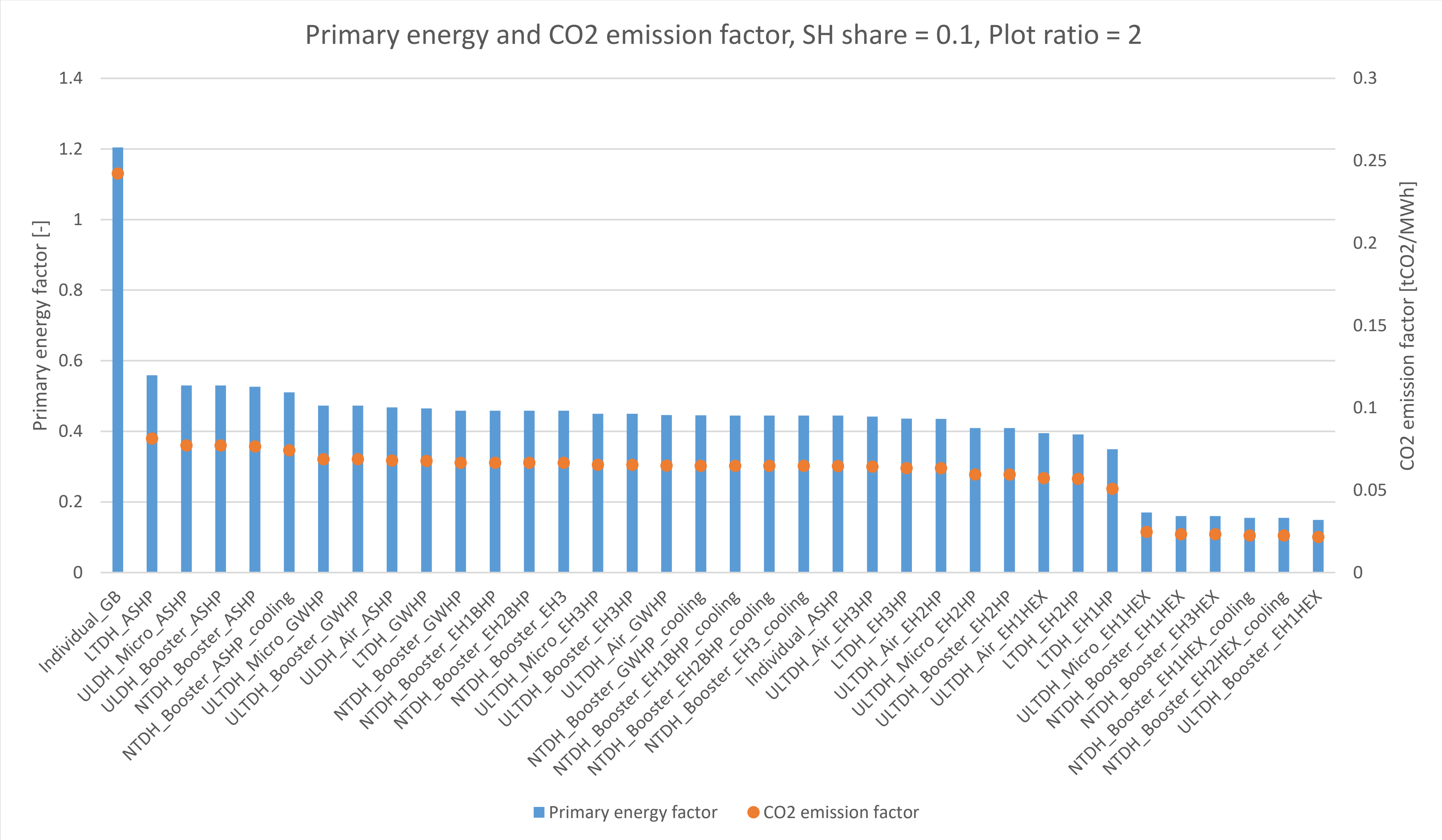

Figure 101 Primary energy and CO2 emission factor for NTDH, ULTDH, LTDH, SH share = 0.1, Plot ratio = 2

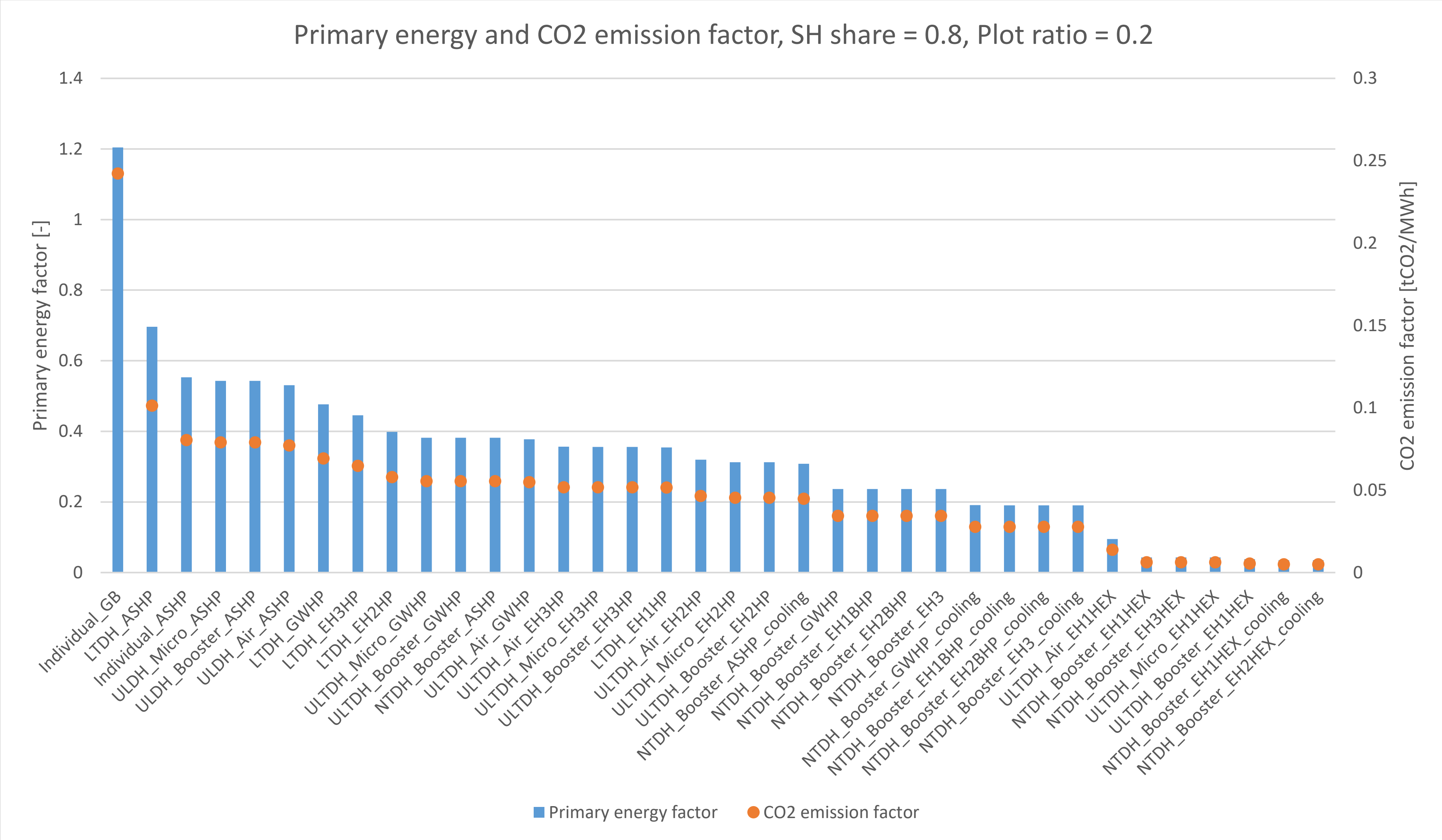

Figure 102 Primary energy and CO2 emission factor for NTDH, ULTDH, LTDH, SH share = 0.8, Plot ratio = 0.2

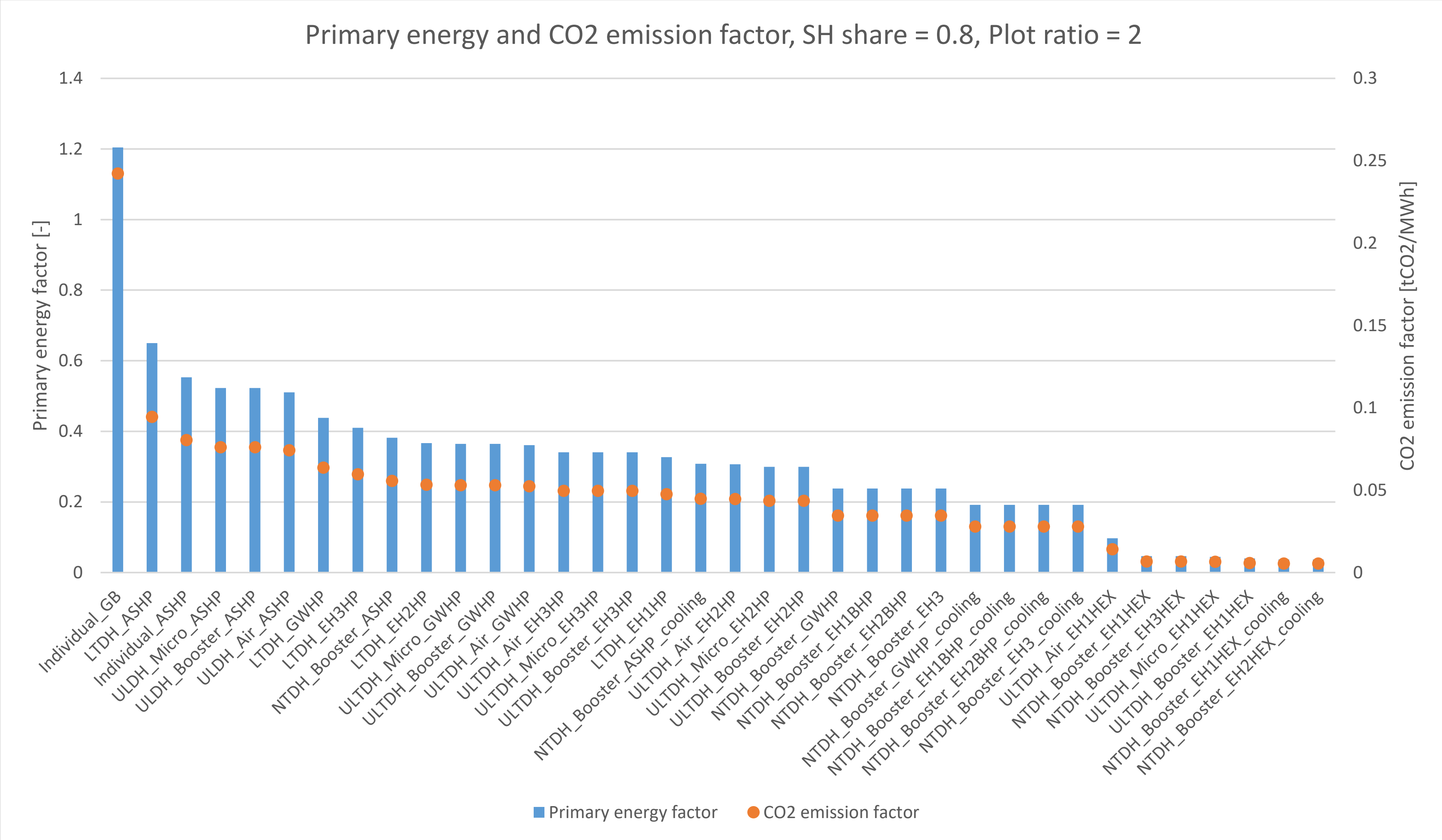

Figure 103 Primary energy and CO2 emission factor for NTDH, ULTDH, LTDH, SH share = 0.8, Plot ratio = 2

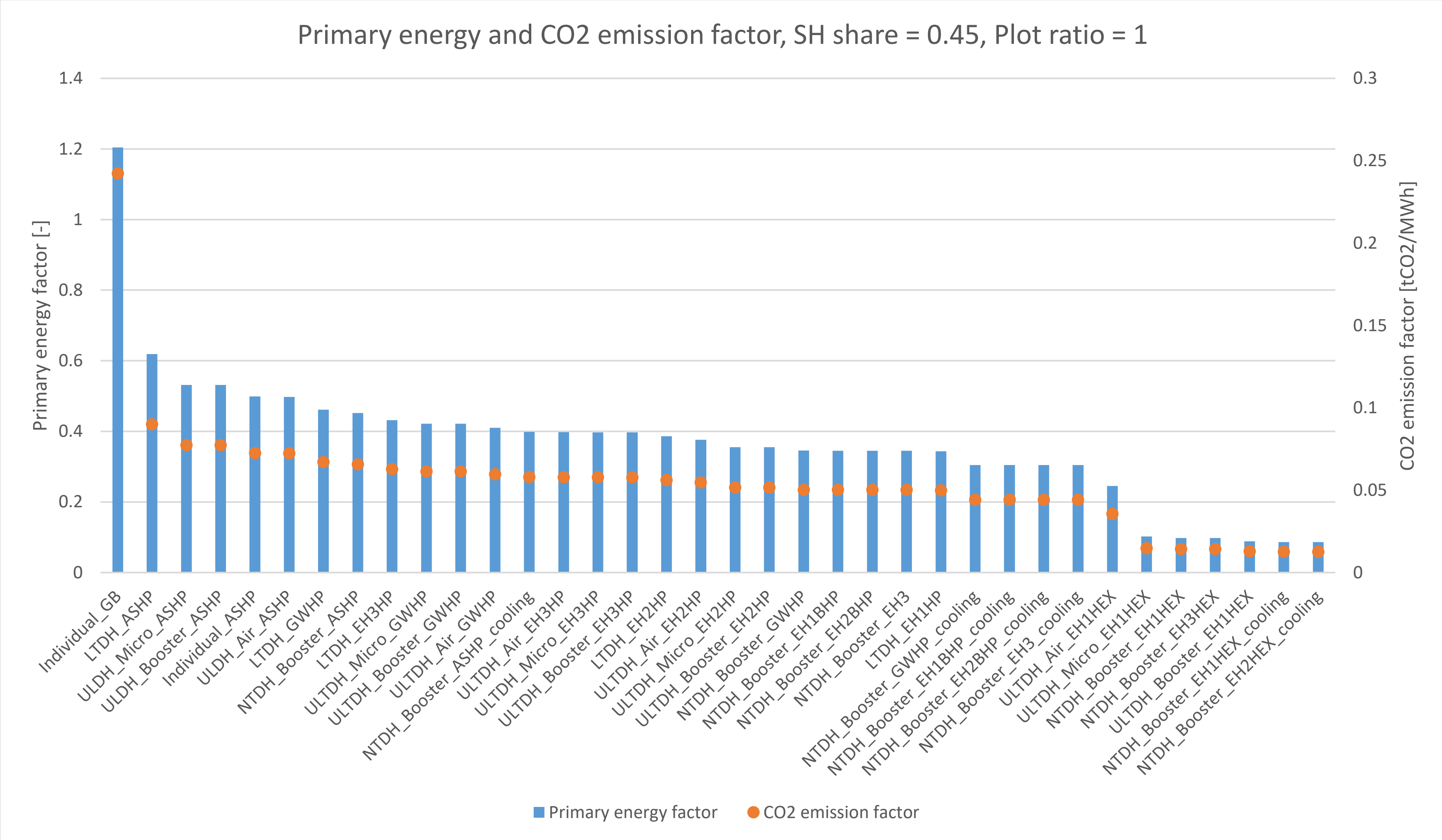

Figure 104 Primary energy and CO2 emission factor for NTDH, ULTDH, LTDH, SH share = 0.45, Plot ratio = 1

10.5 Sensitivity analysis

10.5.1 Electrical energy price

The electric energy cost was varied, as the future electricity price development is uncertain. The analysis of the sensitivity of the system to changes in electricity prices was conducted with the assumption that electricity could increase in price by up to 70% or become 70% cheaper in the future. Figure 105, Figure 106, Figure 107 shows how the LCOE will change in the event of a price change, in this analysis SH share and Plot ratio are fixed at 0.45 and 1 which represent semi-urban areas with medium energy efficiency buildings. We can assume that building blocks are characteristic of suburbs.

Figure 105 shows the sensitivity analysis for ULTDH systems. Systems that use micro heat pumps in a decentralized unit have a higher LCOE than other ULTDH systems. It is also evident that increasing the price of electricity leads to divergence of LCOE, i.e. the differences between the amount of LCOE for systems become larger, while in the case of reduced there is the convergence of LCOE, and we can assume that there is a price of electricity for which LCOE would be the same for all systems. Figure 105 shows that the system is the most sensitive to changes in the price of electricity ULTDH_Micro_ASHP, the reason lies in the fact that this curve has the highest coefficient of slope (the steepest). On the other hand, the systems that are least sensitive to changes in electricity prices are ULTDH_Micro_EH1HEX and ULTDH_Booster_EH3HP. These systems have the lowest slope coefficient of the first, which results in smaller changes in the LCOE in the event of a change in the price of electricity.

The following Figure 106 shows the sensitivity analysis for NTDH systems. In the case of NTDH systems, the greatest sensitivity to changes in the price of electricity is the NTDH_Booster_ASHP system. According to Figure 106, this system has the highest slope coefficient, and for this reason, changes in the price of electricity will lead to larger differences in the amount of LCOE. On the other hand, the systems that are least sensitive to changes in the price of electricity are the NTDH_Booster_EH1HEX_cooling and NTDH_Booster_EH2HEX_cooling systems, and with such systems, there will be small changes in the amount of LCOE when the electricity changes.

Figure 107 shows the sensitivity analysis for LTDH systems. The most sensitive LTDH system is LTDH_ASHP which for small changes in the price of electricity shows significant changes in the amount of LCOE, the reason for this is in the amount of the coefficient of the slope of the direction which is high. The least sensitive LTDH system is LTDH_EH1BHP and shows small changes in the amount of LCOE when changing the price of electricity. Also, NTDH systems show significant divergence of LCOE amounts when increasing electricity prices. On the other hand, reducing the price of electricity leads to the convergence of LCOE amounts. A further reduction in the price of electricity will lead to the intersection of the route and this place will indicate the amount of the price of electricity for which the LCOE for all systems will be the same amount.

From the figures, it can be concluded that in general, all systems will record a change in the amount of LCOE by changing the price of electricity. The reason for this is that all systems rely on electricity for operation, especially for the operation of heat pumps (in central and decentralized units), and generally, such systems will be more sensitive to changes in electricity prices, while systems that rely on heat exchangers record minor changes in the amount of LCOE due to changes in electricity prices.

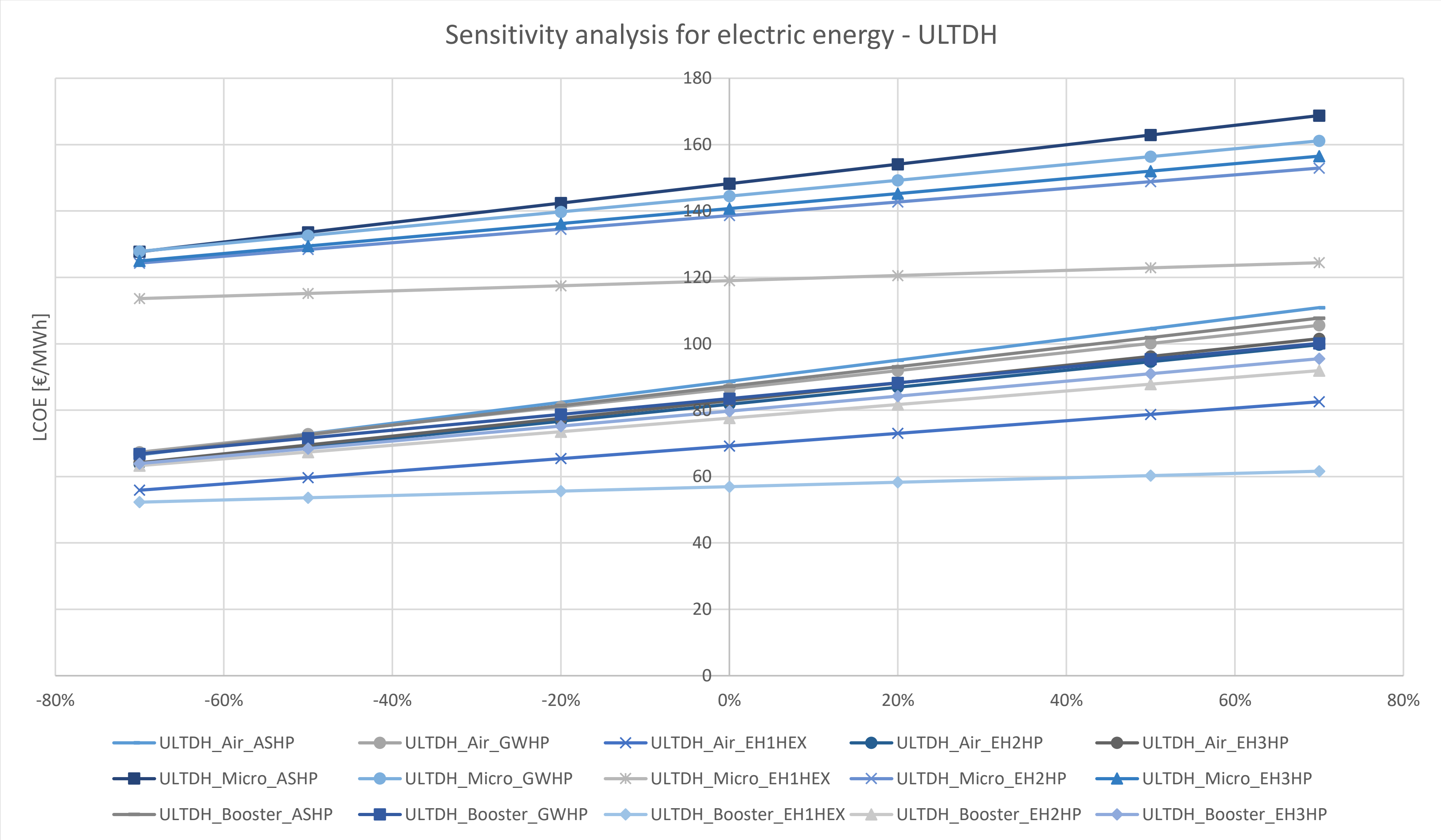
Sensitivity analysis for electric energy - ULTDH
LCOE [€/MWh]
180
160
140
120
100
80
60
40
20
0
-80%
-60%
-40%
-20%
0%
20%
40%
60%
80%
ULTDH_Air_ASHP
ULTDH_Air_GWHP
ULTDH_Air_EH1HEX
ULTDH_Air_EH2HP
ULTDH_Air_EH3HP
ULTDH_Micro_ASHP
ULTDH_Micro_GWHP
ULTDH_Micro_EH1HEX
ULTDH_Micro_EH2HP
ULTDH_Micro_EH3HP
ULTDH_Booster_ASHP
ULTDH_Booster_GWHP
ULTDH_Booster_EH1HEX
ULTDH_Booster_EH2HP
ULTDH_Booster_EH3HP

Figure 105 Sensitivity analysis for electric energy - ULTDH, SH share = 0.45, Plot ratio = 1

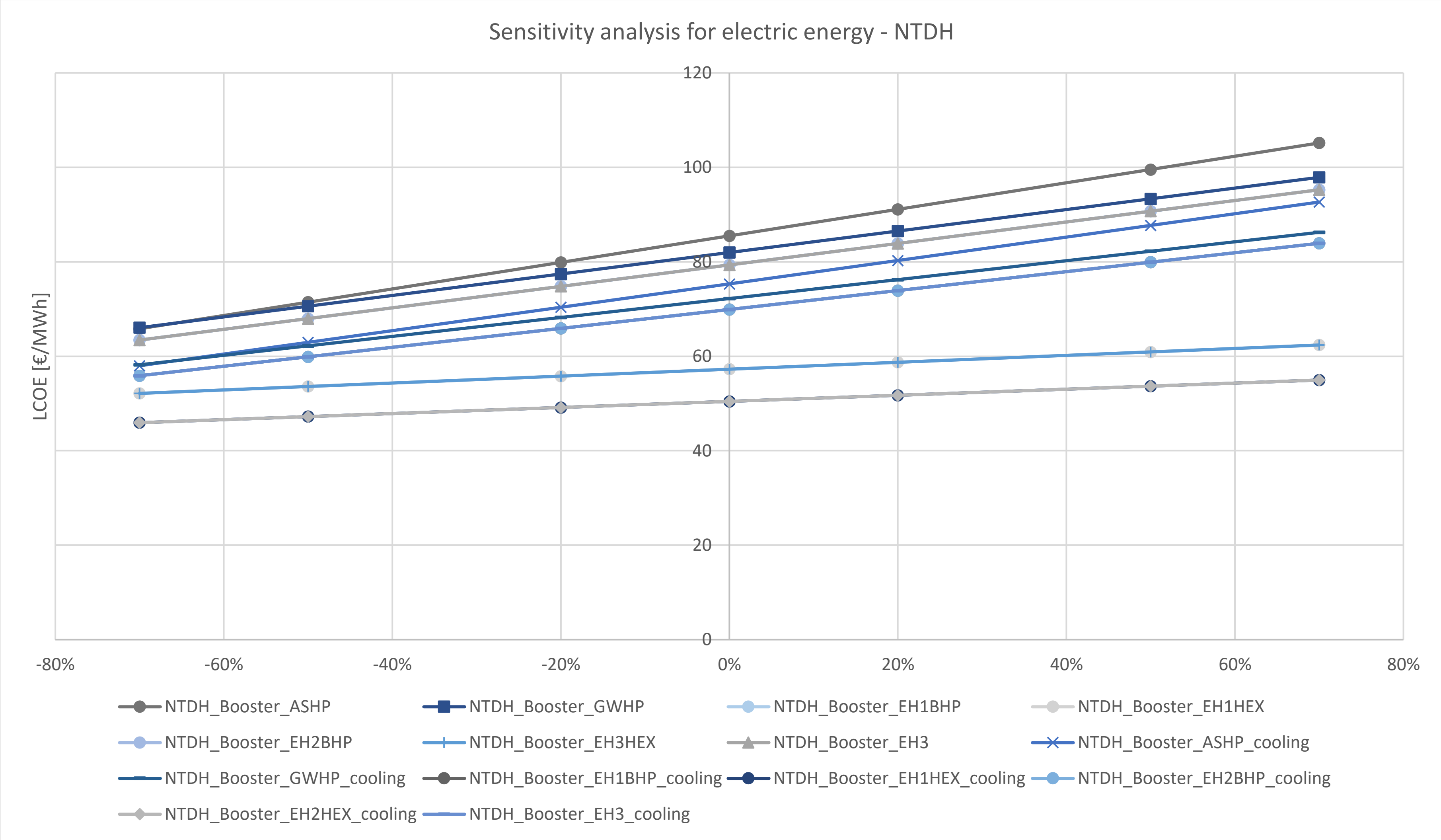

Figure 106 Sensitivity analysis for electric energy - NTDH, SH share = 0.45, Plot ratio = 1

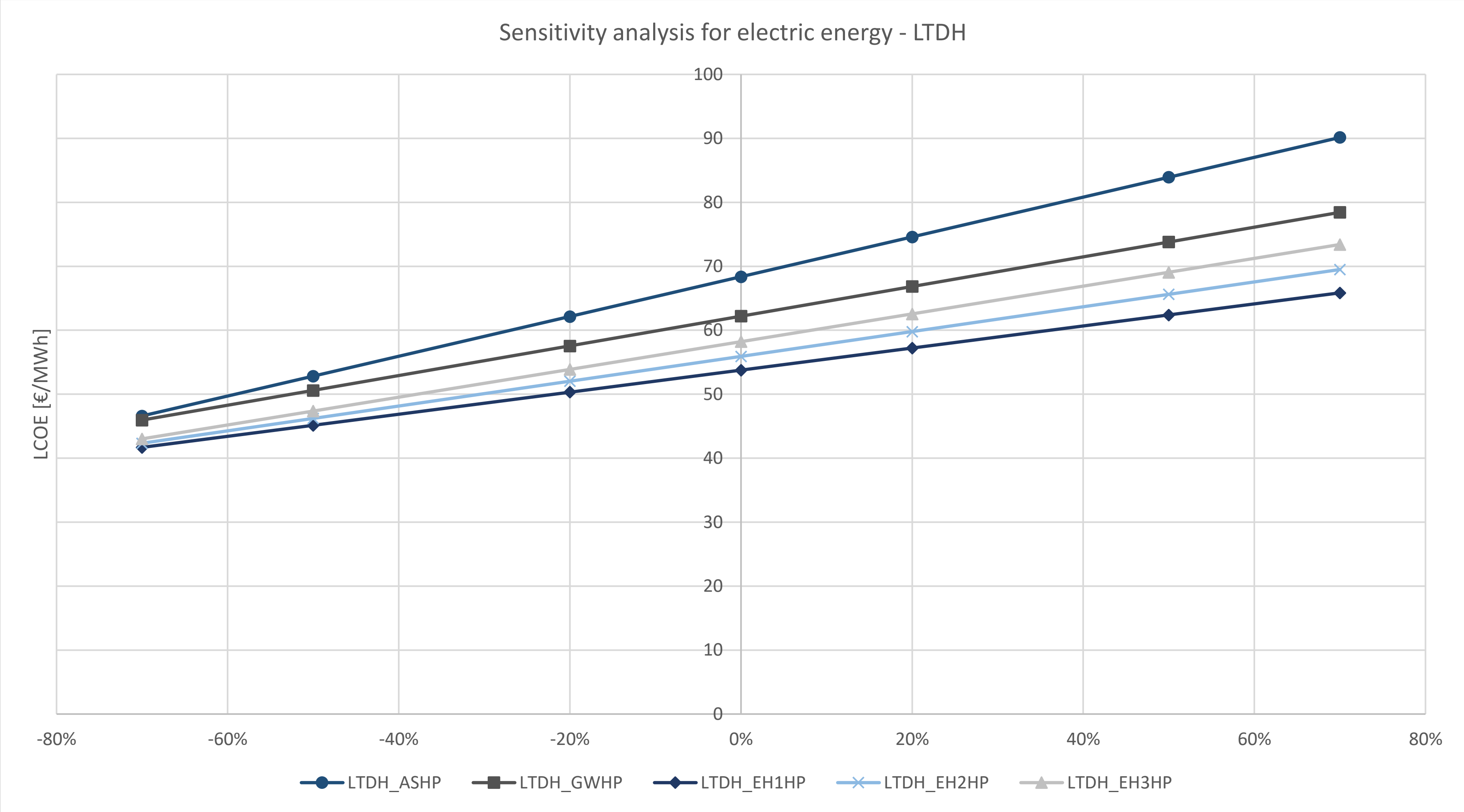

Figure 107 Sensitivity analysis for electric energy - LTDH, SH share = 0.45, Plot ratio = 1

10.5.2 Investment cost

The heat pump investment cost was based on currently available technology and recent project, but they might decrease. To examine the impact of investment cost on LCOE, the systems underwent investment sensitivity analysis. To conduct a sensitivity analysis, the investment cost (CAPEX) of the network, central unit, decentralized unit, and backup unit was varied. CAPEX has ranged from a price increase of 70% to a price reduction of 70%. Figure 108, Figure 109, Figure 110 shows how the LCOE will change in the event of a price change, in this analysis SH share and Plot ratio are fixed at 0.45 and 1 which represent semi-urban areas with medium energy efficiency buildings. We can assume that building blocks are characteristic of suburbs. It can be seen from the figures that a change in the investment price will result in a linear change in the LCOE.

The results of the sensitivity analysis to the change in investment price for ULTDH systems are shown in Figure 108. We see that in the event of an increase in the price of the investment, there will be an increase in the LCOE, while a decrease in the price of the investment will also lead to a decrease in the LCOE. The following Figure 109 shows the sensitivity analysis for NTDH systems. LCOE NTDH system will increase in case of an increase in investment price, in case of a decrease in investment price will decrease. Similar results obtained as in ULTDH and NTDH were obtained for LTDH systems, shown in Figure 110. By changing the price of the LTDH system, the LCOE will rearrange depending on whether it is an increase in the cost of the investment or a decrease. In the case of an increase in the price of the investment, there will be an increase in the LCOE, while a decrease in the price of the investment will lead to a decrease in the LCOE.

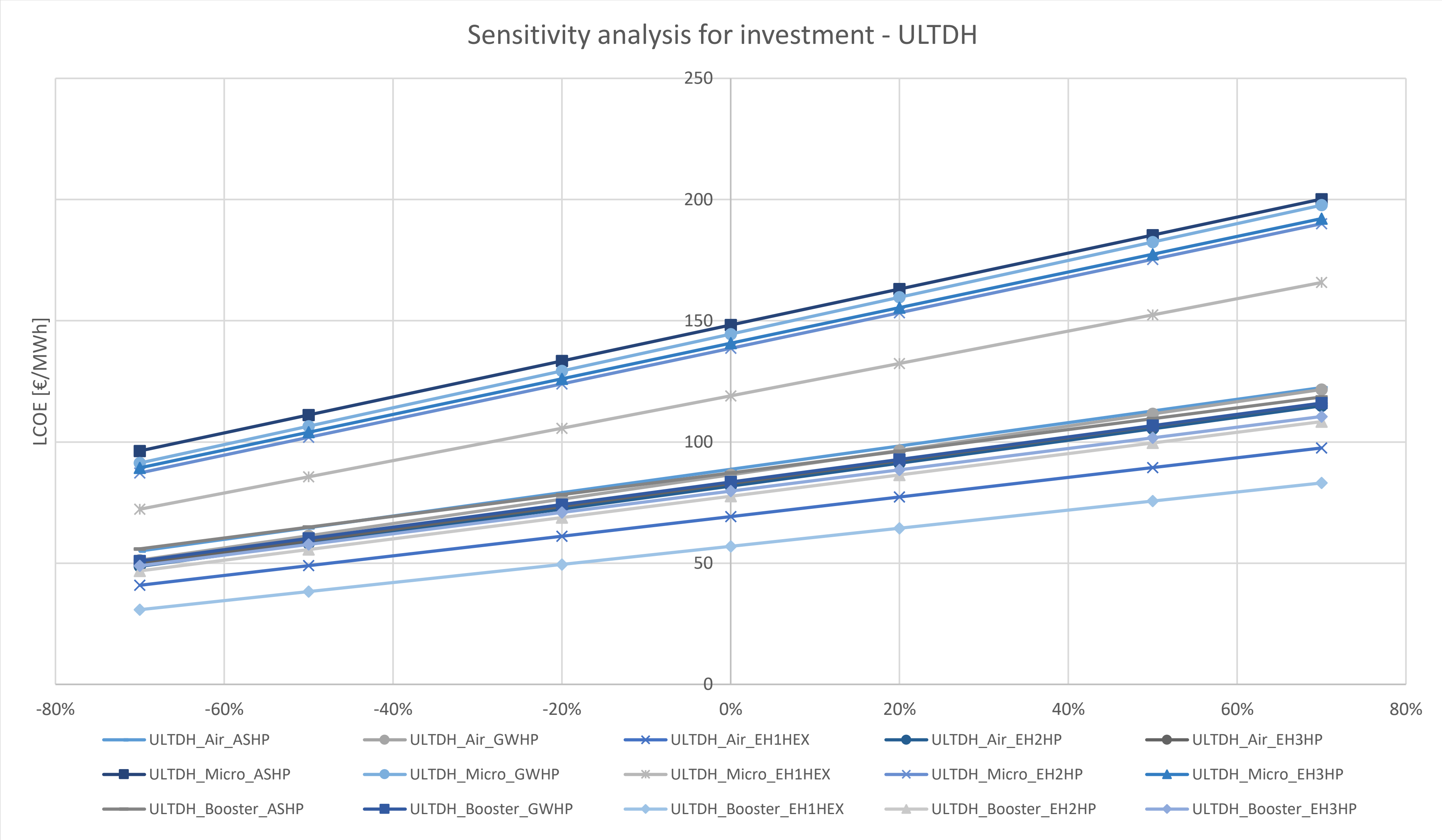
Sensitivity analysis for investment - ULTDH
LCOE [€/MWh]
250
200
150
100
50
0
-80%
-60%
-40%
-20%
0%
20%
40%
60%
80%
ULTDH_Air_ASHP
ULTDH_Air_GWHP
ULTDH_Air_EH1HEX
ULTDH_Air_EH2HP
ULTDH_Air_EH3HP
ULTDH_Micro_ASHP
ULTDH_Micro_GWHP
ULTDH_Micro_EH1HEX
ULTDH_Micro_EH2HP
ULTDH_Micro_EH3HP
ULTDH_Booster_ASHP
ULTDH_Booster_GWHP
ULTDH_Booster_EH1HEX
ULTDH_Booster_EH2HP
ULTDH_Booster_EH3HP

Figure 108 Sensitivity analysis for investment cost - ULTDH, SH share = 0.45, Plot ratio = 1

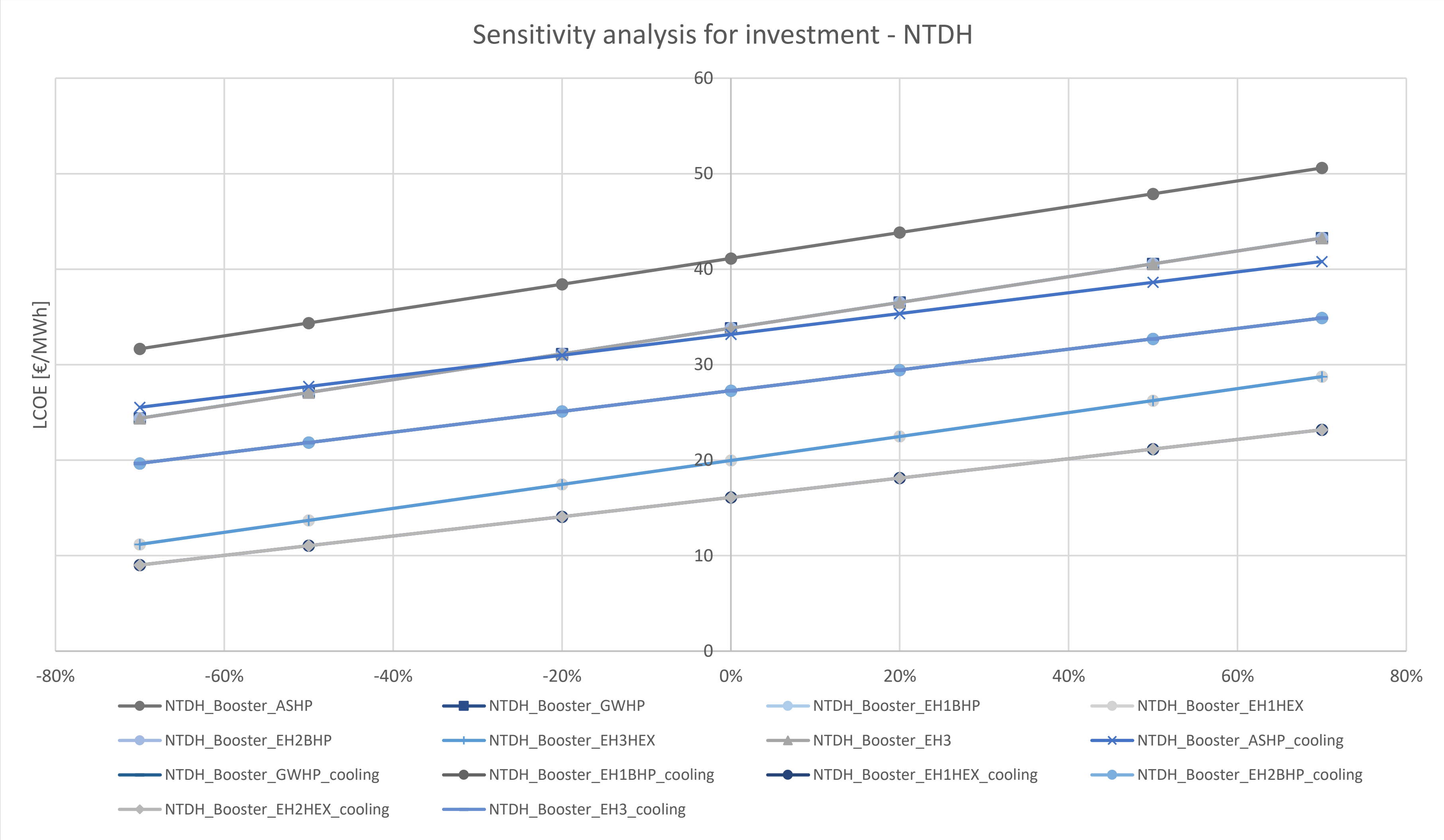

Figure 109 Sensitivity analysis for investment cost - NTDH, SH share = 0.45, Plot ratio = 1

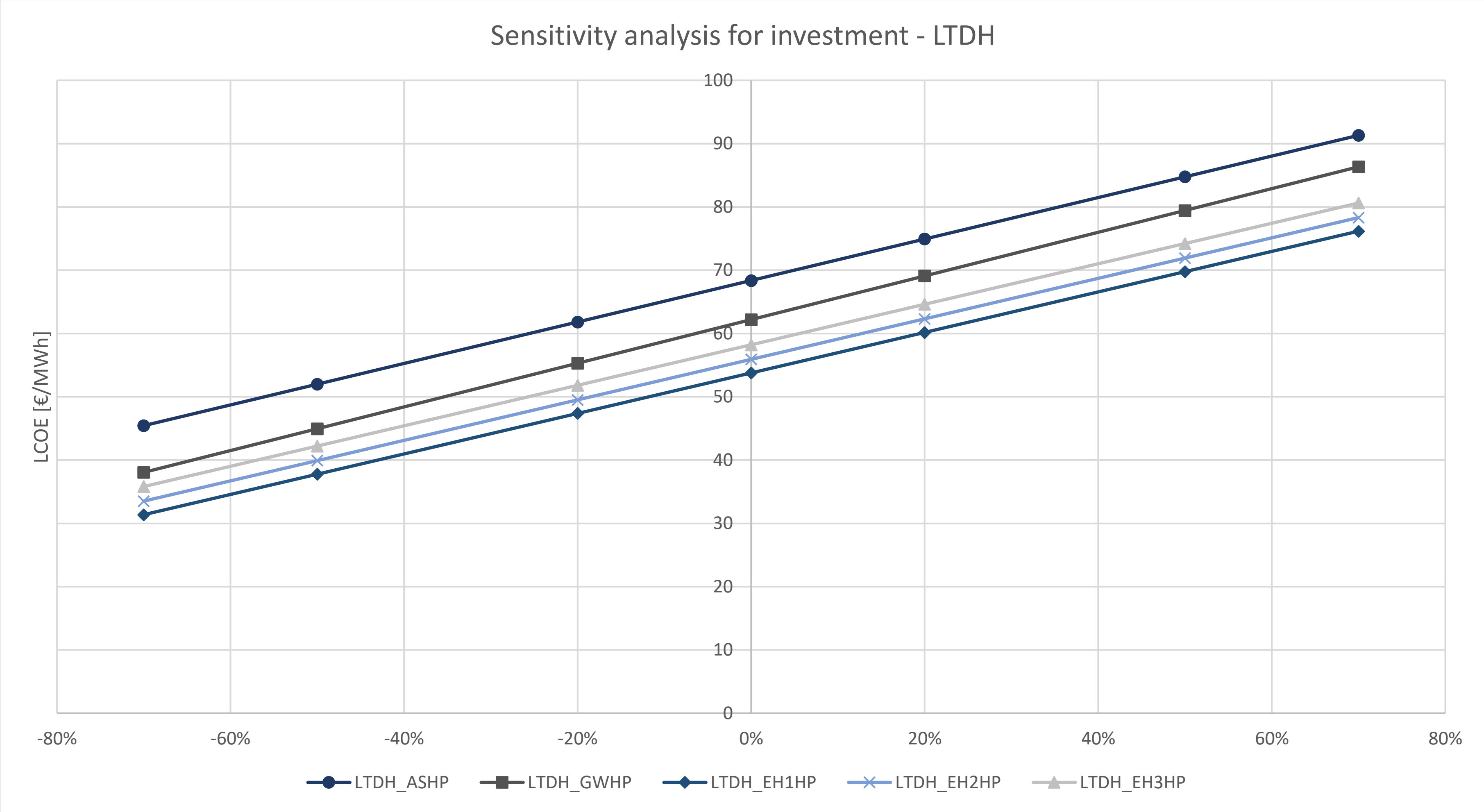

Figure 110 Sensitivity analysis for investment cost - LTDH, SH share = 0.45, Plot ratio = 1

10.6 Key takeaways

After conduction of cost and benefit analysis of low, ultra-low, neutral temperature district heating systems following was observed. Low plot ratios and space heating shares make these new networks infeasible compared to individual gas boiler heating. However, if technology advancements continue at current pace cost of this systems could be significantly reduced and make them more competitive. It has been shown that network investment accounts only for a fraction of total investment cost and most of costs is result of central and decentral heat pumps. Also, in cases where heat pumps are in each apartment, operation, and maintenance costs, as well as electricity cost, increases which affects profitability of these systems. At higher plot ratios (urban, densely populated area) these systems are profitable if domestic hot water demand is low compared to space heating demand. That is also supported by decentral heat pumps being main expenditure in these networks. That means that currently, network losses cannot cover costs of extra equipment and electricity. NTDH networks perform slightly better because they do not need central heat pumps and heat losses are low enough to avoid additional cost of losing heat. Also, NTDH networks allows users to achieve cooling effect during summer period. However, these systems are not price competitive to individual heating solutions in rural areas with highly efficient buildings whose space heating need is only a fraction of their domestic hot water need. This analysis showed that NTDH, ULTDH and LTDH systems performs the best in areas where is high share of building with high energy efficient.

Primary energy factor and CO_2 emission factor showed that, compared to fossil fuel heating, these systems help to reduce energy consumption and CO_2 emissions. All NTDH, ULTDH and LTDH variants examined in this thesis showed better factors than individual gas boiler heating.

Overall, these systems are great for energy conservation and CO_2 reduction, but they are still not feasible as other heating sources. To boost their implementation heat pump cost must fall and more people needs to become electricity producers

11 PESTLE analysis of ULTDH and NTDH networks

11.1 Political

To draw attention to the importance of the district heating sector the European Union has adopted a collective plan and strategy named *EU Strategy for heating and cooling*. This strategy enhances the development of the heating and cooling sector and proposes and gives the direction that needs to be taken in the future. This strategy aims to decarbonise the district heating sector with the simultaneous renovation of buildings, which would improve their energy efficiency and encourage the use of renewable energy sources. Also, with this strategy, the EU encourages the electrification of district heating, which builds on another strategy related to Energy System Integration.

EU Energy System Integration strategy aims to connect the energy sectors to improve and achieve more efficient use of energy flows. One example of such coupling is the utilization of waste heat to meet the thermal needs of DH systems and integration of central and decentral heat pumps in the system.

All countries within the European Union have committed themselves to reduce greenhouse gas emissions, reducing dependence on fossil fuels, streamlining energy use, and improving the energy efficiency of processes, systems, and construction funds. In line with these goals, EU members have developed energy action plans and strategies at the political level that could achieve the set goals, named net-zero strategies. In line with these plans, countries will act and set the framework in which energy-intensive sectors will operate. One of these sectors is the district heating and cooling sector is generally covered, as well as the closely related building sector. Encouraging the use of renewable energy sources is generally applicable to the district heating sector. One type of renewable energy source can be considered the recovery of waste heat, which today often remains unused. The use of waste heat can reduce the required primary energy in district heating, and consequently reduce the dependence on fossil fuels and even greenhouse gas emissions. By acting in the renovation and improvement of the energy properties of the building stock, the energy required for heating is reduced, but also opens the possibility of applying low-temperature regimes in heating. Following the above, the policies have enabled the co-financing of such projects through various EU structural funds, but also national and local funds and grants. Also, in the future, to improve the development of low-temperature heating systems, it is necessary to discourage fossil energy sources (abolition of subsidies, weaken and discourage the fossil lobby, etc.). Also, one type of incentive could be the privatization of district heating, which due to competitiveness would strive for cheaper options for heat production, and for which low-temperature heating networks have proven to be more appropriate.

It is necessary to mention several EU directives that have a direct or indirect impact on district heating and shape the goals that need to be achieved. The most important directives concerning district heating are the Energy Efficiency Directive, the Energy Performance of Buildings Directive, and the Renewable Energy Directive.

From all the above, it can be concluded that ULTDH and NTDH networks are in line with future policy plans and goals at the EU level, but also at the national level. These systems that contribute to the reduction of the required primary energy because it is based on the utilization of already existing energy flows, such as waste heat. Such a principle is achieved by coupling different energy-intensive sectors. Furthermore, such systems are characterized by low heat losses which contribute to improved energy efficiency, have a lower LCOE which makes them more economically viable. ULTDH and NTDH systems also contribute to reducing greenhouse gas emissions. All of this puts these systems on the line with both goals and objectives for the future.

More detailed Political background for PESTLE analysis is available in D3.1 – REWARDHeat PESTLE analysis.

11.2 Economic

ULTDH systems

From an economic point of view, the cost of thermal energy produced is of the utmost importance, the Levelized cost of energy (LCOE). By comparing LCOE with different ways of producing heat, ULTDH networks have lower LCOE as opposed to high temperatures district heating, which also uses fossil fuels to produce heat. The lower amount of LCOE is a consequence of lower production costs of thermal energy, as well as the possibility of using waste heat sources that have temperatures suitable for integration into the heating system. This advantage is important from the point of view of heat producers, but also for users, buyers of heat. The economic benefits of using a low-temperature regime are particularly visible in urban areas with high population density and buildings with high energy efficiency.

ULTDH systems are proving unprofitable and will have a high LCOE when used in areas of sparse or medium population density. Then there will be very high investment costs, but also operating costs, and in that case, it is necessary to consider some other economically more suitable solutions.

To maximize the impact of ULTDH systems, it is necessary to meet the goals in the building industry, which is to carry out energy renovation of the building stock.

NTDH systems

By comparing LCOE with different ways of producing heat, NTDH networks have the lowest LCOE as opposed to traditional low-temperatures district heating (LTDH) which uses fossil fuels to produce heat. The lower amount of LCOE is a consequence of lower production costs of thermal energy, as well as the possibility of using waste heat sources that have temperatures suitable for integration into the heating system. This advantage is important from the point of view of heat producers, but also for users, buyers of heat. The economic benefits of using a neutral temperature regime are particularly visible in urban areas with high population density and buildings with high energy efficiency. It is also necessary to consider the economic benefits of district cooling that can be achieved using NTDH systems.

11.3 Social

From the social point of view, the focus is on public awareness of the opinion and potential of the low-temperature regime in district heating, but also the cost of using such systems. In general, society is poorly or not at all aware of the possibilities of using low-temperature regimes in district heating, as well as the conditions that need to be met for the application of such systems to become widespread. To recognize the social aspect of low-temperature district heating, it is necessary to acquaint society with the technology, opportunities, and the benefits, especially economic, of such systems. From an economic point of view, social groups are interested in tariffs at which to pay low-temperature heat, price structure, but also the management of such systems given the change in the structure of decentralized units that have so far been simple heat exchangers. By using low-temperature regimes in DH, heat pumps are used in decentralized units whose management becomes more complex and demanding.

11.4 Technical

ULTDH systems

The technology required to use low-temperature regimes in DH exists and there are no obstacles in this regard. The central units in ULTDH networks use heat pumps or simple heat exchangers. Heat pumps are used to raise the heat source (e.g. waste heat source, etc.) to a temperature level to make it suitable for integration into a DH network. In decentralized units, so-called substations, there are three possibilities. In the first version, a booster heat pump is used in the substation to heat domestic hot water. Next to the heat pump, there is a heated tank for domestic hot water. A heat exchanger is still used for heating as the temperature in the network is sufficient to meet the temperature regime in the heating system. The second version is with a micro heat pump used to heat domestic hot water, while a heat exchanger is still used for the heating system in the substation. In the third version, a heat exchanger is used in the substation. The most challenging part of such technical performances is the issue of managing and balancing the DH network.

As already mentioned, ULTDH systems are suitable for buildings with high energy efficiency, and in practice, this is the most common problem. The share of buildings that have poorer energy properties in practice is very high in the states and large investments are needed in this aspect so that low temperature and neutral temperature networks can be used.

NTDH systems

The technology required to use the NTDH system already exists and can be implemented. We can divide the technology that needs to be used in central units, and the technology for decentralized units, i.e. substations. In central stations, heat exchangers are most often used in practice because the heat source generally has higher temperatures than the DH network temperature, exceptions maybe if the source is air or groundwater. Heat pumps are mainly used in substations for heating to ensure a sufficiently high heating temperature, but also the temperature required for domestic hot water. NTDH systems are also suitable for achieving a cooling effect by installing a simple heat exchanger in the substation because in the summer the temperature in buildings is higher than the temperature regime in DH. This is of great importance for NTDH systems and is one of the greatest values of such systems. The most challenging part of such technical performances is the issue of managing and balancing such DHC network.

As already mentioned, NTDH systems are suitable for buildings with high energy efficiency, and in practice, this is the most common problem. The share of buildings that have poorer energy properties (old buildings) in practice is very high in the states and large investments are needed in this so that neutral temperature networks can be used.

11.5 Legal

From a legal perspective, the question arises as to who is responsible for the modifications required for the necessary adaptations of existing systems to use the ULTDH/NTDH system. Equally, there is the question of responsibility for who and how will manage the system and bear the responsibilities. For example, the use of heat pumps in substations leads to higher electricity consumption and the question arises as to how and in what way it is fair to share the cost of electricity and the like. Also, for ULTDH/NTDH it is necessary to create a legal framework for the formation of the price of thermal energy that users will pay. In many countries, such procedures are complex and need to be simplified. Legal documents on buildings also need to be considered to ensure access to ULTDH/NTDH networks of buildings with very good energy performance in the future.

11.6 Environmental

From an environmental point of view, two factors are important: the Primary energy factor (PEF) and the Carbon emission factor (CEF). Strategies and plans at the EU and national levels envisage is a reduction in the primary energy used for supply. To achieve this goal NTDH showed good results, i.e. low PEF. CEF is directly related to the use of primary energy and the results of this factor have proven to be very suitable for use due to its low amount. The results obtained from the analysis of ULTDH/NTDH systems showed that these systems can significantly contribute to reduction of PEF and CEF, and that they can be relied on and counted on in the future.

11.7 PESTLE analysis – summary

The following can be said as a summary of this analysis. In terms of Policy, new generations of district heating such as ULTDH and NTDH have a strong foothold in plans and strategies at EU level, but also at national levels.

There is strong **Political** will on EU level which support decarbonisation of district heating and cooling systems, implantation of low-temperature networks and integration of available waste heat. Usually, this also translates to national energy plans and strategies. This means that ULTDH and NTDH systems are technology which have political support. However, national-level district heating strategies are usually focused on decarbonisation and refurbishment of existing high-temperature district heating networks.

Economic analysis of ULTDH and NTDH prove to be cost-effective options with low LCOEs, subject to two essential conditions. The first condition is that ULTDH and LTDH systems are suitable for areas with high population density with high heat needs, while on the other hand the buildings of such areas have good energy characteristics, which is also the second condition. Economically comparing ULTDH and NTDH systems, NTDH systems prove to be better due to lower LCOE because of lower investment and operating costs, lower PEF and CEF.

From the **Social** point of view, the problem of insufficient information and lack of knowledge about the advantages of ULTDH and NTDH stakeholder systems was recognized. NTDH differs in the sense that society does not recognize the potential or does not know about it that such systems can be used for centralized cooling.

Technical analysis has shown that the technology for the application of ULTDH and NTDH systems exists and is already used for various purposes. ULTDH and NTDH systems in central stations can use heat exchangers or heat pumps depending on the heat source. On the other hand, ULTDH and LTDH substations differ significantly although they both use heat exchangers and heat pumps. The main difference is the additional subsystem in NTDH systems due to the possibility of cooling. The main technical problem of ULTDH and NTDH systems are buildings with poor energy performance. Since ULTDH and NTDH are characteristic of urban areas that are mostly old in Europe, before the application of these systems it is necessary to renew and adjust the stock of buildings ULTDH and NTDH systems.

Analysis of **Legal** document show that prior to the wider application of ULTDH and NTDH, it will be necessary to regulate property legal relations in terms of rights and obligations related to substations, i.e. who will oversee maintaining and managing more complicated designs of thermal substations.

Environmental analysis has shown that ULTDH and NTDH systems reduce PEF and CEF, which shows that these systems are in line with environmental policies at EU level, but also at national levels. These systems will contribute to reducing the need for primary energy, which will result in a reduction in pollutant emissions. The reason for this is that such systems use less carbon-intensive energy sources, i.e. electricity. By comparing ULTDH and NTDH systems, NTDH systems showed better results in PEF and CEF amounts although the differences in amounts are small

12 Conclusions

This deliverable (D2.1 – REWARDHeat planning schemes database) was developed as the part of WP2 - Design of low temperature networks with multiple energy sources. The deliverable serves as the knowledge database for ultra-low (ULTDH) and neutral temperature (NTDH) district heating systems. This document is complemented with three additional Excel files publicly available at Zenodo platform, on this **link**:

- Calculation tool for ULTDH and LTDH networks
- Calculation tool for NTDH networks
- Database of existing next-generation district heating networks.

The document provided detailed literature overview of research papers and best practice examples related to ULTDH and NTDH networks, while focusing on thermal sources, supply technologies, thermal networks and end-user substation. Then, the overview of existing next-generation networks has been presented and analysed with the respect to temperature regimes and used thermal sources. Based on the carried-out literature review and existing cases, the database of NTDH and ULTDH system components has been developed: end-user substations, thermal networks, thermal source and thermal source connection configuration. SWOT analysis of different components has been carried out and comparison with "traditional" low-temperature district heating (LTDH) networks has been provided.

Afterwards, more than 30 ULTDH and NTDH system topologies has been defined and analysed with respect to energy performance, total cost and carbon emissions. Different boundary conditions, such as plot ratio and space heating share, has been considered. Furthermore, sensitivity analysis of electrical energy price and investment cost has been carried out. Obtained results have been ranked and compared with traditional LTDH networks and individual solutions such as air-source heat pump and natural gas boiler. For this purpose, already mentioned Excel-based calculation tools have been used. It has been shown that ULTDH and NTDH networks have lower cost that individual solutions in dense urban areas (high plot ratio) and lower carbon emissions, including primary energy factor.

Finally, PESTLE analysis of ULTDH and NTDH systems has been carried out and presented in concise manner.

This deliverable will serve as the input for deliverable D2.2 – REWARDHeat planning guidelines.

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