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Connecting district heating networks in different pressures

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Tiivistelmä:

Energiasektorin muutos kohti hiilineutraaliutta ja irtautuminen polttamiseen perustuvasta lämmöntuotannosta asettaa uusia vaatimuksia kaukolämpö toiminnalle kaupungistuvassa maailmassa, mikä megatrendinä lisää energiapalveluiden kysyntää. Muuttuva tuotanto- ja markkinaympäristö yhdessä ympäristökysymysten kanssa pakottaa kaukolämmön tuottajat siirtymään pois fossiilista polttoaineista kohti polttamisvapaata lämmöntuotantoa. Tämä asettaa kasvavia tehokkuus vaatimuksia lämmöntuotannolle ja -jakelulle, jossa synergiat eri toimijoiden välillä tulevat entistä tärkeämmiksi hukkaenergian hyötykäytön ja siirron energiatehokkuuden suhteen. Uusien tuotantomuotojen vaihteleva tuotantoprofiili luo tarvetta lisätä energiajärjestelmän joustavuutta ja kykyä siirtää energiaa tehokkaasti tuottajien ja tarvitsijoiden kesken sekä varastoida energiaa myöhempää käyttöä varten.

Työn tavoitteena on selvittää Helsingin kaukolämpöverkon hydraulisesti erotettujen verkkojen yhdistämisen teknistä mahdollisuutta kaikissa tuotantotilanteissa eri vuodenaikoina ja sen edellyttämiä toimenpiteitä. Yhdistämisellä tavoitellaan energiansäästöhyötyjä kaukolämpöverkossa lämmönvaihdinhäviöiden pienenemisen kautta. Verkossa olevien pullonkaulojen vähentämisen kautta pyritään parantamaan järjestelmän joustavuutta tulevaisuudessa sekä helpottamaan tulevaisuuden kehitystoimintaa seuraavan sukupolven verkkoja kohti.

Työssä tutustuttiin kaukolämpöjärjestelmään, tähän liittyviin lämmityslaitteistoihin, lämmönsiirron teoriaan alan tieteellistä kirjallisuutta ja toimittajien aineistoa sekä alalla pitkään toimineiden asiantuntijoiden haastatteluita hyödyntäen. Verkkojen yhdistäminen Helsingissä todettiin teknisesti mahdolliseksi suoritettujen kokeiden pohjalta rajallisin muutoksin kaukolämpöverkolle ja tuotantojärjestelmälle. Työssä selvitettiin ja kerättiin saatujen tietojen ja kokemusten pohjalta implementoinnin edellyttämät toimenpiteet ja jatkotutkimustarpeet uudistukselle.

KEYWORDS: kaukolämmitys, lämmitysjärjestelmät, lämmönsiirto, lämpöenergia, uusiutuva energia, lämmönvaihdin, energiatehokkuus

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ABSTRACT:

The energy sector is under developmental pressure due to energy transition away from fossil fuels and burning based energy generation. This affects the district heating (DH) sector with new requirements as urbanization increases demand for energy services. New heat and electricity market challenges established market actors and increases efficiency demand towards district heating networks (DHN). Renewable energy resources (RES) production and its variability increase demand for a more synergistic approach from DHN operators to increase ability to incorporate better waste heat utilization and heat transfer efficiency. These developments require actions towards a more flexible energy network between multiple stakeholders and ability to store energy for later usage.

The thesis discusses the feasibility to connect hydraulically separated parts of Helsinki DHN as one DHN that could be operated together in all demand conditions. The goal for unification is to reduce heat transfer losses from heat exchangers (HE) between DHNs and network flexibility from reduced bottlenecks around the DHN. Next generation DH developments are easier to implement into more flexible DHN.

The thesis considers DH systems and its future development according to current scientific and industrial literature on the topic along with industrial partners and senior engineering experience on the subject. In practice testing was used to confirm the feasibility of DHN unification with limited changes. Results were used to define next actions and required topics to investigate during the following development project.

KEYWORDS: district heating, heating systems, heat transfer, heat energy, renewable energy, heat exchanger, energy efficiency

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Greek

ΔT	temperature difference
Δp_V	pressure loss [Pa]
ξ	friction modifier [dimensionless]
ζ	singular friction factor
η	dynamic viscosity [kg/ms = Pas]
v	kinematic viscosity [m^2/s]
λ	friction factor [dimensionless]
ρ	fluid density [kg/m^3]

Roman

d	pipe length [m]
d_{calc}	pipeline diameter [m]
d_S	inside diameter of the pipeline [m]
k	pipeline´s roughness factor
L	inner pipe diameter [m]

L_p	length of a pipeline [m]
$\dot{m}$	mass flow [kg/s]
q_v	mass flow of DH water [m^3/s]
$T_{h.i}$	hot flow in
$T_{l.o}$	cold flow out
$T_{h.o}$	hot flow out
$T_{l.i}$	cold flow in
V	density flow [m^3/s]
v	flow velocity [m/s]
v_{design}	DH water flow speed [m/s]
w	flow speed [m/s]

Abbreviations

4GDH	4th generation district heating
COP	Coefficient of performance
CHP	Combined heat and power
DH	District heating
DHN	District heating network
DER	Distributed energy resources
DES	District energy system
DN	Dimension normal
FF	Fossil fuel
HE	Heat exchanger
HOB	Heat-only boilers
HP	Heat pump
IBR	Inverter-based resource
Mpuk	Prefabricated district heating pipe attached in polyurethane insulation
Mpul	Prefabricated district heating pipe moving inside polyurethane insulation
PG	Power generation
PP	Power plant
RES	Renewable energy resources
SG	Synchronous generation
TES	Thermal energy storage
VRE	Variable renewable energy resources

1 Introduction

District heating (DH) is an important part of urban infrastructure in the world and the need for reliable and inexpensive heat sources is growing as a larger portion of the world's population lives in cities. Urbanization development increases demand for heating and cooling services. A growing need to reduce greenhouse gas emissions in an energy sector will force changes to DH generation and finding alternatives to burning fossil fuels (FF). Increasing system efficiency is paramount to system providers to keep key aspects and customers happy in the world of new alternative heating systems. The key aspects of high reliability and total low end-user cost level are not possible without constant improvements from DH providers for daily operations.

1.1 Background

Cities are a large source of total global energy demand, and heating comprises most of their total energy consumption. In the EU space heating consumes 27 % and heating in large over the half of total energy demand. Urbanization is predicted to increase the share of people living in cities from 55 % in 2019 to 68 % by 2050. This trend will grow energy demand in cities in future and heating and cooling will demand more energy unless energy efficiency can be improved and largely used FFs replaced with non-greenhouse gas emitting energy sources. (Suhonen et. al., 2023, p. 1092).

DH holds a strong position in temperate and cold climate heating systems (Sorknæs et al., 2020, p. 1-2). While DH has a reputation of being highly efficient and having low emissions due to centralized production, emission controls and waste energy utilization in cogeneration, DH is still a significant emission source and its costs have increased significantly during the last decades (Sun et al., 2016, p. 323-324). The thesis considers all relevant production and regulatory costs, e.g. taxes and emission allowances, included in costs so different methods can be compared with each other. Majority of DH and cooling energy in the EU comes from FFs and emission reduction requires an increase in energy efficiency and further reuse of waste heat to reduce demand for energy import. Increasing DH penetration in low market share markets enables better waste heat utilization, more fuel flexibility and local energy sourcing to make it easier to reduce FF usage in urban areas and increase the energy efficiency of production. (Pardo-Bosch et al., 2023, p. 1-2) Efficiency improvements in DH help to reduce energy consumption at system level, a need to reduce carbon emissions and increase production efficiency in a short term that requires investments to stay competitive with modern independent heating systems like heat pumps (HP) that customers can install independently of DH provider. (Sun et al., 2016, p. 324)

In northern developed countries power generation (PG) in cities and municipalities has relied on cogenerated heat and electricity for decades. DH has provided easy, dependable, and inexpensive heating solutions for these urban areas powered by FFs. Recent developments in electricity generation and regulation have changed the energy market and made it a more challenging task to compete in the market with FFs and high inertia PG, a traditional power plant with a grid synchronized turbine-generator. Rising amounts of intermittent renewable energy resources (RES), like wind and solar, increase volatility in electricity market pricing. The costs of burning-based PG have increased due to increasing fuel and emission allowance prices and reduced electricity prices during peak RES production. This reduces the viability of high inertia PG. Many municipal energy companies rely on waste heat from other processes, like electricity or other industrial processes, to provide inexpensive DH. Phase-out of coal and other high emission fuels like peat may increase the price of other fuels and reduce total price competitiveness. (Khosravi et al., 2020, p. 1-2, 15-16) The transition away from FFs and increased market volatility are making management of high inertia PG units harder. Investments have been steered towards more distributed and local power and heat generation. This development creates new challenges for DH providers to adjust from centralized waste heat from electricity production to heat-centric production, which can be heat-only-boilers (HOB) or heat demand -limited cogeneration. Heat-focused production is less affected by RES electricity production. DH’s providers need to adapt to market changes while keeping up reliable supply to customers. This requires increasing the efficiency of a DH system and reducing losses during transfer and delivery. Legacy generation and delivery infrastructure provides a challenge to rapid changes for existing providers, but an old customer base enables investments for the future. (Koskelainen et al., 2006, p. 25-29)

1.2 Scope, research questions and goals

This thesis aims to investigate and evaluate the requirements of connecting two adjacent hydraulically separated legacy DHN parts with significant height and distance difference together. In the experimental part, it is studied how these existing infrastructures operate together. This acts as a base for the evaluation of required actions and future studies needed to make unification possible in all customer demand, weather conditions and attempts to form a good understanding about a DHN in Helsinki with its development needs for next generation DHN.

1.3 Structure of the thesis

This thesis describes DH and DHN technology and its development along with future needs from DH providers. It reflects knowledge from operating the largest DHN in Finland for decades by experience from interviews with senior staff, scientific articles, industry publications and public sources on the subject. This thesis considers the benefits and risks of connecting hydraulically separated DHNs together and possibilities of reducing heat losses with more direct DHN control as well as the required investments for the DHN. Chapter 2 describes DH and DHN systems, their design, development, and deployment in Finland in large and in Helsinki region. Chapter 3 describes pressurized parts of the DHN and their control in terms of pressure and temperature for heat delivery and heat exchangers that separate different pressure areas and heat transfer in DHN context are discussed in Chapter 4. The experiments on Helsinki DHN are described in Chapter 5 and followed by discussion in Chapter 6 what is found in experiments and collected from a cross-department workshop considering risks and benefits on DHN unification. Conclusions from these are presented in Chapter 7 and thesis summarized in Chapter 8.

2 District heating

According to Frederiksen and Werner, DH can be defined as an energy service that provides immediate heat access to heat source for customers by a DHN (Frederiksen and Werner, 2013, p. 21). Koskelainen et al. (2006, p. 25) defines DH as a centralized commercially organized heat generation and delivery of heat for large areas to differentiate it with more communal block and apartment scale central heating. In addition, Woods (2023, p. 1) focuses on its centralized form of generation and networked delivery. DH enables customers and providers to share heating investment costs and risks in such a manner that customers gain affordable and scalable heating, which is managed by professionals, while the providers receive a stable customer base that enables long-term investments (Figure 1).

DH is distributed to multiple buildings from one or more heat generation units (Woods, 2023, p. 1). It is a distribution and generation method and service that connects centralized heat generation and customers as a single market efficiently. This provides a way to utilize low-cost waste heat energy for low temperature heat needs and use low energy fuels that are not well suited for small-scale burning. (Frederiksen and Werner, 2013, p. 21; Koskelainen et al., 2006, p. 25-26) DHN scale ranges from large extensive networks that support most of the buildings in a city to a small shared urban supplier, possibly with large expansion potential to local industry and campus scale (Woods, 2023, p. 1).

Heat in DHN comes from primary and secondary energy sources and their classification depends on is heat produced primary for DH or collected from some other process as waste heat after primary use. DH primary energy sources are renewable or FFs used directly for DH generation. Secondary energy sources are a by-product of some other primary activity such as industrial processes and electricity generation and recycled for DH usage. (Frederiksen and Werner, 2013, p. 21-22)

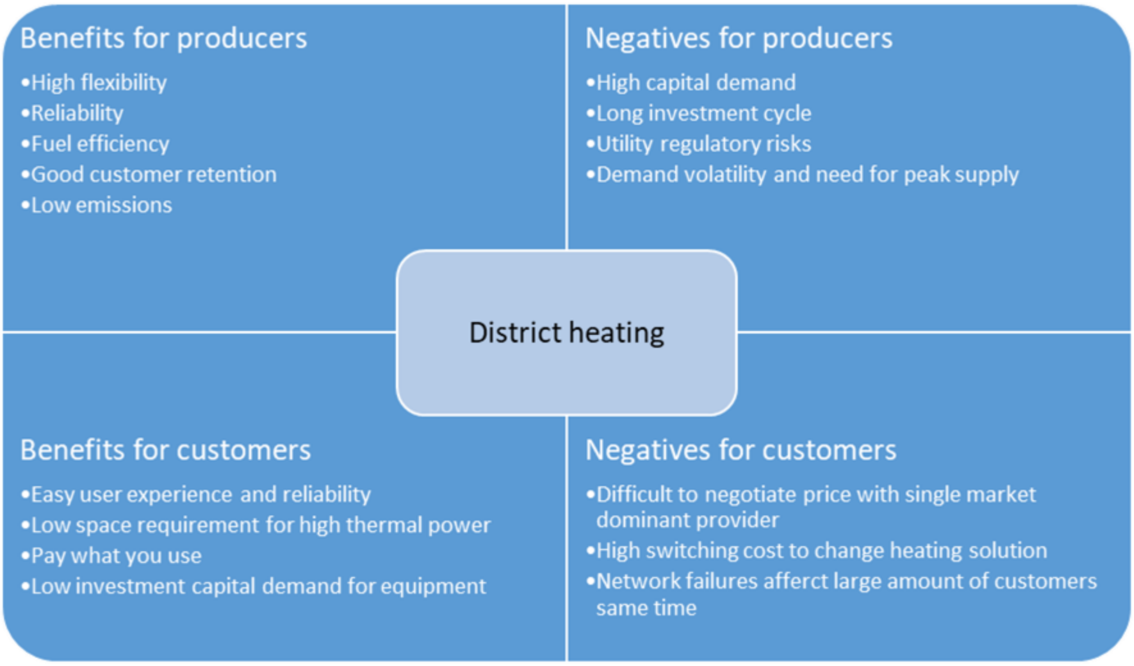
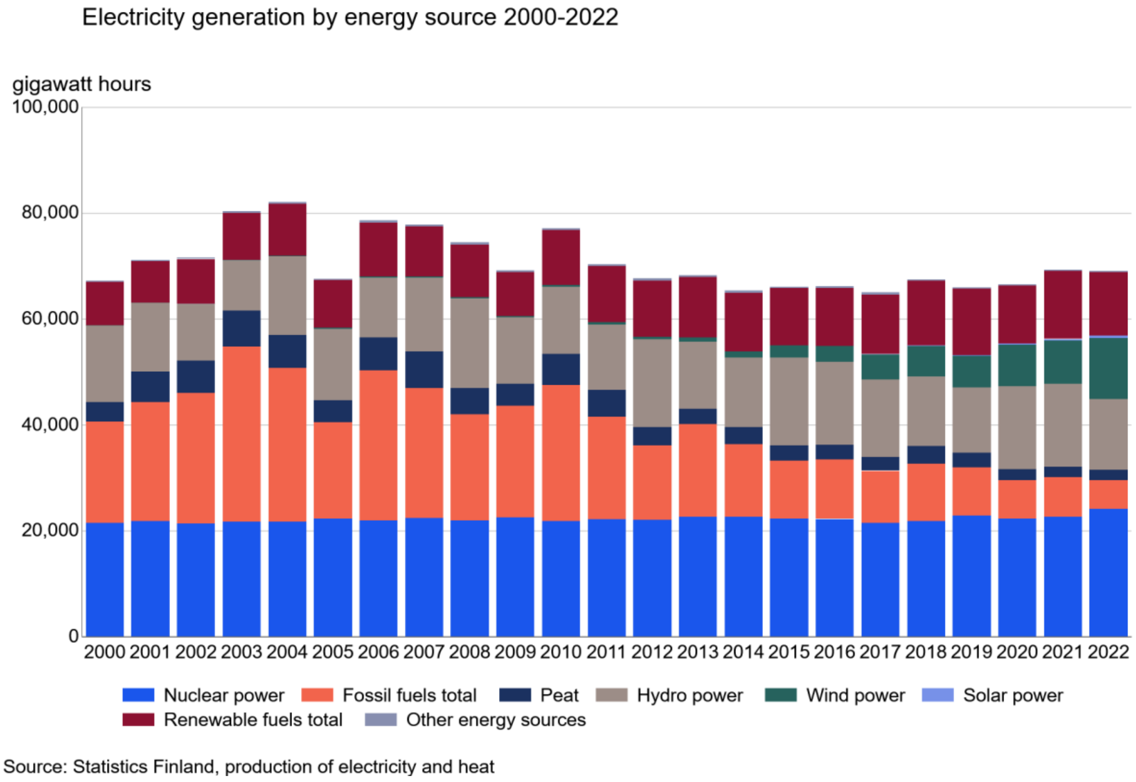


Figure 1 DH's strengths, weaknesses, opportunities, and threats (Koskelainen et al., 2006, p. 25)

Technology in centralized DH generation and delivery is similar to local boilers and area heating networks but on a larger scale that enables the more efficient operation and use of cheaper fuels. The largest difference between local heating networks and DH is organizational, as DH is often managed by an independent commercial entity and run as a utility business while local heating solutions are communal. (Koskelainen et al., 2006, p. 25-26) To be economically competitive with other heating solutions, DH service providers require a low-cost heat source, demand from market close by and a DHN to connect between heat producers and customers relatively cost efficiently. Ideal heat source for a DHN would be waste heat or cheap local fuel and demand for a heat rate needed by residential, public, or commercial building and a domestic water heating needs to be of significant density to make network investment reasonable. (Frederiksen and Werner, 2013, p. 21)

The rising quantity of variable renewable energy resources (VRE), like wind and solar, in the Nordic electricity market (Figure 2) has made electricity more competitive as an input in heat production. In this market, HPs provide low-cost heat from low temperature waste heat sources like datacenters using electricity as input (Helen Oy, 2021) that weren't previously commercially viable to utilize in DH production (Frederiksen and Werner, 2013, p. 22). Electric boilers act as flexible demand and inexpensive heat sources on electricity overproduction situations and enable balancing the power system (Pelli, 2023). Low electricity prices reduce cost competitiveness of combined heat and power (CHP) heat generation (Averfalk et al., 2017, p. 1275). Cogeneration capacity might end up being retired from the market and replaced with electricity as input heat generation such as HPs, electric boilers and with heat-only-boilers (Helin et al., 2018, p. 14). Heat storage solutions along with power-to-heat options in the future will affect the viability of CHP generation. Possible power-to-heat options include HPs and electric boilers to absorb inexpensive surplus electricity and provide flexibility for fuel sources in DH context. (Averfalk et al., 2017, p. 1275)


Electricity generation by energy source 2000-2022

Source: Statistics Finland, production of electricity and heat

Figure 2 Electricity prices in Finland 2020-2022 (Statistics Finland, 2024)

2.1 History and generational shifts of DH

DH history runs down to local geothermal heat source utilization. The oldest documented DH use is from 14th century Cantal France for unpaid heating bills for geothermal district heating that utilized old Roman infrastructure for heat distribution. The first modern commercially successful DH service is credited to Lockport USA 1877 and the oldest service still in use is in Denver. Thus, the first modern DH were first implemented in the United States but today DHs market share is low in the United States and outside a few dense cities DH is limited to some commercial downtown areas and university campuses. European projects followed American examples and focused on fire hazard reduction and fuel price incentivized commercial projects. In the Soviet Union CHP was part of an electrification plan in the 1920s. It aimed to reduce fuel consumption in the future as national energy policies focused on the reduction of primary energy consumption. DH gained popularity in urban settings by planning by the degree during an expansion period. Focus on DH development was in quantity and its market share left a legacy of maintenance and reliability problems that have required major rehabilitation works. (Frederiksen and Werner, 2013, p. 541-544)

More recent DH is classified in academic literature into different generations (Table 1) depending on methods used to provide and deliver heat to customers. The first generation used steam as a transfer medium, and its downsides were large transfer losses, safety and technical challenges concerning transfer lines. The second generation reduced these problems by changing transfer medium to high temperature pressured water. Third generation focused on improving energy efficiency, which was achieved by reducing transfer temperatures and increasing the use of more local fuels in response to the 1970s oil crisis. Fourth generation provides better low-temperature heat source integration with higher building efficiency, lower transfer losses from lower DHN temperature and utilization of smart energy systems to balance large cooling needs with heating demand. The fifth generation aims to lower DHN temperatures even further to a flexible low-to-neutral temperature level. This minimizes transfer losses and allows better utilization of DHN for heating or cooling using heat pumps. The structural demands of such a DHN are lower than previous generations and it allows for less expensive DHN construction. (Jodeiri et al., 2022, p. 3-4)

Table 1 District heating development and generational characteristics (Jodeiri et al., 2022, p. 4)

DH generation	Period of best availability technology	Heat carrier	Piping	Heat production
1st generation	**1880–1930**	**Steam**	**In situ insulated steel pipes**	**Coal steam boilers and some combined heat and power (CHP) plants**
2nd generation	**1930–1980**	**Pressurized hot water above 100 °C**	**In situ insulated steel pipes**	**Coal and oil-based CHP and some heat-only boilers**
3rd generation	**1980-onwards**	**Pressurized hot water below 100 °C**	**Pre-insulated steel pipes**	**Large-scale CHP, distributed CHP, biomass and waste, or FF boilers**
4th generation	**2014-onwards**	**Low-temperature water 50–70 °C**	**Pre-insulated flexible (possibly twin) pipes**	**Renewable and excess heat sources in addition to conventional**
5th generation	**2016-onwards**	**Ambient temperature water/brine 10–40 °C**	**Pre-insulated or uninsulated flexible pipes**	**Low-grade heat sources e.g., local urban waste heat and renewable sources**

A transition process to the next generation is difficult for large market share DHN, as centralized DHN is too large to be upgraded at once while keeping service running. Development to enable this is gradual change to increase local waste heat utilization, reduce heat transfer distances and islanding areas of the network with thermal energy storage (TES) units to utilize low and negative heat demand during summer and collect heat to be used during the heating season. (Rämä et al., 2024, p. 1)

DH requires a generational shift to enable the full usage and synergies of RES, distributed energy resources (DER), and reduce losses, and heating demand from low energy housing stock. Old housing stock is designed for high input temperature heating and demand renovation to be compatible with 4th generation DH (4GDH) framework (Figure 3). (Lund et al., 2018, p. 148-150) Customer substation`s heat exchangers (HE) are designed according to DH changes. Heating flow through the substations is controlled by substation control valves and too high design input temperature will cause problems to the DHN in terms of unnecessary flow, pressure loss and rising return temperature. (M. Wisak, personal conversation on heat exchanger design in DHN, 28.2.2024; T. Marttinen, 12.3.2024) This requires adequate regulation in the right time to balance investment needed and received energy savings on a system level (Lund et al., 2018, p. 153-154).

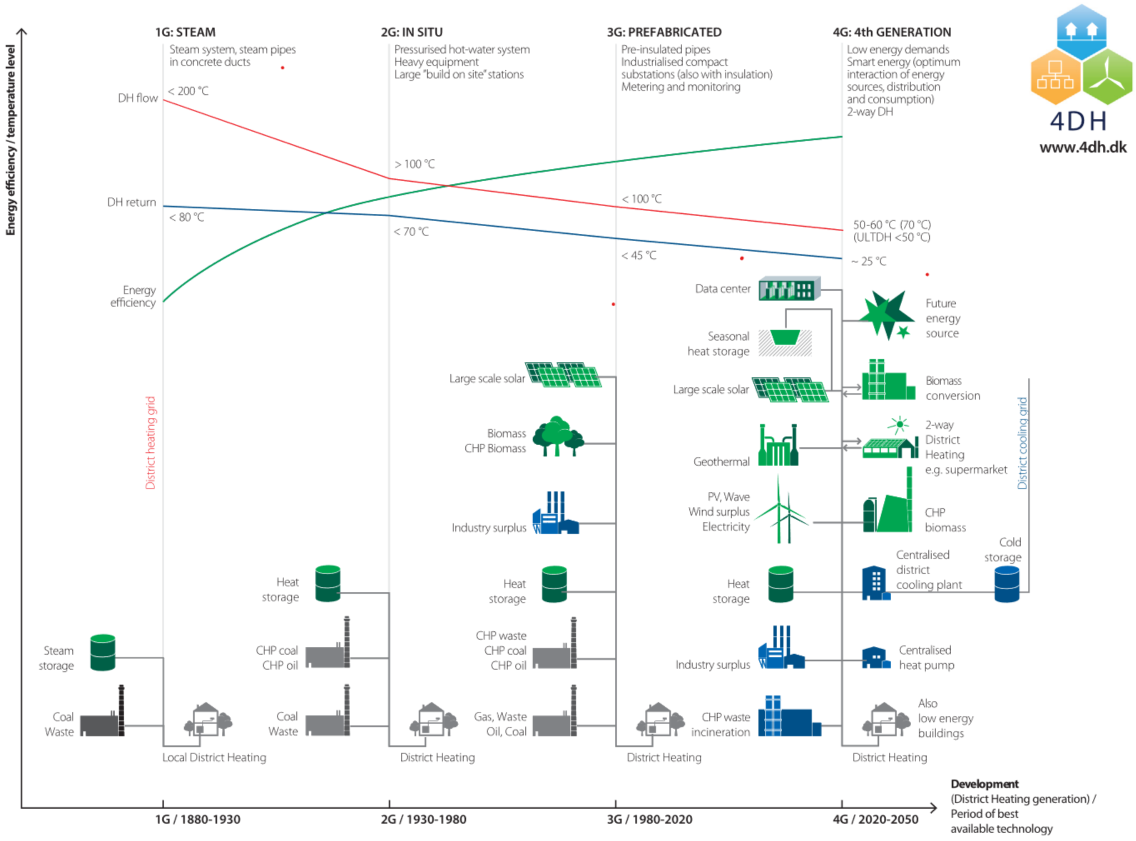


Figure 3 The concept of 4GDH compared to previous DH generations updated version (Lund et al., 2018, p. 149)

2.2 District heating network

A DHN connects heat sources and heat customers together. A DHN consists of high temperature pipes, but the used temperature varies from country and network to another. DH temperatures range from 90 °C and below up to 120 °C, and to even 180 °C in some parts of central Europe where DH is used for steam generation. DHN transfer capacity increase is dependent on temperature difference between supply and return flows and pumping speed. A higher temperature in the supply flow enables longer transfer lengths from the thermal generation units to customers and reduces delivery costs, as the higher temperature raises energy content per volume and lowers pumping needs (Koskelainen et al., 2006, p. 137). A low-temperature supply, on the other hand, will cause additional investment costs for DHN and the building sector to be 4GDH compatible, but lower DH temperatures reduce costs on DHN and production side, making the system more efficient (Lund et al., 2018, p. 156-157).

2.3 District heating network design

A pipeline route design process starts from a district plan which describes possible DH-pipeline routes (Koskelainen et al., 2006, p. 159). DHN design starts with defining peak heat demand in the area in future and flow requirements that define major pipeline dimensions. Heat demand growth in the area defines an investment timescale and extent. Accurate prediction on future heat demand development is required for adequately sized DHN design and planning. It enables lower initial spending with later compensation for smaller system capacity with additional pumping capacity or pipelines after area development has matured. This reduces required initial investment and prevents long-time over-investment. (Koskelainen et al., 2006, p. 153) During the planning stage co-operation and information sharing between stakeholders is important. Information sharing ensures adequate room and connections for customers to DH pipelines in the area and enables fitting upcoming structures to existing and upcoming infrastructure, land rights and construction environment in the most cost-efficient way. (Koskelainen et al., 2006, p. 159)

Overcapacity investments in growing new DHN areas long before required can be prevented with smaller capacity investments during buildup phase that predict demand by reduced pipeline dimensions and filling demand with additional lines or increased flow by pumping stations nearby as demand is realized. Design parameters for DHN are network location from heat generation units, local buildings, domestic and water heating demand, the pressure losses of the system and temperature difference between a supply and a return along with peak heating demand. Peak heating demand for the area depends on the nature of area heating needs and possible upcoming construction during the following decade according to local municipality development plans. Heating demand from buildings depends on their specific heating capacity by area for peak load and by volume for an annual heating need. Industrial heating customers' demand might vary highly and requires a more individual approach during a design phase than domestic buildings. (Koskelainen et al., 2006, p. 153)

DHNs are built over a long time and have a long reinvestment cycle. This leaves operators with large legacy systems over time in the network that few employees in the company still completely understand. Staff changes reduce organizational experience over time and operational solutions are passed along without a full understanding of the systems in question. The company culture also forms around working solutions. New technical solutions, like more energy efficient pipeline design, are from time to time designed in the most problematic parts in DHN, but cultural inertia reduces implementation speed of more advanced solutions over an old working solution to overcome a previous default solution. A working solution often becomes a default selection for fitting to a default method or technology due to space or other limitations. (T. Korhonen, personal conversation, 17.1.2024; M. Mikkonen, personal conversation, 8.2.2024)

DHN pipeline size is determined by designed flow speed and pipelines required total heating power. It defines the needed mass flow of DH water. The DH pipeline diameter d_{calc} can be calculated by Equation 1:

$$d_{calc} = \sqrt{\frac{4q_v}{\pi v_{design}}}, \tag{1}$$

where d_{calc} is a pipeline diameter [m], q_v is DH water flow [m^3/s] and v_{design} is DH water flow speed [m/s]. Flow speed v_{design} is determined by acceptable pressure loss from pipeline tables (Mäkelä & Tuunanen, 2015, p. 53).

DH water mass flow can be calculated from equation 2 at given temperature:

$$q_v = \frac{\dot{m}}{\rho}, \tag{2}$$

where $\dot{m}$ is DH water mass flow [kg/s] and ρ is water density at given temperature (Koskelainen et al., 2006, p. 198).

2.4 Future development in district heating

DH developed during the last century towards today's reliable and affordable urban heating solutions with utilization of local waste and inexpensive energy sources. Development is described in literature as DH generations with focus to improve energy efficiency by reducing losses and using better methods for transfer and heat generation. Literature focuses on lowering DHN delivery temperatures, increasing flexibility in the DHN by seasonal and temporal TES, RES and power to heat solutions like HPs, electric boilers and system integration between waste heat sources, electricity markets and heat networks. (Sorknæs et al., 2022, p. 1, 8)

Carbon neutrality requires large changes to the European energy infrastructure as synchronous generators (SG) are replaced by non-synchronous low to zero inertia RES, DES inverter-based resources (IBR) (Laaksonen, 2022, p.4). Electrification of heating, formerly done by burning fuels, will increase demand for growing VRE. VRE requires balancing services and solutions to integrate different demands from customers and the energy industry. Energy transfer between sources needs a smart energy system to connect variable demands and broader market participation for electricity, heat, natural gas and future hydrogen networks to cost effectively enable production optimization and energy storage utilization. (Afry, 2022, p. 2, 28-30) The following sections discuss a few developments forward from third generation DH and ways to reduce emissions in the DH sector.

2.4.1 Lowering network supply temperatures

DH requires energy to transfer for customers` space heating and a domestic water system. Transfer of heat requires a temperature difference between mediums or an installed HP in a customer or an area substation. A DHN is designed based on area heat demand and the temperature on a network that affect required pipeline size. The required flow volumes and flow arrangement in a larger network are dependent on both but are limited by an installed DH pipeline. Lower supply temperature in DHNs has been the focus of DH generational evolution. Lower supply temperature allows DH providers to reduce temperature difference between the inside and outside of the pipeline. Reduced temperature difference reduces transfer losses and the total costs of DH. Lower supply temperatures make it possible to use waste heat and HPs in DH on a larger scale and more efficiently than before and reduce the costs of DH as possible low-cost heat sources grow. Recent changes in general design guidelines, e.g., Finnish Energy K1/2021, reflect this development on enabling lower supply temperatures by requiring new installations to handle peak heat transfer at lower supply temperatures than before. Guidelines are a slow way to implement changes at the DHN, as customer substations are long-lifetime investments, and it will take time before a sizable portion of the market has implemented new guidelines. (Korpinen et. al., 2023, p. 10-12).

Another way to reduce the average temperature in the short term in DHN is supply temperature management of outgoing DH water around the year. One way to set the temperature of supply DH water in DHNs is based on an outside temperature measurement according to the prefixed supply temperature chart. Ambient temperature-measurement-based supply temperature is a straightforward way to ensure adequate heat supply, but it often provides unnecessarily high supply temperatures for networks. Lowering supply temperature from chart values offers DH companies a way to reduce energy transfer losses but requires one to match the supply temperature more closely with momentary heat demand and DHN capacity, so that all parts of a network still get the required pressure difference and heat. Required heat quantity can be simulated with different load levels or by historical consumption data and network pipeline dimensions. The most cost-efficient temperature depends on network heat demand and DHN. A temperature that is too low with respect to demand would increase the pumping requirement more than a reduction of transfer losses would provide cost savings. This problem can be addressed by dynamic multi factor control and maintaining the DHN pressure differential in a predetermined range to lower the temperature when the pressure differential is too low and raise it when it exceeds the desired range value. Dynamic supply temperature is a way to reduce costs and CO_2 emissions from heat transfer losses as increased pumping costs are typically lower than gained energy efficiency savings (Finnish energy, 2021, p. 14-15, 18,21). Low supply temperatures are beneficial for DH production, enable higher efficiency, lower fuel consumption, and increase renewable heat production in DHN. Low temperature heat sources need to be raised to DHN temperature by HPs. They are the most efficient when temperature difference is limited between HP's input and output. Higher the need to raise HP output temperature to meet DHN temperature more work is required and lower the HP efficiency. (Laitinen, 2020, p. 38-40) Lower DHN temperatures can reduce transfer losses by 28 % and increase HP COP number by one (Sorknæs et al., 2020, p. 9).

2.4.2 Electrification of heat generation

Electrification of heat generation means moving from burning based heat production to directly producing heat from available electricity, preferably from RES using HPs or resistive heating boilers.

Increasing variable RES production reduces greenhouse gas emissions of electricity generation and provides ways to synergize electricity and heat networks with each other, developing smart grids, and heat markets from traditional cogeneration and industrial waste heat utilization. (Sorknaes, 2021, p. 222-223) Power-to-Heat development of the energy sector offers flexible and a low single investment option to add for a heating system from HPs and electric boilers. Electricity consuming production can balance volatile electricity prices and provide demand during low price hours. (Averfalk et. al., 2017, p. 1275) Electrification of heat generation enables the better utilization and usage of low-cost heat storage options and underutilized low temperature waste heat in DH cost-efficiently from waste heat collection produced by industrial processes to electro fuel production. (Sorknaes, 2021, p.223) DHN in an urban setting provides a connecting medium for different production methods and serves as a system balancing function along with thermal storage options (Averfalk et. al., 2017, p. 1275).

2.4.3 Load and peak shaving with thermal storage

DH is the most efficient when demand can be met with waste heat sources from secondary energy sources such as industrial processes or electricity generation (Frederiksen and Werner, 2013, p.25). Unfortunately heat demand and waste heat production do not always align timewise and heat demand has peaks exceeding momentary waste heat production. Peak power is significantly more expensive to provide, and it reduces the system level efficiency of the DHN system, due to high readiness heating plants using expensive fossil fuels like oil and gas that are easy to store locally or access at time of need and operate remotely. The system has a designed capacity and load demand can bottleneck some DHN pipelines in peak hours, preventing system expansion without larger overhauls to the DHN. (Averfalk et. al., 2017, p. 1275) Peak loads can be met better with demand side management techniques, which increase energy efficiency by increasing storage, reducing energy consumption from demand profile changes to better match momentary energy supply and to enable meeting demand with low-cost heat sources. A demand response can be achieved with incentives or dynamic pricing to reduce the most expensive supplementary fuel usage in district heating. (Suhonen et. al, 2023, p. 1094) Smart heating control can reduce demand during peak hours to minimize emissions from heat generation and bottlenecks in the DHN along with reducing costs from the most expensive DH production. Smart controls provide savings for customers' energy consumption during spring and fall seasons by reducing overheating of buildings. They also enable better heat distribution over the DHN during production disturbances and larger thermal storage in the DHN. (Helen Oy internal heat flexibility report, 2024) Seasonal and general thermal storage increases DHN flexibility and option to operate parts of the DHN independently in an island mode that provides a way to transition DHN to a lower temperature 4GDH system gradually and increase the use of local inexpensive waste heat resources in cost effective manner. (Rämä et. al., 2024, p. 1)

2.4.4 Bidirectional district heating

DHN has been formed over the last century from a unidirectional thermal transfer grid and developed rapidly over the decades to a modern DHN with increasing RES and waste heat utilization. The aim is to gain more thermal efficiency in the system by lowering delivery temperatures on the DHN in the future. This development connects to smart thermal and electrical grids which improve the network´s ability to integrate more DER production sources like buildings that, with smart grids, help to include them as balancing capacity to an energy system in addition to RES and TES. Buildings provide both demand and supply for the DHN. Electrical networks work on a prosumer, a consumer that participates in the energy market as producer, model and customers are able to generate electricity into the electrical network. In thermal networks this development requires new technical, financial and legislative solutions to enable third party network access. In new regulatory environments thermal networks would evolve more active participation platforms and new pricing structure for heat to encourage effective heat utilization on site and balancing the service towards the network. Literature considers buildings to have significant amounts of excess heat compared with their yearly consumption, between 50 % and 120 %. The local low temperature delivery enables higher RES integration with local solar collectors that can reduce their total heat demand, losses and increase RES usage in heating due to shorter transfer distances and losses. The most promising industrial prosumer category is datacenters, as their load characteristics are stable and their waste heat supply is high, so with other prosumers a significant part of the day or year can be managed without thermal or cogeneration plants when adequate storage and smart controls are available and local geography and climate enables it as some locations can fulfill only a part of their peak demand by prosumer DER heat. This development requires DHN operators to develop better forecasting models to manage prosumer integrated DHN and its efficiency largely dependent on DHN temperature. (Pipiciello, 2021, p. 1-3)

2.4.5 Nuclear district heating

Rising coproduction prices and electricity price volatility have increased interest toward nuclear power in DH generation (Helen Oy, 2023a). DH networks in Finland rely on FFs and high emission domestic fuels like peat while electricity increasingly from low emission sources. Renewable fuels, like forestry by products, have other industrial usages and put pressure on the energy sector to find alternative heat sources to meet climate and heat demands for this northern location. (Teräsvirta et al., 2020, p. 1). Small modular reactors (SMR), under gigawatt, have been a popular topic as potential replacement for heat from cogeneration in DH (Teräsvirta et al., 2020, p. 2). Low temperature heat-only reactors for DH usage are not a new concept, but the need to reduce carbon emissions from DH have ignited new interest in the topic. DH is a large source of total urban energy consumption and emissions, and recent studies show promise for small nuclear reactors in DH generation. (Khosravi et. al., 2020, p. 3) SMR concept relays prefabricated on site assembled units that can be added flexibly over time with lower capital requirements than conventional nuclear power plants. SMR can reduce demand and price pressure on forestry fuels in energy generation as carbon neutrality goal 2035 increases demand for alternatives to FF and domestic high emission fuels. (Teräsvirta et al., 2020, p. 2)

2.5 District heating in Finland

DH development in Finland started in the 1920s inside the professional electrical engineering union. International experiences from DH and the findings of the union committee by 1939 left interest in cogeneration, but after the war electricity generation buildup was focused on hydropower and DH was popularized after industry electricity generation expanded to condensing power plants that provided large amounts of waste heat as a byproduct. Waste heat from electricity generation was provided to industry, the first in Finland in Espoo in 1953 and Helsinki in 1957 followed by Mikkeli and Lahti the next year. By the 1950s the usage of imported FFs increased for DH and grew during the following decade. Same time state actions incentivized the usage of domestic fuels that increased significantly after the 1973s energy crisis. DH had significant government incentives during these years to improve the energy efficiency of heating and enable more domestic energy source usage like different wood sources and peat. These domestic sources increased their share of used fuels until oil prices along with natural gas prices stabilized in the 1980s. (Koskelainen et al., 2006, p. 34-35) DH-companies have long been public property, but sector privatization has become more common as capital requirements are not as large during the operation phase compared with the earlier expansion phase (Koskelainen, 2006, p. 29). Future trend in the heating sector is electrification of heat generation as VRE sources increase comparable profitability of the P2H solutions like heat pumps and electric boilers together with increased integration with waste heat sources from industry like datacenters (Rämä et al., 2024, p. 2). Same-time total energy consumption is predicted to fall in following years due to increasing regulatory demands for building energy efficiency and population movement from rural to urban areas, decreasing the need to heat older, more sparsely populated and less energy-efficient housing stock (Paiho & Saastamoinen, 2018, p. 669)

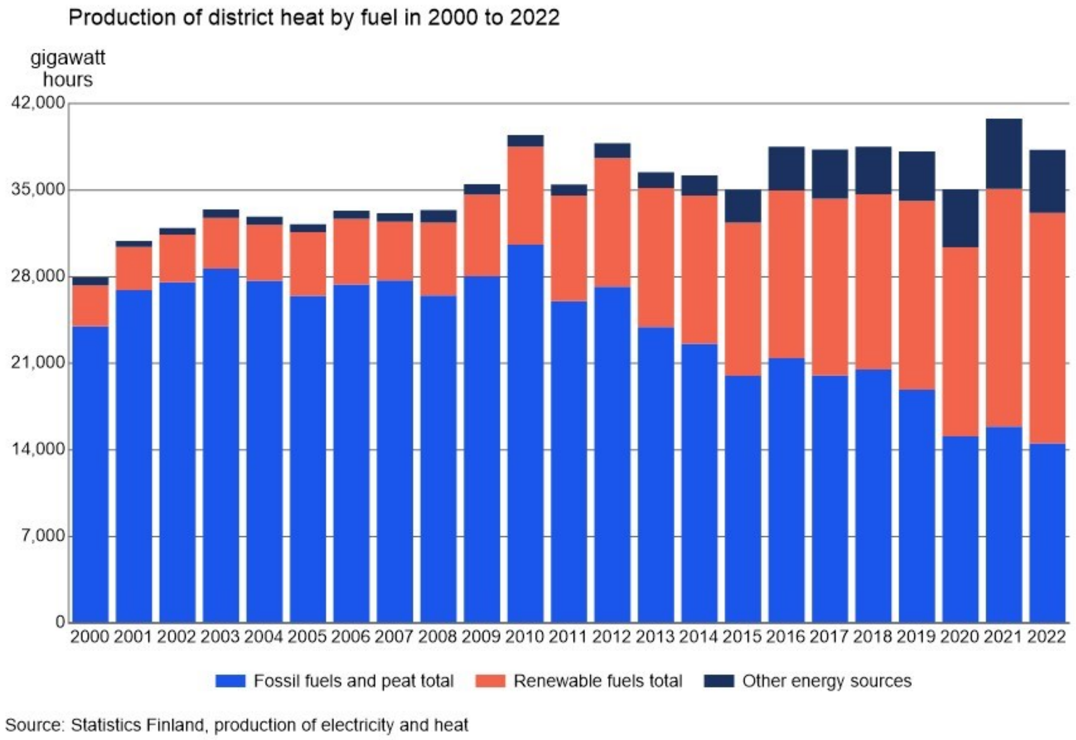


Figure 4 District heat fuel usage in Finland 2000-2020 (Finnish Statistics, 2023, stat.fi)

The Nordic area has a high share of low carbon emission production in electric production, which has increased in the 21st century (Figure 4). They also have energy efficient PG with the flexibility of fuel sources (Figure 2) as demand for electricity and heat coincide in the market, but burning-based solutions are still the largest energy source in DH production as cogeneration has provided a large share of DH consumption (Figure 5; Figure 6). Cogeneration has been in competitive pressure on an electricity market from variable renewable energy sources and lower average electricity prices have made cheaper HOBs and HPs more competitive in comparison with CHPs to provide DH than before. (Helin et al., 2018, p. 1-2).

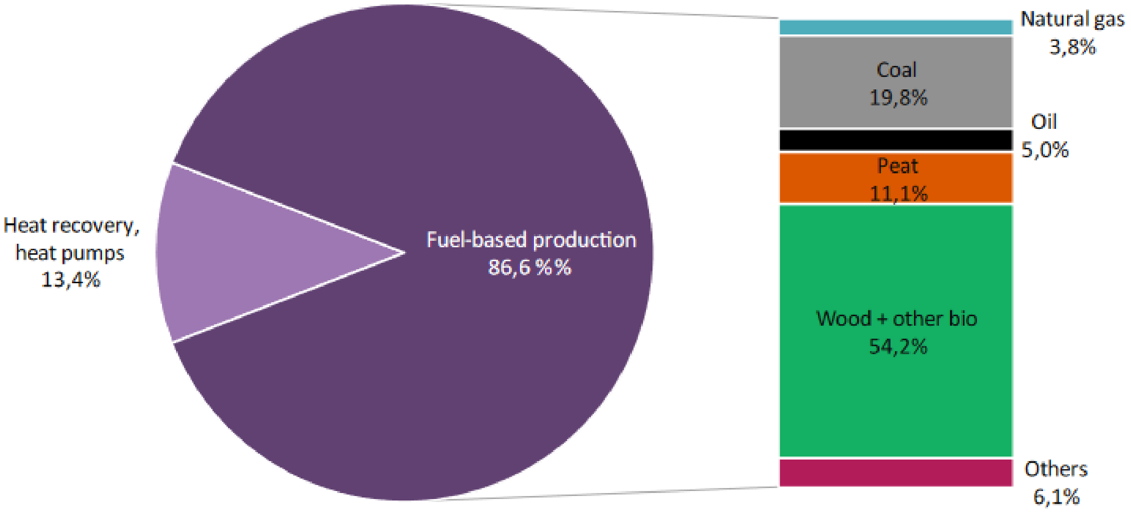


Figure 5 Fuels used to produce district heat and CHP electricity in year 2022 (Finnish Energy, 2023, p. 4)

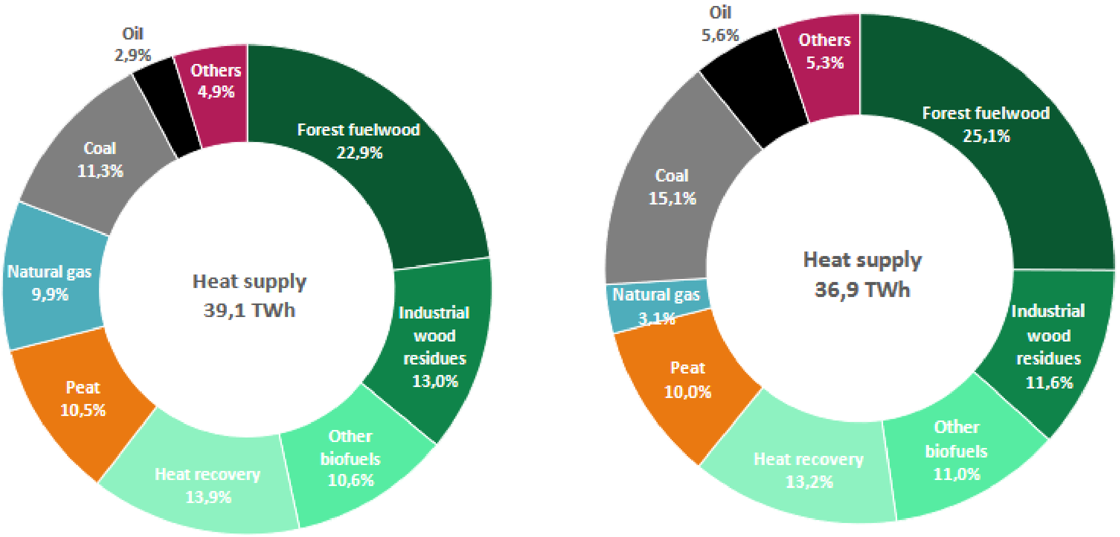


Figure 6 Energy sources of district heating supply in 2021 (left) and in 2022 (right) (Finnish Energy, 2023, p. 4)

2.6 District heating in Helsinki region

Energy generation in Helsinki has played a key part in city history and public energy production can be traced back to the 1908-13 built Suvilahti power plant in Sörnäinen, Helsinki (Lignell, 2018, p. 2). District heating as a product in Helsinki originates from the 1940s and the 1950s. Waste heat from electric generation in heating was not used and it did not have commercial use before DH in Helsinki, but using a major part of the fuel energy to merely to heat local aquatic wildlife was seen as wasteful by the city government. (Mäki, 2012, p. 23) In the 19th and 20th century heating in a central city was performed in individual apartments or as local central heating for buildings or blocks (Lignell, 2018, p. 3). Increase in centralized district heating generation and usage reduced negative effects from local heat generation and the number of smokestacks in the city horizon during the 20th century (Lignell, 2018, p. 5). In the 1940 first DHN was built in Olympic village for the 1940s Olympics, and it was supplied by its own local heat plant that used wood as fuel. Experiences at the time were mixed due to high costs (Lignell, 2018, p. 17). The first commercial customer for DHN was connected 1952 in central Helsinki in Sörnäinen (Mäkelä & Tuunanen, 2015, p. 12) and then decision for expanding DH to housing and additional commercial building heating was done following year (Lignell, 2018, p. 5). District heating was provided in the early 50s at first as steam, but the technology changed later during the same decade to hot water (Mäki, 2012, p. 7). In the 1960s DHN provided district heating in the central city area, while the customer pool was still modest in numbers compared to the 1970s expansion (Mäki, 2012, p. 23). After replacing older independent heating boilers and other solutions in a central city, further growth came from providing heating for a new suburb's apartment buildings. This was motivated by the 1970s energy crisis and rising fuel prices along with security of supply concerns (Lignell, 2018, p. 5). Suburban areas required heat before a local network was connected to the main network and district heating was provided with mobile or local heating plants, most of which were shut down by the 80s and the 90s, and district heating generation focused on larger cogeneration units and peak thermal plants. (Lignell, 2018, p. 5-6, 16).

2.6.1 District heat generation in Helsinki region

The Helsinki region currently provides heat for DHN from multiple sources across the town. Large part of DH is provided by coal and natural gas (Figure 7). Cogeneration units are in Vuosaari and Salmisaari, which are supported with smaller thermal energy storage (TES) units close by along with larger underground TES facilities in Mustikkamaa and Kruunuvuorenranta. CHP, an HP, and thermal generation is supplemented with multiple local heat plants during peak demand. Vuosaari has three power plants, two natural gas combined cycle power plants with a combined heat capacity of 582 MW. The third power plant uses forestry by-products like wood chips to generate DH from bioenergy and has a heat capacity of 260MW. Salmisaari CHP plant produces 300 MW heat from coal and wood pellets to DHN and the close future site will have two electric boilers along with air-water HP plant. Coal usage will be discontinued after the 2024-25 heating season (Helen Oy, 2023b; Helen Oy, n. d.-c). Heating plants around the city provide up to 2200 MW of DH from natural gas and fuel oil during the coldest parts of the year and during fault and maintenance periods and supplement other DH sources when peak power is required. HPs in Helen Oy HP sites provide DHN with heat and the cooling network with cold from low temperature heat sources. Katri Vala combined heating and cooling plant

(CHC) provides 126 MW heat and 80 MW from purified wastewater, and the Esplanade CHC plant produces 50 MW heat and 22 MW cooling. (Helen Oy, 2023b)

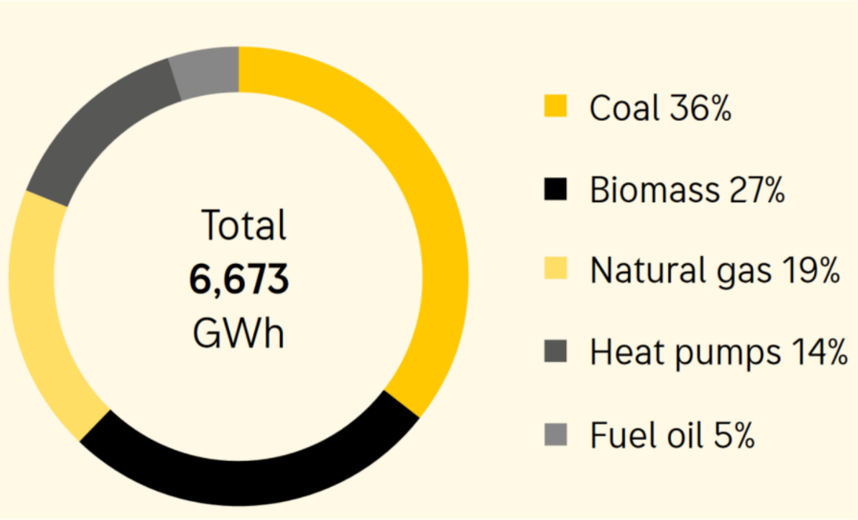


Figure 7 Heating production in Helsinki 2023 (Helen Oy, (n.d.-a), p. 9)

2.6.2 District heating distribution in Helsinki

DHN in Helsinki is over 1400 km long and 157 000 m^3 in volume. (Helen Oy, 2022) It forms a mesh network that provides additional short term heat storage capacity from its large volume and ability to stand high input temperatures in exchange for additional heat losses from the network. The network structure is discussed in chapter 3.3. Helsinki DHN is formed from meshed rings within rings topology that connect smaller pipelines together from consumption points to PG units (Figure 10) and from a transfer tunnel between the east and central parts of the city which enables heat transfer between hydraulically separated main and east networks, as the east network has larger generation capacity than demand. Meshed DHN structure enables a network operator to provide heat for customers during maintenance and fault times as heat transfers within a network can be routed multiple ways. This flexibility increases network complexity and makes it harder to predict system behavior with DHN simulation systems beforehand.

System operation and decision-making is difficult to automate due to its complexity and experienced operators are important to keep DHN in operation and when returning to a normal running plan after faults. (T. Marttinen, personal conversation, 28.2.2024)

2.6.3 Measurements and automation in Helsinki DHN

The Helsinki DHN is controlled by an automation and managed from a staffed control room. Control room monitors automated network controls, heat demand development from customers during different times a day, the temperature, weather, and a pre-planned run plan for daily production. A run plan is prepared with the help of an optimization system that predicts upcoming production requirements based on history, weather and competing production forecasts to the following day. It also suggests the cheapest way to meet the demand and to minimize energy losses and emissions from transfer. Network controls monitor process measurements from the power plants and the network, but the network has a limited amount of measurement points. Distribution flow measurements are collected from return lines of power plants, pumps and HE-stations. (T. Marttinen, personal conversation, 12.03.2024)

3 Pressure and temperature in DHN and equipment

DHN transfers heat by pressurized hot water from production units to customer heat exchangers and back for reheating and this heat can’t be billed from customers. This requires all parts of the networks to be designed around the operating parameters of the DHN. Legacy systems might add additional limitations to the DHN operability as operated supply temperature and pressure have changed over the years as acquired experience has evolved industry guidelines. Decades of development and usage have left local DHN operators with a network that is built during different decades and with different technologies. As the network matures, it necessitates an upgrade to contemporary technology that facilitates modifications and enhances the efficiency of DHN. However, this transition introduces new organizational complexities.

3.1 Pressure and pumps in DHN

Pumps in a DHN provide pressure difference and required water flow through the system along with adding new water to a system (Koskelainen et al., 2006, p. 169). Pumps are in general centrifugal type pumps and their main locations are DH power plants and pumping stations but their amount and location in the network depends on where pumping is the most cost-efficient to do all costs included. They are controlled by a variable-frequency drive (VFD) based on pressure differential and flow rate in DHN and throttle valves, that limit flow after a pump for control, have phased out in most cases. Pump´s rotation speed and provided pressure differential is controlled by VFDs to match customers and DHN requirements in terms of DHN safety and optimal operating costs. (Mäkelä & Tuunanen, 2015, p. 44-46)

Pumping scheme depends on DHN size and other local requirements like height variations that increase pressure demand. It can be done centrally with PPs pressurization and circulation pumps in smaller DHNs but in larger DHNs are uneconomical to manage this way due to increased required supply pressure increases pressure losses on the DHN p_V [Pa] according to Equation 3. (Koskelainen et al., 2006, p. 199):

$$\Delta p_V = \xi \frac{L_p}{d_S} \frac{\rho w^2}{2} = \xi \frac{8L}{d_s^5} \frac{\rho \dot{V}^2}{\pi^2} = \xi \frac{8L}{d_s^5} \frac{\dot{m}^2}{\pi^2}, \tag{3}$$

where Δp_V is pressure loss [Pa], ξ is friction modifier [dimensionless], ρ is fluid density [kg/m^3], *w* is flow speed [m/s], L_p is length of a pipeline [m], d_S is inside diameter of the pipeline [m], V density flow [m^3/s] and $\dot{m}$ is mass flow [kg/s]. (Koskelainen et al., 2006, p. 199) Reynolds number Re is calculated according to Equation 4:

$$Re = \frac{w d_s}{\mathrm{\eta}} = \frac{4\dot{V}\rho}{\pi d_s \nu} = \frac{4\dot{V}}{\pi \eta d_s}, \tag{4}$$

where v is kinematic viscosity [m^2/s] and η is dynamic viscosity [kg/ms = Pas]. Viscosity is dependent on the temperature and friction factor ξ that is calculated using *Re* from Equation 4 and roughness factor *k* [mm] divided by pipeline inside diameter *ds* [mm] from precalculated figure tables. (Koskelainen et al., 2006, p. 200-201) ξ is calculated according to Equation 5 (Finnish energy, 2024, p. 4):

$$\xi = \frac{1.325}{(ln[\frac{k}{3.7 d_S} + \frac{5.74}{Re^{0.9}}])^2}, \tag{5}$$

where *k* is pipeline´s roughness factor that is between 0.1 mm and 0.04 mm depending on a pipeline and its age. (Koskelainen et. al., 2006, p. 200)

Flow restricting features like fittings, turns, valves and pipe diameter changes during the flow path add to total pipeline pressure losses to DHN. These need to be taken into consideration when calculating total pressure losses. They are calculated with Equation 6 and total pressure losses according to Equation 7:

$$\Delta p_K = \zeta \frac{\rho w^2}{2} = \zeta \frac{8\rho \dot{V}^2}{\pi^2 d_s^4}, \tag{6}$$

where ζ is a singular friction factor and usually between 0-3 depending on a restrictive feature (Figure 8) (Koskelainen et al., 2006, p. 202).

$$\Delta p = \Delta p_V + \Delta p_K = \left(\xi \frac{L}{d_s} + \sum\zeta\right) \frac{\rho w^2}{2}, \tag{7}$$

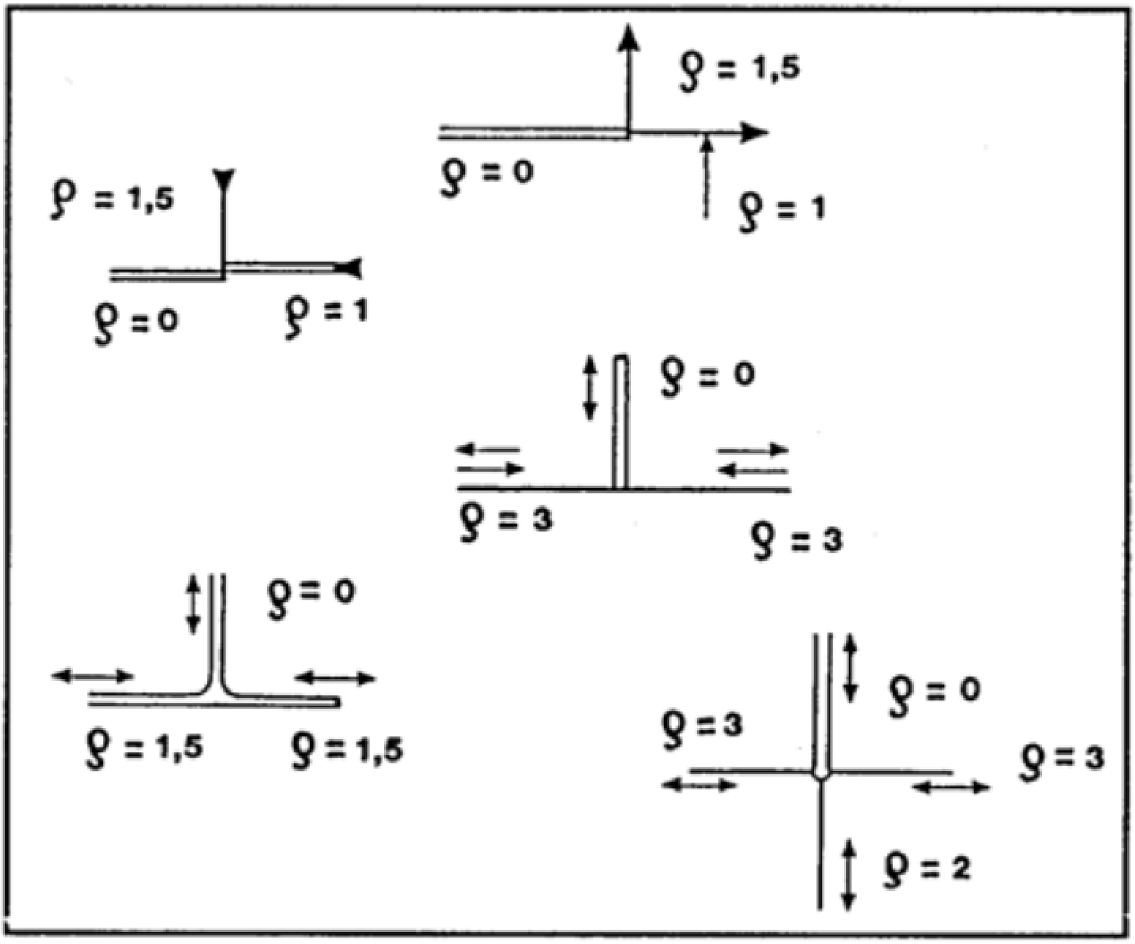


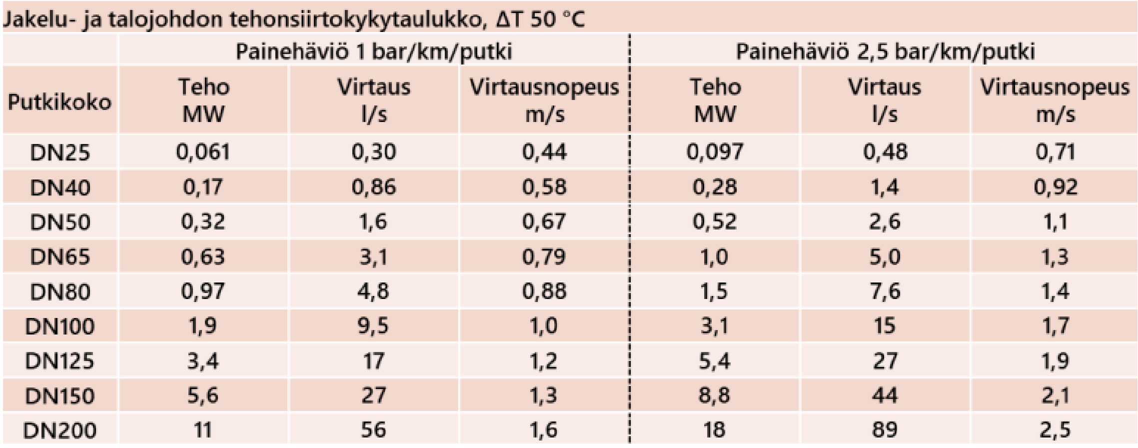
Figure 8 Typical values for restrictive features (Koskelainen et al., 2006, p. 202)

When pressure losses are known at one volumetric flow others can be calculated with Equation 8:

$$\frac{\Delta p_1}{\Delta p_2} = (\frac{\dot{V}_1}{\dot{V}_2})^2, \quad (8)$$

Design workflow for required heat demand and pressure loss in a pipeline is made using computer programs that significantly reduce the amount of work needed to calculate the required parameters. Industry guidelines offer pre calculated tables (Table 2) with default values for standard pipeline dimensions which provide the rough first estimates. (T. Korhonen, personal conversation, 22.2.2024)

Table 2 Distribution and delivery pipeline transfer capacity (Finnish energy, 2024, p. 2)



Jakelu- ja talojohdon tehonsiirtokykytaulukko, ΔT 50 °C

	Painehäviö 1 bar/km/putki			Painehäviö 2,5 bar/km/putki		
Putkikoko	Teho MW	Virtaus l/s	Virtausnopeus m/s	Teho MW	Virtaus l/s	Virtausnopeus m/s
DN25	0,061	0,30	0,44	0,097	0,48	0,71
DN40	0,17	0,86	0,58	0,28	1,4	0,92
DN50	0,32	1,6	0,67	0,52	2,6	1,1
DN65	0,63	3,1	0,79	1,0	5,0	1,3
DN80	0,97	4,8	0,88	1,5	7,6	1,4
DN100	1,9	9,5	1,0	3,1	15	1,7
DN125	3,4	17	1,2	5,4	27	1,9
DN150	5,6	27	1,3	8,8	44	2,1
DN200	11	56	1,6	18	89	2,5

3.2 Temperature in DHN

The temperature in DHN depends on network design parameters and customers' collective heat demand. DHN transfer capacity depends on network temperature and maximum flow rate and describes required DHN temperature. A standard method for managing the network supply temperature has been to adhere to a chart that designates the output temperature in relation to the ambient temperature (Figure 9) (Koskelainen & al., 2006, p. 335-337). DHN design guidelines have been updated recently in Finland to reduce DHN temperature from 115 °C to 90 °C and customer heat exchangers design the temperature from 70 °C in 40 °C out to 60 °C in 30 °C out. (Finnish Energy, 2021, p. 8)

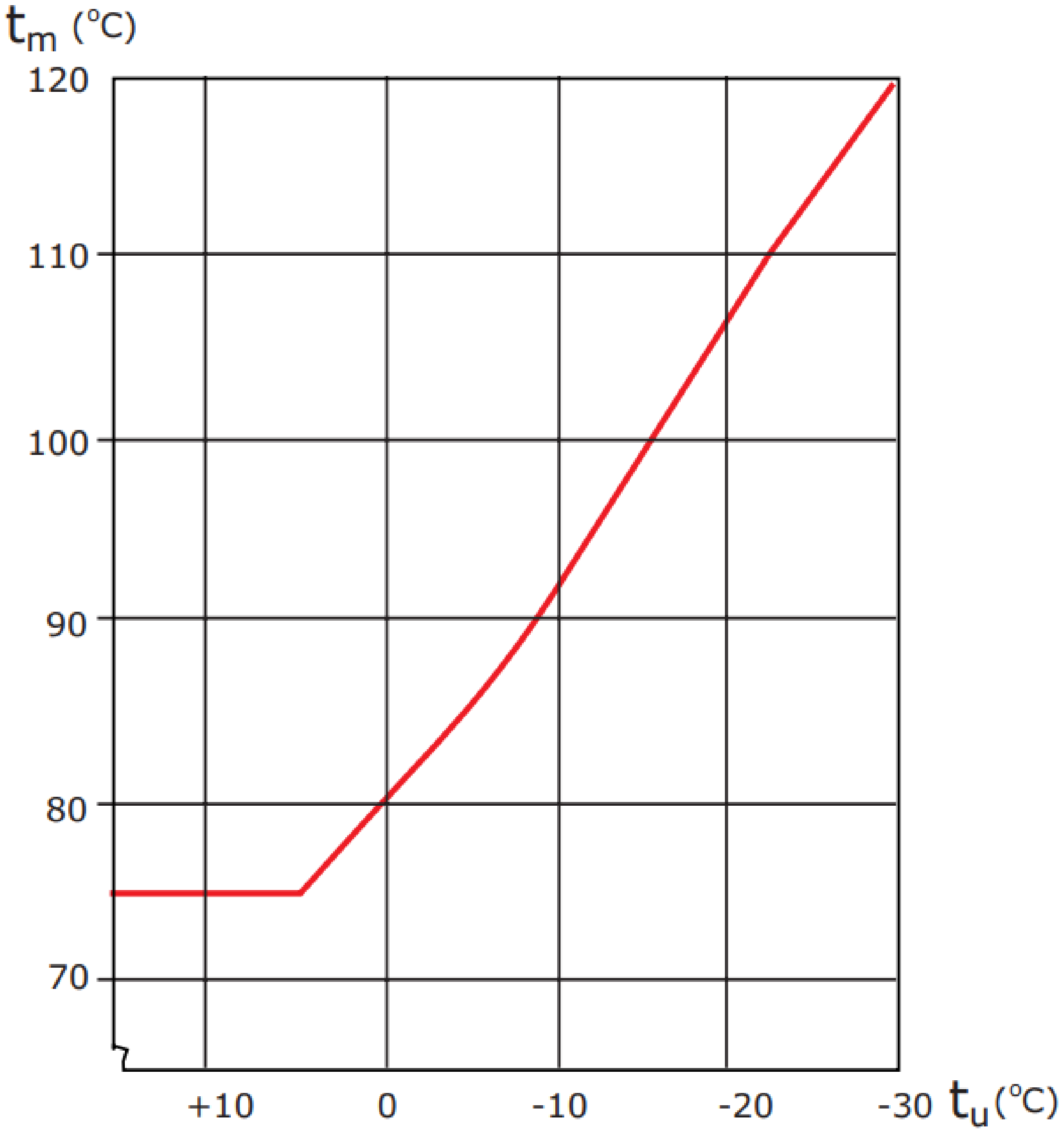


Figure 9 DH supply temperature control curve based on ambient temperature (Koskelainen et al., 2006, p. 336)

Temperature measurements from DHN are collected with PT100 resistance temperature sensors inside DH flow from remote operable DH valve centers in underground utility space and from a pipe surface under the insulation. (J. Carpén, personal conversation, 26.1.2024)

3.3 Network topology

A piping layout and a topology depend on the local requirements and follow one of the three primary ones that are radial, ring and meshed grid topologies (Figure 10). The radial grid has a tree topology with a central district energy system (DES) and pipes that connect with consumption points. This provides the least expensive grid investment costs due to the lowest network pipeline length. DES can be any adequate heat and cold source. The ring topology can have multiple heat and cold sources in a network. The security of a supply increases as the main pipeline forms a closed loop that allows more variability on which way and source energy can be provided to each consumption point. The meshed topology provides more flexibility and security of supply and enables the integration of distributed energy sources to the network as load and demand diversity between areas can be balanced with bidirectional flow and lower temperature decline across the network. The improved supply security and flexibility offered by the meshed grid topology come at a higher investment cost compared to other network configurations. Meshed network offers the best security, extendibility, and distributed generation integration for the highest investment cost while radial offers the cheapest cost while being worse at all other aspects. Ring topology offers medium cost, complexity, and flexibility. (Figure 11) (Von Rhein et al., 2019, p. 707-708)

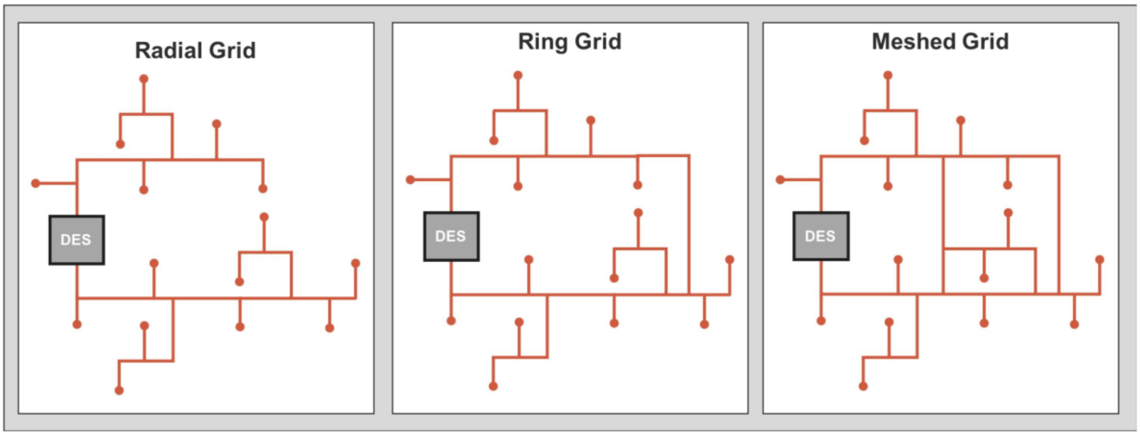
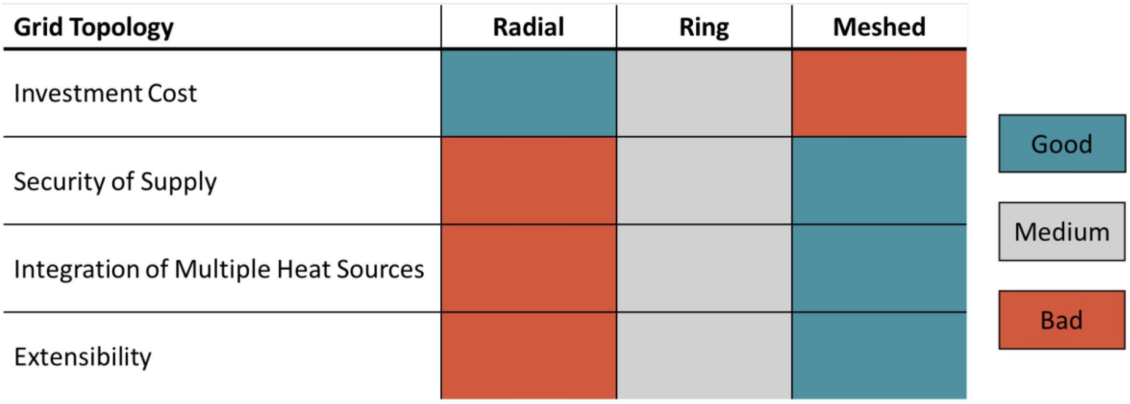


Figure 10 Grid topologies for district heating and cooling networks (Von Rhein et al, 2019, p. 708)



Grid Topology	Radial	Ring	Meshed
Investment Cost	🟦	⬜	🟥
Security of Supply	🟥	⬜	🟦
Integration of Multiple Heat Sources	🟥	⬜	🟦
Extensibility	🟥	⬜	🟦

🟦 Good
⬜ Medium
🟥 Bad

Figure 11 Qualitative comparison of the grid topologies (Von Rhein et al, 2019, p. 708)

3.4 Pressure management/Static and dynamic pressure in DHN

Static pressure at each point in a DHN depends on its level from sea level that defines local ambient pressure (Figure 12) (Koskelainen et al., 2006, p. 345). A DHN requires greater than ambient pressure inside all points of the network to prevent air from leaking in. If pressure inside a network at some point drops under static pressure, air might leak into the pipe and restrict the flow. Water in a pipeline may also reach a boiling point when pressure on flow drops below the ambient pressure. Boiling water may cause two phase flow, in line steam restricts flow and can in the worst case stop it abruptly, and as a result stop pumps or automation can increase pumping speed. It raises the average pressure as well as pressure difference over a pump in the network. This can eliminate an underpressure situation abruptly in the network and endanger the network for water hammer damages, cavitation and gas or steam forming inside a DHN. (Koskelainen et al., 2006, p. 344)

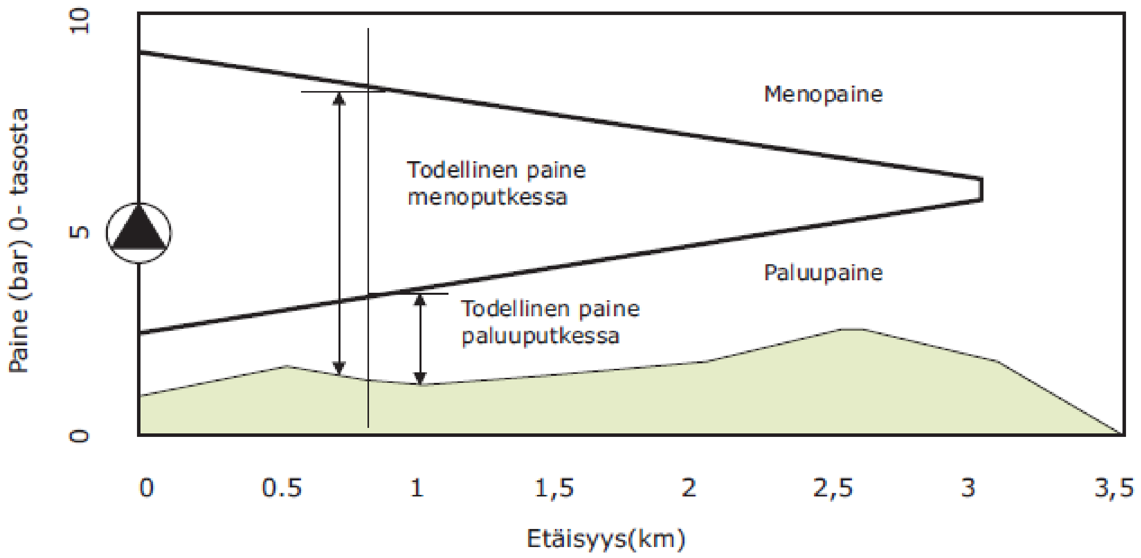


Figure 12 Pressure difference between static and dynamic pressure (Koskelainen et al., 2006, p. 344)

Water flow, its magnitude and direction, is regulated with a pressure drop in a system in a desired direction. Flow magnitude depends on pipeline capacity, dependent on a pipeline diameter, and provided pressure drop (Equation 9). (Frederiksen & Werner, 2013, p. 447):

$$\Delta p = -\left(\frac{\lambda L}{d}\right) \rho \frac{v^2}{2} \tag{9}$$

where λ is friction factor [dimensionless], L is inner pipe diameter [m], d is pipe length [m], ρ is fluid density [kg/m^3] and v is flow velocity [m/s].

Flow in a DHN requires pressure differential between flow water pumps inflow and outflow sides to enable a flow rate required by customer demand and pressure differential between inflow and an outflow to every customer's substation (Koskelainen et al., 2006, p. 335). Pressure differential is monitored from the most peripheral point of the network by the DH provider and control actions are based on that information.

A pressure gradient in a pipeline is managed in closed pressured systems by keeping flow pressure within a system's designed pressure limit, how much pressure lines are designed to hold, and a boiling point of the flow at given temperature and location. (Frederiksen & Werner, 2013, p. 447) DHN requires positive dynamic pressure at every point of a DHN to function and prevent damage from low-pressure phenomena like pump cavitation and water hammer (Mäkelä & Tuunanen, 2015, p. 46). A boiling limit in the line defines the required minimal pressure level at each point so that the design temperature stays below the boiling point and the line stays safe to operate (Frederiksen & Werner, 2013, p. 450). Pressurization of the DHN, can be done using pumps, gravity feed water tanks or power plant steam drums providing ability to prevent water boiling in the system without a need to have flow in the pipelines. Pressurization compensates water volume variations in the DHN. Leaks in the network require additional water to be added to the system to compensate. (Frederiksen & Werner, 2013, p. 450-451). Pressure loss in DHN requires pumping in a network to maintain adequate pressure at the needed flow rate to keep up with the thermal power demand of the DHN. Pressure loss is caused by friction in pipelines and main effects are pipeline diameter and flow rate, and they are due to require a flow rate for temperature difference between supply and return flows. (Mäkelä & Tuunanen, 2015, p. 46) A design pressure of the pipeline states the maximum allowed safe pressure for the pipeline. This might limit pressure differential in the network and maximal flow in a pipeline from the return pipe required minimal pressure to keep flow away from a boiling limit. Options to increase the output of a DHN are increasing the temperature difference and moving part of the pressurization away from a starting point with pumping station booster pumps (Figure 13). Decentralizing pumping in DHN enables smaller supply and return pressure differences in similar load, reducing the electricity cost of pumping and enables higher flow in DHN (Figure 14). (Frederiksen & Werner, 2013, p. 452)

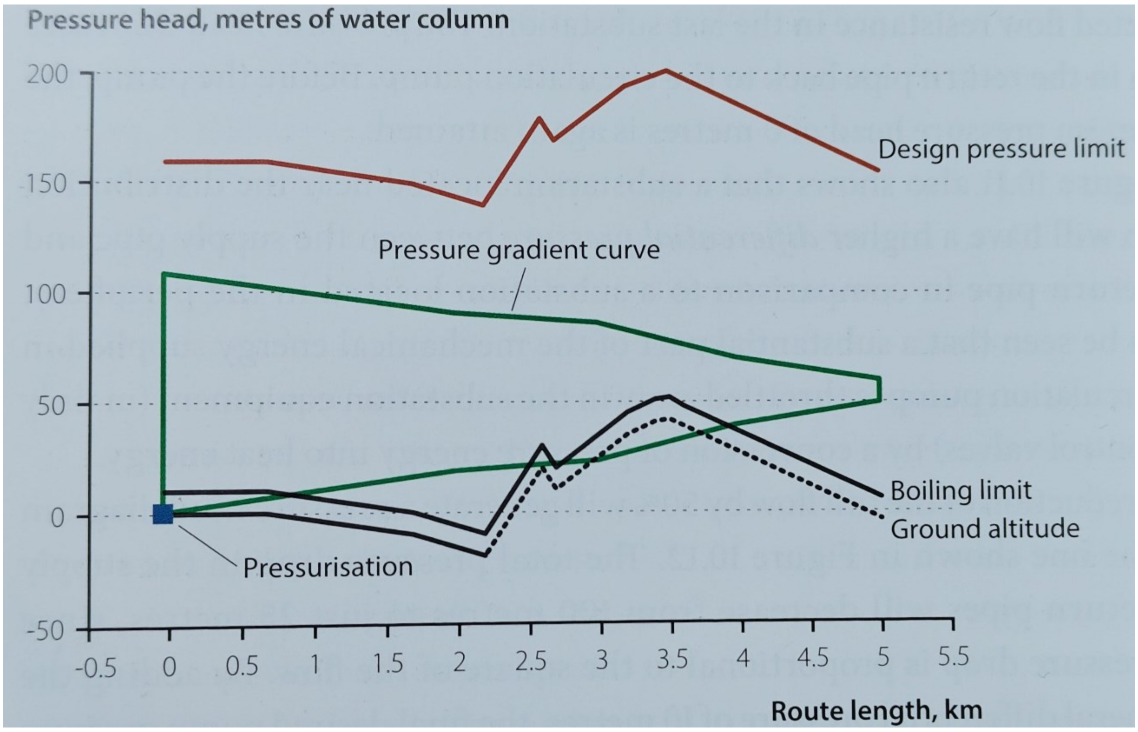


Figure 13 Pressure gradient lines compared to the boiling and pressure limits without pressurization before the circulation pump (Frederiksen & Werner, 2013, p. 450)

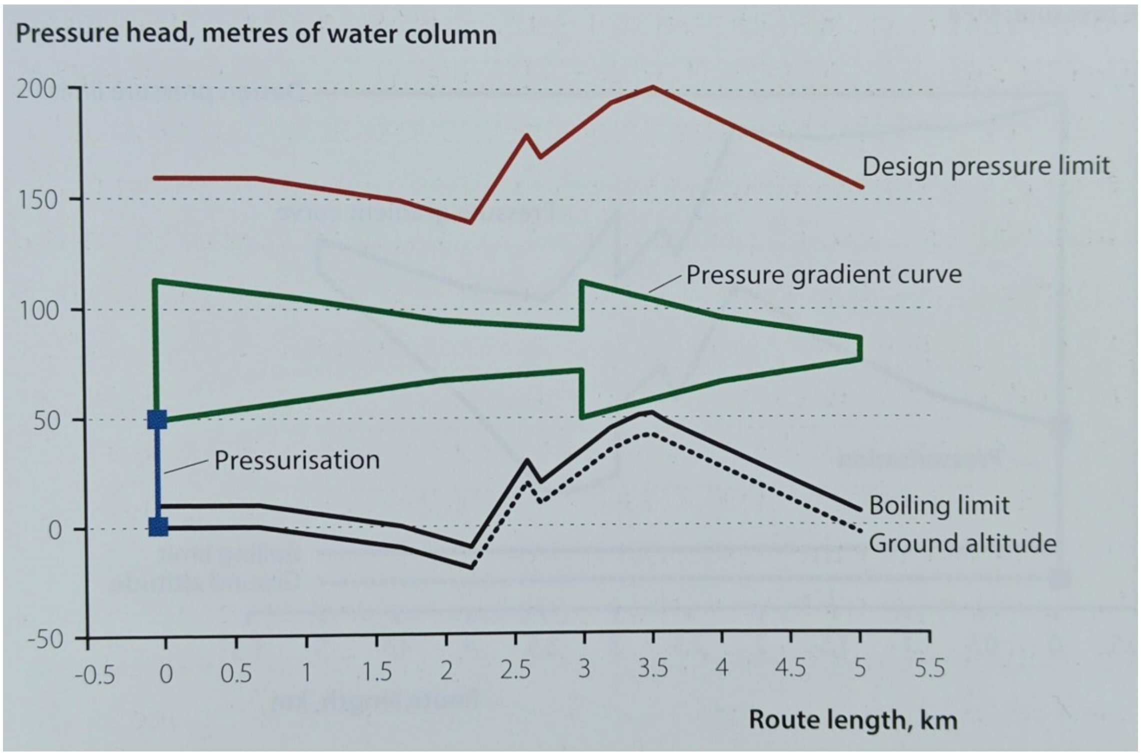


Figure 14 Pressure gradient with booster pumps in the line (Frederiksen & Werner, 2013, p. 453)

3.5 DHN equipment

DHNs have grown significantly during the last decades. This has produced a lot of different technical solutions around the world. Single, dual and four pipeline systems are in use in different parts of the world with varying temperatures and transfer mediums. Due to the long lifecycle of systems, over 50 years for pipelines for example, it is possible to work with DHNs that have extensive regions containing obsolete and discontinued solutions from installations a long time ago.

3.5.1 Piping in DHN

DHN piping provides access to heat from thermal PG. Depending on DH system generation, heat is transferred in pre-insulated steel pipes via water or steam to consumption points (Koskelainen et al., 2006, p. 137). New DHN pipes in Finland have evolved from on-site insulated pipes in a concrete channel to factory pre-insulated units. A two-pipe system has been seen as the most effective solution and the most common pipe for this has been two individual pre-insulated pipes. Modern pre-insulated pipes are designed for 120 °C in 1.6 MPa pressure for 30 years or more, depending on the environment. (Koskelainen et al., 2006, p. 137). Some DHNs use lower 1 MPa restriction for supply pressure that needs to be taken into accord when working with legacy networks (Mäkelä & Tuunanen, 2015, p. 56).

3.5.1.1 Pre-insulated steel pipes in plastic shell

Most common DH pipes since the 1970s and market dominant solution after the middle 1980s in Finland are steel pipes with fixed polyurethane insulation covered in a plastic shell. They offer easy to handle modules that can cope well with changes in earthworks around the pipe. Changes around the pipe do not affect the function of modules. Standardized modules with a wide array of turn and connection elements that are interchangeable between vendors prevent DH-companies getting vendor locked in their DHN. They come in two popular formats, single (2Mpuk), separate supply and return and dual pipe in shell format (Mpuk), single pipe 2Mpuk from DN 20 to DN 600 and up to DN 1200 (Figure 15) and dual pipe in shell Mpuk from DN 2x20 to DN 2x200 (Figure 16) as called in Finnish industry guidelines. (Koskelainen et al., 2006, p. 137-139) DN sizes describe standardized delivery pipes diameter inside insulated plastic shell.

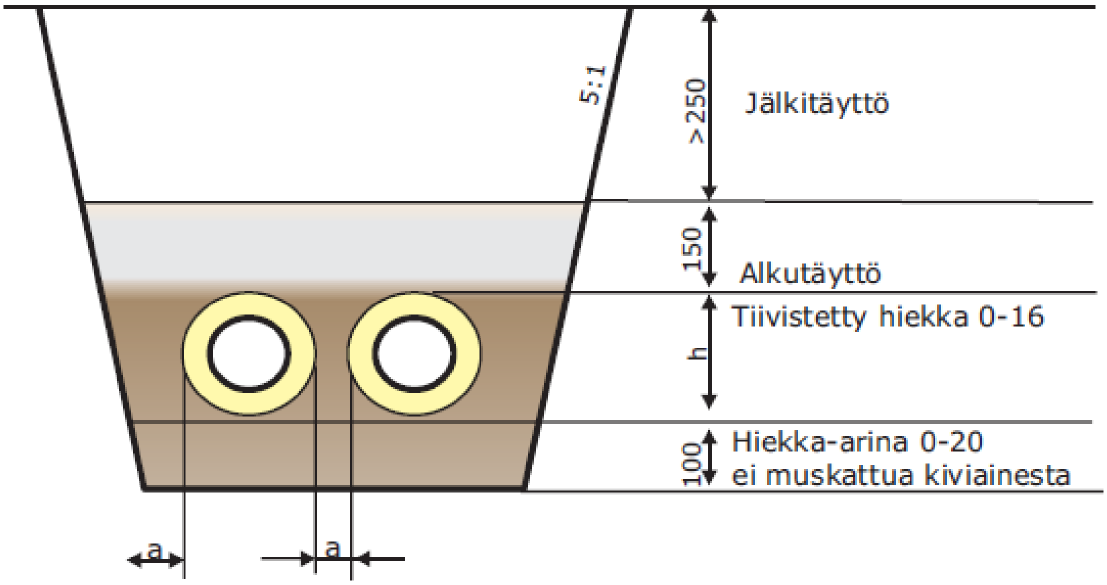


Figure 15 Prefabricated insulated individual district heating pipe with plastic shell with soil description for construction (Koskelainen et al., 2006, p. 139)

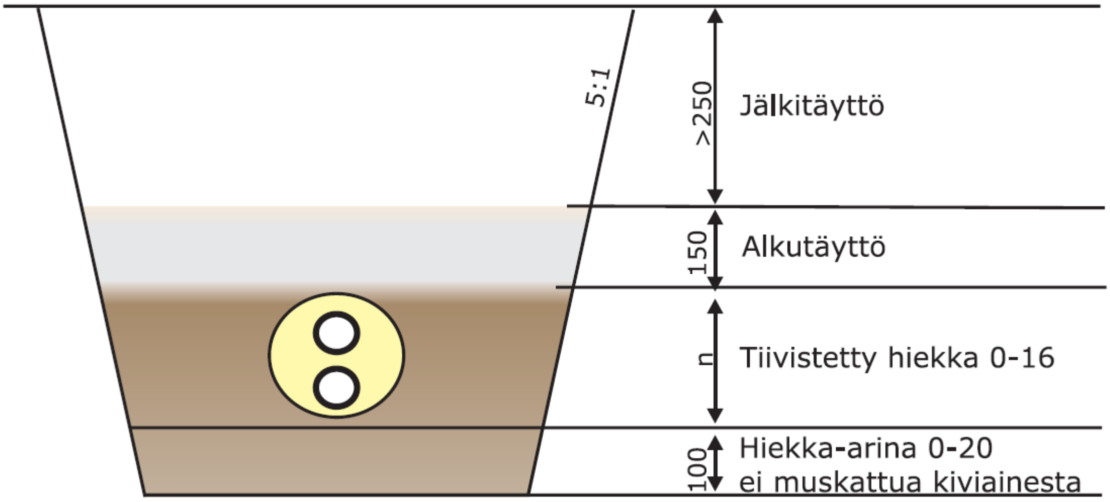


Figure 16 Prefabricated DH dual pipe in single shell with soil description for construction (Koskelainen et al., 2006, p. 140)

3.5.1.2 Moving district heating pipelines (Mpul)

In the 1960s to the 1980s common pipeline design contained (Figure 17) prefabricated insulated fiberglass pipe in a plastic shell with a smaller leak water pipe on the bottom. A steel DH pipeline inside a fiberglass pipe allows the thermal expansion of the steel pipe in a network. This pipeline design was discontinued by the 1980s due to design`s problems. Identified problems are vulnerability to ground shifting that can damage pipelines and cause corrosion problems along with the designs lacking ventilation and a structure endangers large sections to corrosion in case of a shell or a DH pipe leak. (Koskelainen et al. 2006, p. 145)

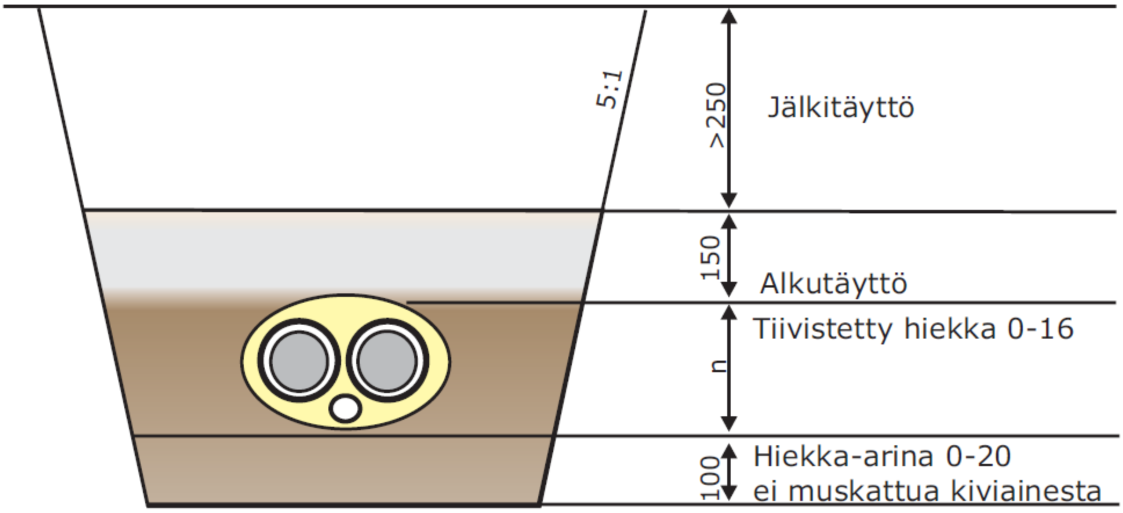


Figure 17 Pre-insulated moving steel pipe in plastic shell, Mpul, with soil description for construction (Koskelainen et al. 2006, p. 145)

3.5.1.3 Concrete canal pipeline

Concrete canal pipelines are old design and discontinued in Finnish DHNs by the 1990s but can be encountered still in a legacy network relatively often. Structure contains prefabricated concrete elements (Figure 18) or on-site poured ones with steel pipe and insulation element made from polyurethane or mineral wool. Prefabricated structure has been found out to be an unsatisfactory insulator in DH usage without moisture proofing the element. (Koskelainen et al., 2006, p.144) According to usage experience, the insulation loses its shape after getting wet, which degrades the insulating capacity of the layer. The lower part of a canal will be connected by welding them together from their steel elements and contains support structures along with fixed points where a pipeline is welded to a canal to allow pipeline stress and tension to be transferred to the ground. (Koskelainen et al., 2006, p.144)

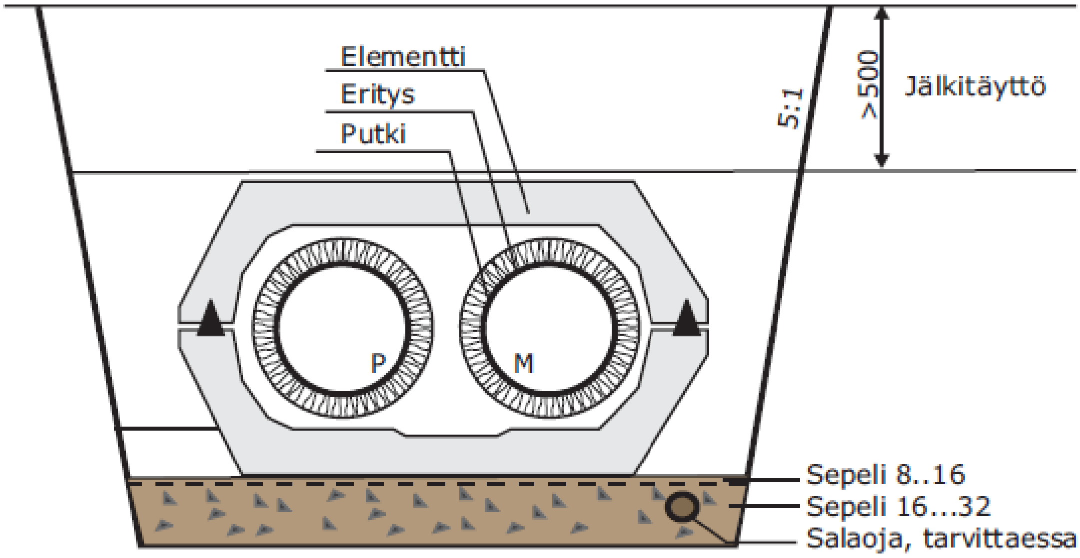


Figure 18 Concrete canal pipeline with soil description for construction (Koskelainen et al., 2006, p. 144)

3.5.1.4 Leak alarms systems in DHN

A DHN is built over a long time and underground structures are hard to monitor in real time (J. Carpén, personal conversation, 5.2.2024). Statistically DHN has 0.07-0.08 leaks per km of DHN yearly (Mäkelä & Tuunanen, 2015, p.16). Small-scale leak monitoring has been tried in Helsinki with a leak alarm system in some pipelines and utility spaces underground. Leak alarm works with a wire installed inside of the DHN pipeline plastic shell (Figure 19) and monitoring equipment that works on measuring the resistance, temperature or measurement change speed. They are still quite new equipment in DHNs, but interest around them has been rising in recent years. The systems are still being developed, and best practices and cost-efficient use cases are not yet fully understood. One promising use for DHN leak monitoring is maintenance planning as leaks inform the DHN-company where the largest leaks are, allowing works to be planned before a leak gets worse and further damage to surrounding structures can be avoided. (Koskelainen et al., 2006, p. 143; J. Carpén, personal conversation, 5.2.2024)

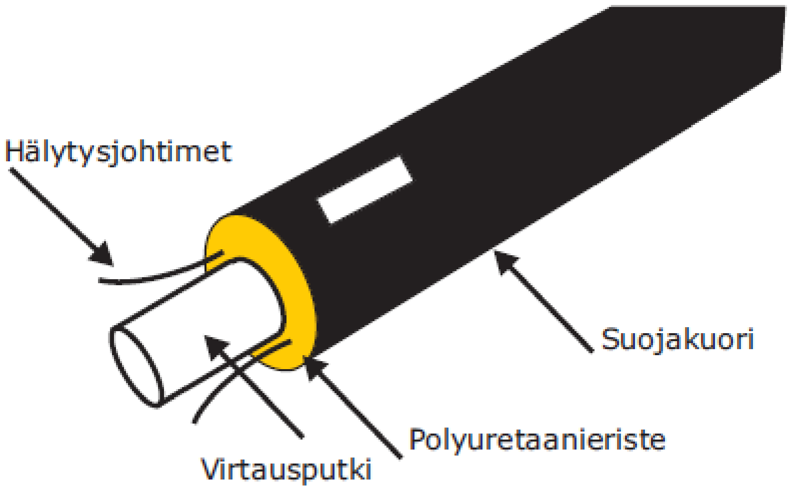


Figure 19 Leak alarm system in pipeline element (Koskelainen et al., 2006, p. 143)

3.5.2 DHN pipelines in Helsinki

As a safety precaution, the central city has a lower supply pressure limit of ten bars. It is difficult to know the exact state of old legacy pipelines and it is expensive to do repair and replacement works in central urban areas, so the design limitations of pre-existing ten bar design pressure lines must be respected. Modern pipelines are made for a 16-bar specification. Transfer lines between the main and the east DHN in underground tunnels are designed to be able to hold 25-bar and are not a limiting factor. A default option has been individual supply and return pipelines in Helsinki. A dual pipe in single shell (Mpuk) has been used in small diameter lines when space for infrastructure underground is limited in the area. (T. Korhonen, personal conversation, 2.2.2024; T. Marttinen, personal conversation, 12.03.2024)

3.5.3 Valves in DHN

Valves in DHN are used to restrict flow when needed for heat transfer, maintenance, and expansion reasons. Flow valves provide the ability to block a flow and vent or empty a pipeline while running a by-pass and to limit leakage effect on DHN heat supply that increases heat and DH water losses in DHN. Isolation valves allow maintenance duty and leak repairs to be done to a limited number of customers while a flow regulation is made with seat valves like in substations. The most common valve types in today's DHN for isolation are quarter turn ball, plug, and butterfly valves depending on pipeline size as the cost and size vary between designs. Butterfly valves are mostly used on medium and large and others in small to medium pipeline sizes. Butterfly valves offer smaller size and lower costs compared to other commonly used valves. (Frederiksen & Werner, 2013, p. 289-292)

Shut-down valves provide ability to control DH flow between areas, its direction and isolate parts of a network for pauses in a flow transfer when required. Larger sized shut-down valves require bypass valves in parallel for safe flow manipulation and to prevent water hammer effect, which can cause severe damage to network equipment due to too fast changes in flow caused by valve position change. Valve types in a DHN are ball or butterfly valves in large diameter lines depending on size limitations along with the criticality of the line. Ball valves offer better leak proof structure, but butterfly valves are smaller and demand smaller infrastructure around them while being less expensive in large sizes. (Koskelainen et al., 2006, p.167)

Excess Pressure Valve (EPV) is a closed-by-default-valve to maintain upstream pressure in a pipeline up to an adjusted set point. It will allow process medium flow thought as pressure is maintained on an inlet side of the valve to overcome self-operated regulators' spring tension. (Samson manual, 2023, p. 12) EPVs can be used in DHN to ensure minimal pressure level in DHN return line and to prevent DHN return line from pressure dropping below static pressure. Below static pressure endangers the DHN to a boiling flow and a water hammer related damage in the higher geographical points of DHN. (T. Marttinen, internal presentation, 2022)

Control valves in customer substations control DH flow through a customer substation HE. To ensure adequate flow and controllability across the demand range they need to be designed for DHN-operator's specified local pressure difference range. They restrict flow from a substation HEs to return pipeline and increase pass through time in HEs. A wrongly sized control valve limits system functionality and operability. A too small valve cannot provide high enough flow to reach designed thermal power and a too big valve cannot control flow well enough in small thermal demand, which comprises most of the year. DH industry guidelines define a 20 kPa max pressure difference between DH supply and return lines after customer HE. Customer´s system after HE allows a larger 50 kPa difference. (Yrjölä, 2015) Too large control valves result in too large a variance and bad control over heating (Mäkelä and Tuunanen, 2015, p. 80) System might require something between standard sized valves to ensure flow controllability and to meet throughput demand. In this situation smaller valves need to be installed and controlled in parallel (Yrjölä, 2015).

4 Heat exchangers in DHN

HEs provide a way to transfer heat efficiently between separate systems without mixing flows within the device, and due to that are common in different industrial applications (Çengel and Boles, 2001, p. 165). A DHN is hydraulically separated from customers and power plant networks by an indirect connection through the HEs. (Mäkelä & Tuunanen, 2015, p. 148)

4.1 Heat exchanger

Heat exchangers are devices that facilitate the exchange of heat between different temperature fluids or other mediums while keeping them from mixing with each other (Cengel, 2003, p. 668). Usual applications for heat exchangers are fluid stream heating or cooling and evaporation or condensation of one or multiple streams. (Shah & Sekulic, 2003, p. 1). Different applications provide different requirements for HE and there are multiple distinctive designs from cost to volume limitations to different use cases. (Cengel, 2003, p. 668) HEs used in DHN have changed over time and legacy systems are common which puts limitations on changes in DHN, as HEs are usually customer property and cannot be easily upgraded by the operator. HE system size needs to be fitted to each use case separately and DH supply temperature is an important system design parameter. (Mäkelä & Tuunanen, 2015, p.19, 68-69)

Mass flow through heat exchanger is driven by pressure difference between supply and return (Vahldiek et al., 2022). Heat exchangers introduce pressure loss into the flow and ensure adequate heat transfer. DHN-operator has a requirement to deliver at least minimal described pressure differential to all parts of the DHN. Customer substation heat exchangers in them are designed according to these requirements.

4.2 Heat transfer

Heat transfer in HE combines convection within fluids and conduction through the HE walls. Temperature difference defines the heat transfer rate (Cengel, 2003, p. 667). DH water is prevented from getting in contact with other customer heating equipment unless the customer´s HE leaks. (Mäkelä & Tuunanen, 2015, p. 148)

Heating power of heat exchanger and the connection between heating power and temperature difference for heat exchangers is presented in Equation 10:

$$\Phi \ = \rho q_v c_p \mathit{\Delta} T = UA(LMTD), \tag{10}$$

where $\mathit{\Phi}$ = district heating power [kW], ρ = water density [kg/dm^3], q_v= water flow [dm^3/s], c_p is specific heat capacity [kJ/kgK] and $\mathit{\Delta} T$ is temperature difference [K], *U* is heat transfer multiplier [W/m^2] and *A* is heat transfer area [m^2]

LMTD is the mean logarithmic temperature difference in the HE that transfers heat across the HE. It is dependent on the actual temperature difference between flows and describes HE’s efficiency as it is calculated in Equation 11 for counter flow configuration and demonstrated in Figure 20. (Mäkelä & Tuunanen, 2015, 73-74)

$$LMTD = T_{lm} = \frac{\Delta T_1 - \Delta T_2}{\ln\left(\frac{\Delta T_1}{\Delta T_{\ 2}}\right)} = \frac{(T_{h.i} - T_{l.o}) - (T_{h.o} - T_{l.i})}{\ln\left(\frac{T_{h.i} - T_{l.o}}{T_{h.o} - T_{l.i}}\right)}, \tag{11}$$

where ΔT_1 represents temperature difference between hot flow in $T_{h.i}$ and cold flow out $T_{l.o}$ and ΔT_2 difference of hot flow out $T_{h.o}$ cold flow in $T_{l.i}$

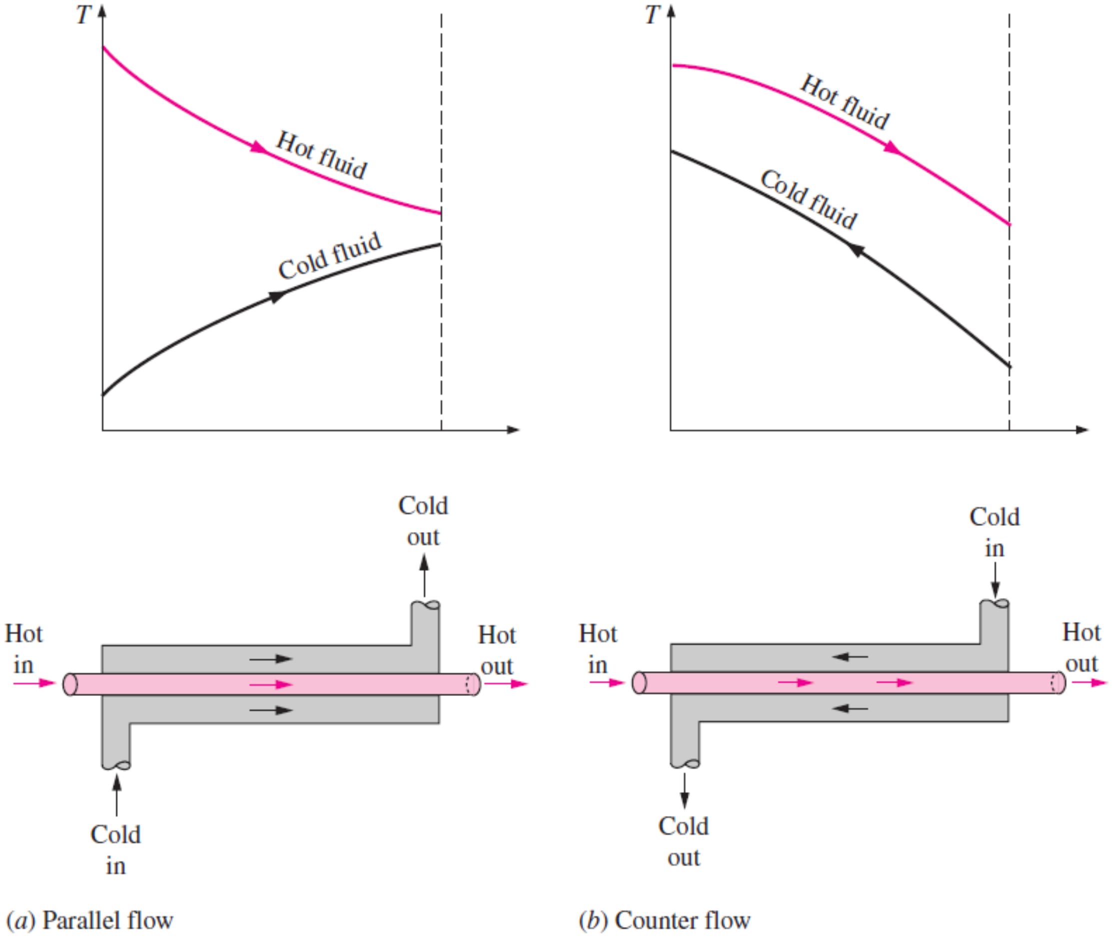


Figure 20 Parallel and counter flow (Cengel, 2003, p. 668)

4.3 Heat exchanger types

Heat exchangers have multiple designs and classifications are varied from construction (Figure 21), flow arrangement to heat transfer method and purpose. Direct transfer, or recuperator HEs provide immediate heat transfer through a transfer surface and fluid mixing or leaking is normally prevented. Indirect transfer, or regenerator HEs transfer heat with intermittent energy storage, a matrix or an exchanger surface, which stores heat from one flow and transfers the stored heat to another flow. (Ezgi, 2017, p. 6-9, Incropera, 2007, p. 670, Shah & Sekulic, 2003, p. 1-6) In indirect HEs it is harder to ensure separation between mediums and this makes them increasingly prone to leaks between flows. (Shah & Sekulic, 2003, p. 1) Counter flow is the most common and more efficient for heat transfer, but special situations might require using a parallel flow configuration. (Serth & Lestina, 2014, p. 67)

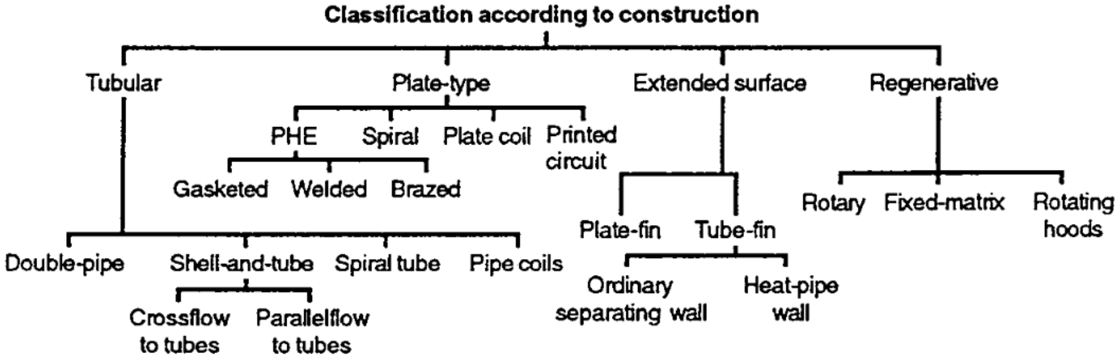


Figure 21 Classification of heat exchangers according to construction (Shah & Sekulic, 2003, p. 2)

4.3.1 Shell and tube heat exchanger

A shell and tube heat exchanger (STHE) (Figure 22) is an extension of the simplest form of a heat exchanger. Instead of an individual tube it contains numerous tubes held together with baffles, which introduce turbulence to increase the convection coefficient. (Incropera, 2007, p. 671) Internal construction details and the number of passes are dependent on the required heat transfer rate and pressure drop. The design is popular in industry for its versatility to be adapted to different demanding conditions like high pressure, temperature, heavy fouling, and corrosion environments. (Shah & Sekulic, 2003, p. 13). A shell and tube HE was a popular type in the 60s and the 70s in customer substations in Finland, but large volume, weight and bad transfer efficiency compared with PHE have made design obsolete. A copper pipe helical design (Figure 23) is still in use in old DH customer systems. Copper pipes' vulnerability to erosion from high water flow speed and corrosion from bad water quality have decreased the design's popularity in new installations. (Mäkelä & Tuunanen, 2015, p. 72)

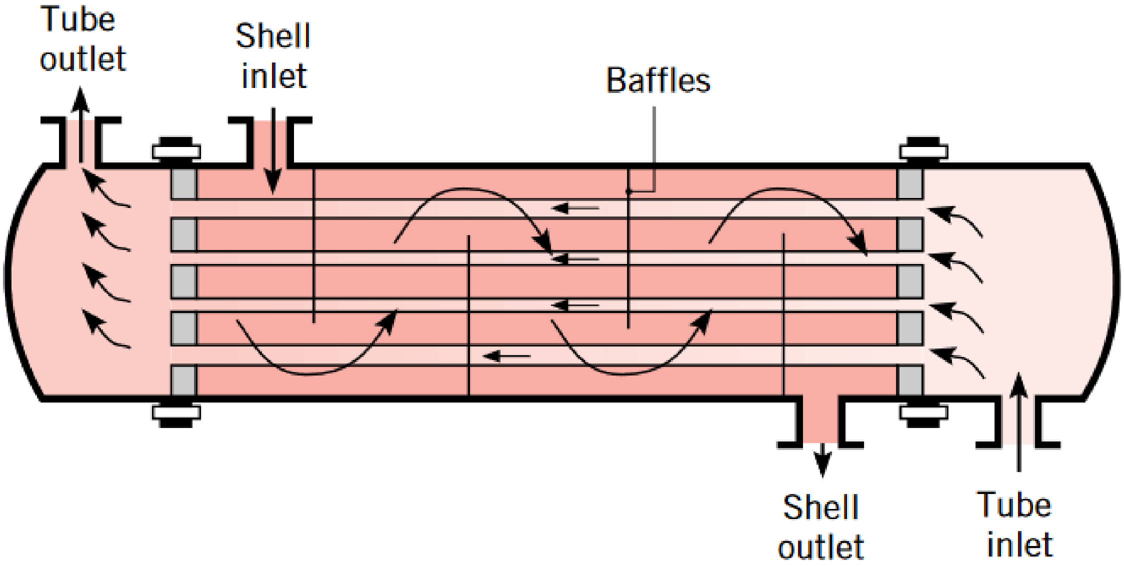


Figure 22 Shell and tube heat exchanger with one shell pass and one tube pass in cross-counterflow mode of operation (Incropera, 2007, p. 671)

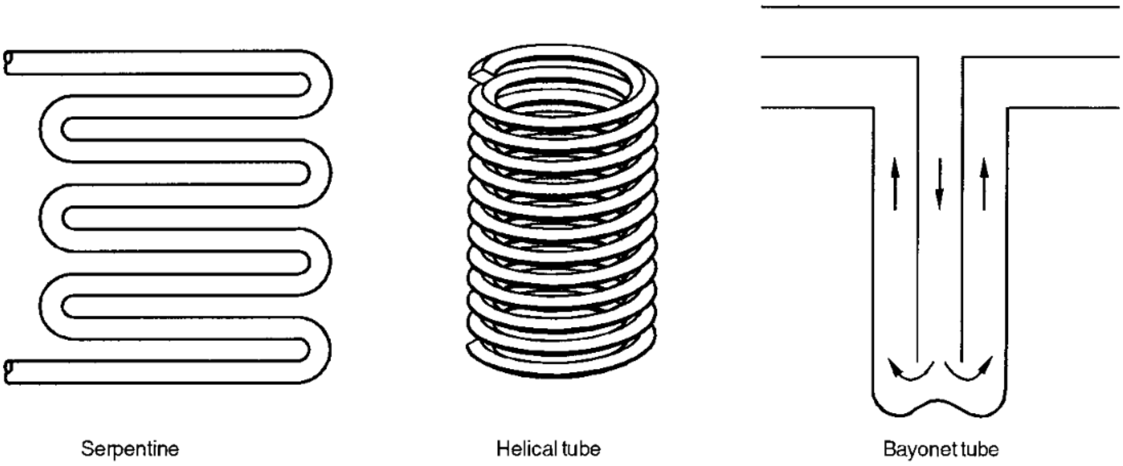


Figure 23 Additional tube configurations used in shell-and-tube exchangers (Shah and Sekulic`, 2003, p.16)

4.3.2 Gasketed plate heat exchangers

The Plate and Frame construction gasketed plate heat exchangers contain thin corrugated metal plates, edge sealing gaskets and frame structure that contain carrying bars and movable and fixed end covers. Carrying bars in a frame suspend and guide plates to correct alignment using plate notches and the pack is compressed and fixed together with compression bolts between the end covers. (Figure 24) This structure makes disassembly for cleaning and repair easy as pipelines can be left untouched and heat transfer surfaces changed when needed. PHE has high transfer efficiency that makes it possible to reach up to 1 °C difference in a counterflow configuration. Due to high turbulence and a sheer rate of the flow in PHEs, the devices have 10 % to 25 % of the fouling compared to shell and tube types and material requirements amount to less than half for the transfer surface and one sixth for the weight when demanding similar performance. Downsides for PHE are limited maximal pressures, normally up to 3 MPa, and gasket materials which are often not compatible with corrosive, toxic or high temperature applications. Gasket lifetime is reduced significantly, and expensive gasket materials are required for demanding applications. (Shah & Sekulic, 2003, p. 23-28) Gasketed PHEs are mainly industrial products in DH context as gaskets require maintenance, propose leak risk and DH water does not normally require a cleaning of HE plates (Mäkelä & Tuunanen, 2015, p. 71).

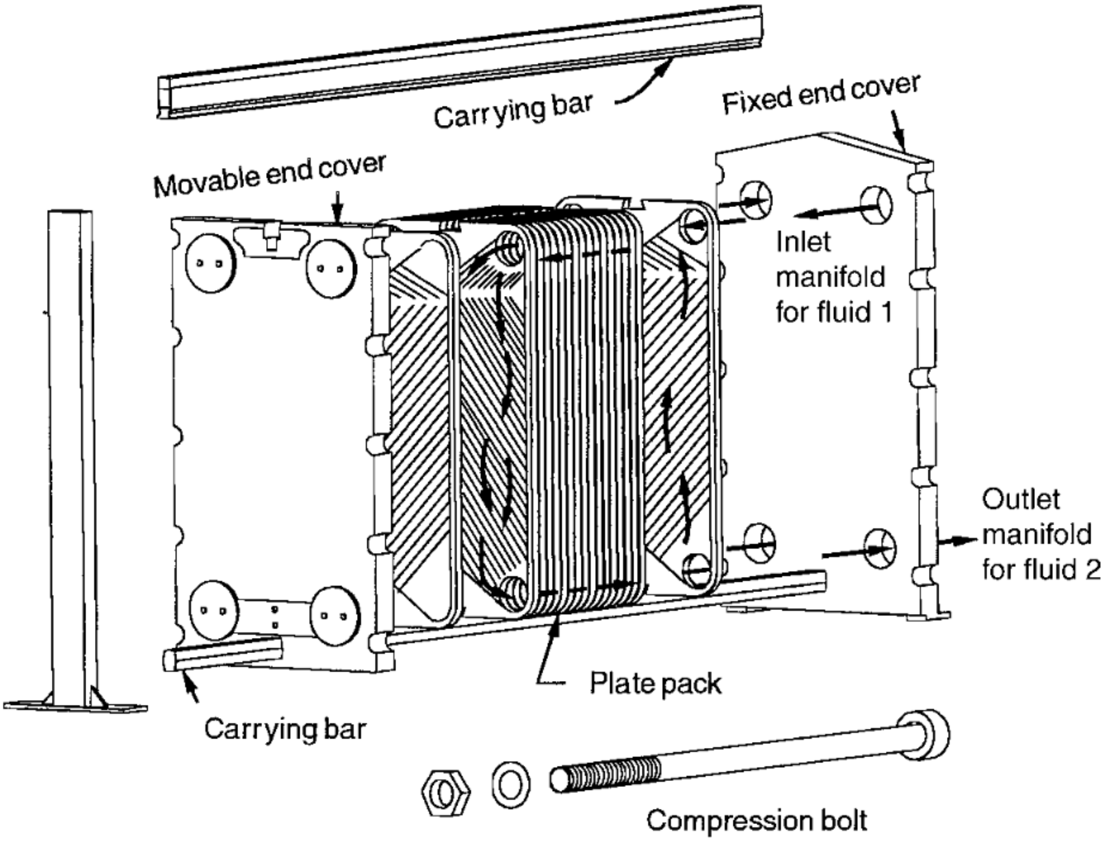


Figure 24 Gasketed plate heat exchanger construction (Shah & Sekulic, 2017, p. 23)

4.3.3 Brazen plate heat exchanger

A brazen plate heat exchanger (BPHE) (Figure 25) is a low-cost high-efficiency compact heat exchanger (Barzegarian et al., 2016, p. 1) that offers a high temperature and pressure for minimal fouling applications. Construction is formed from stainless or acid-proof steel plates between end plates that are vacuum brazen together with copper, or nickel to form a sealed self-carrying structure without gaskets. The concept´s downsides are inflexibility to changing transfer requirements and low thermal capacity that reduces ability to keep up temperature during e.g. domestic water heating peaks. (Shah & Sekulic, 2017, p. 30; Mäkelä & Tuunanen, 2015, p.70)

Figure 25 Brazed compact heat exchanger (Kilic, 2021, p. 3908)

4.3.4 Shell-and-plate heat exchanger

Shell and plate heat exchangers (SPHE) are combination designs of PHE and STHE (Wang et al., 2020, p. 1). They offer heat transfer efficiency closer to PHE than STHE in compact form without the gasket’s downsides in terms of pressure and temperature limitations (Figure 26). In similar pressure and temperature conditions PHE offers better heat transfer efficiency due to lower shell side efficiency but structural benefits in terms of leak prevention, pressure, temperature and corrosion resistance. (Beckedorff, 2022, p. 1, 16-17) They have applications in chemical, energy and cold technology industries in heating, cooling condensing and evaporating needs where higher temperature and pressure variations than what the PHE can provide are required in smaller unit sizes with better transfer efficiency than STHE (Vahterus, n.d.)

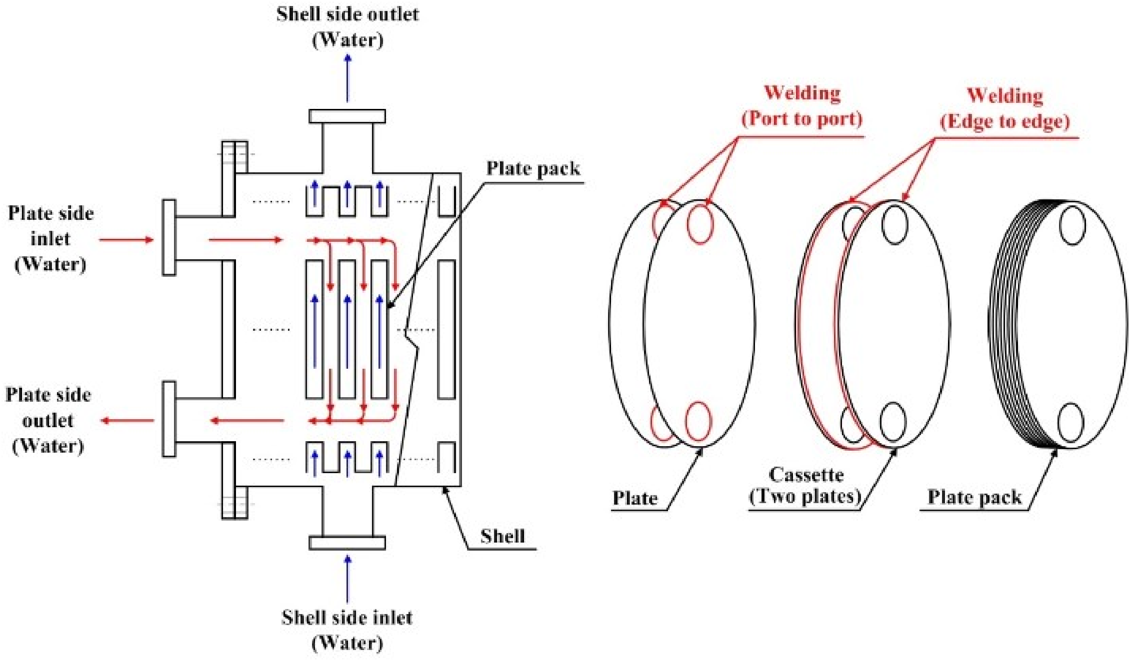


Figure 26 Schematic of the PSHE (Kim et al., 2021, p. 2)

4.4 Customer substations

Substations provide a control point to adjust the temperature and pressure between DHN and customer networks. This allows less expensive system requirements and materials in a customer system compared to the DHN (Frederiksen & Werner, 2013, p. 359-362). Substation's function is to control intake heat from DHN by adjusting flow through the substation`s heat exchanger according to the customer's heat demand. Separation from DHN can be done in a customer's substation or by a larger area substation depending on a local pipeline infrastructure design as lower temperatures in lower pressure require less expensive pipelines. A substation location varies largely depending on local design practice from an area substation to a building, and in extreme cases to apartment substations in Germany. In Nordic literature apartment level substations are viewed as an expensive solution to legal requirements of individual monitoring and billing. (Frederiksen & Werner, 2013, p. 359-362) This thesis focuses mainly on district heating systems in Finland and the local market follows building substation layout requirements (Mäkelä & Tuunanen, 2015, p. 64). Legionella bacteria prevention mandates heat providers in Finland to supply heat to all customers at least at 65 °C to ensure that customers' network always stays above the danger zone of Legionella bacteria. (Korpinen et al., 2023, p. 53) Due to the degree on domestic and wastewater equipment (water temperature 1047/2017 6 §) hot domestic water is required to always be above 55 °C, heat exchangers are required to be designed for new buildings to work with 58 °C minimal outflow temperature to prevent the growth of Legionella bacteria in hot water circulation. (Finnish Energy, 2022, p. 9). A hydraulic separation between a customer heating network and district heating providers` network has been deemed necessary to reduce the risks of high-pressure DHN connection to endpoint buildings. The leak risk and pressure design requirements for customer systems are lower as customer systems are not directly connected to DHN. It is possible to run hydraulically separated systems in different pressures and end user systems can be less expensive when run in lower pressure. (Mäkelä & Tuunanen, 2015, p. 64). Substation control valves are discussed more in chapter 3.5.3.

Responsibility between a building owner and a district heating provider in Helsinki DHN is defined so that main valves and substation equipment (Figure 27 #12) behind them is the building owner's responsibility and DH provider owns equipment before them. A district heating provider owns heat metering equipment, strain, and a heating provider`s main valves in a network side. A building owner is responsible for their side of the equipment. Customers are incentivized to keep their systems up to date and well maintained to minimize return flow temperature by DH pricing as return temperature increases unnecessary transfer losses for a DHN and affects network pressure regulation requirements. (Helen Oy, n.d. -b, Helen.fi)

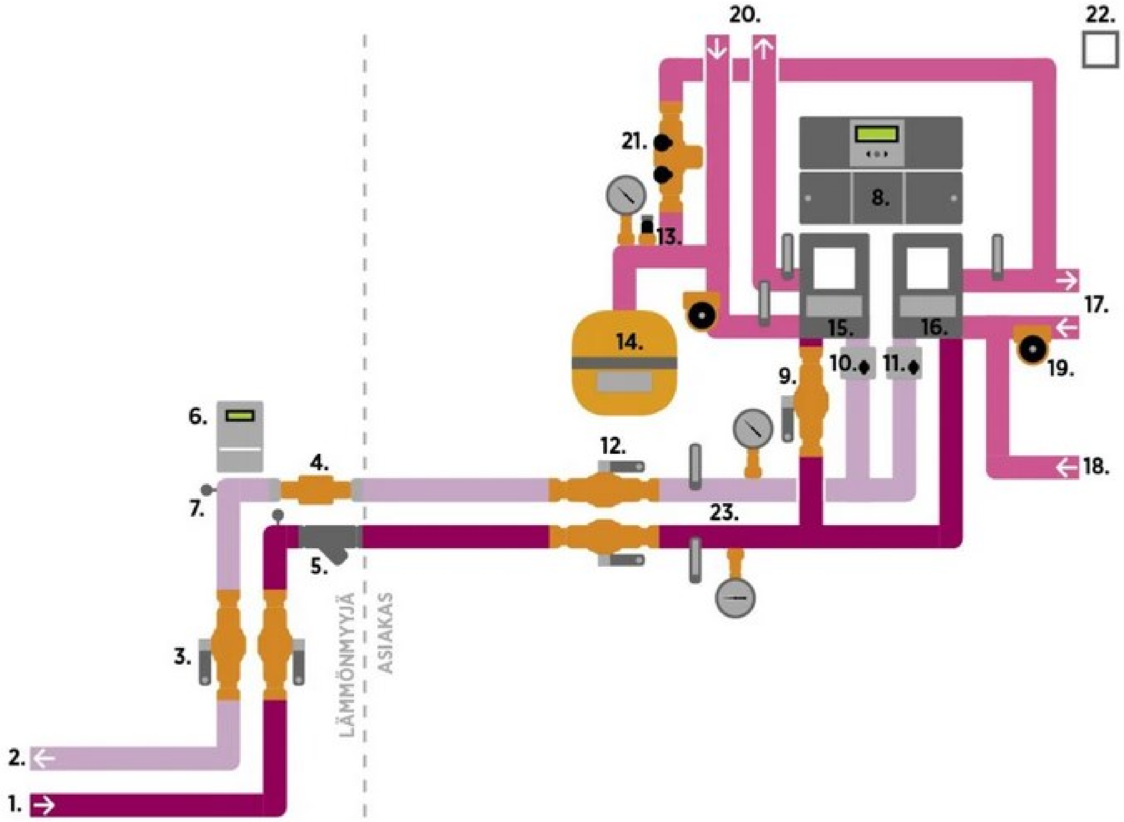


Figure 27 Customer substation in Helsinki district heating system (Helen Oy, n.d.-c, Helen.fi)

4.5 Heat exchangers in DHN

Heat exchanger stations are used in DHNs sometimes to separate parts of a network in different pressure or heat levels. This enables different heat levels in production and energy storage solutions in a network. Benefit of their usage as part of a distribution network is to ensure better control in larger networks to the end user pressure level and prevent overpressure in network lines. Heat exchanger stations provide a way to keep minimum pressure in control in areas of significant differences in ground pressure level. (Koskelainen et al., 2006, p. 175)

4.6 Heat exchangers in Helsinki DHN

Helsinki DHN contains two different pressure level DHNs due to the historical limitations of network construction. Pressure requirements in the eastern part of the network are significantly higher due to larger changes in elevation than in the older central city-supplying the main network. The main network is older design and construction and has a lower design pressure specification. Lower design pressure limits supply pressure below 10 bar that is lower than modern standard sixteen bar for DHN pipelines. Main and east DHNs are connected to each other with heat exchanger stations that allow heat transfer between networks at different pressure levels but introduce 1-1.5 bar pressure loss to the DH flow. This loss requires additional pumping work and increases the cost of the DH for customers. Temperature difference required to enable heat transfer between exchanger sides increase heat transfer losses and increase costs in heat generation due to rise in return temperature. DHN customers are connected to a DHN by HEs in their substations for warm space heating and domestic hot water networks. Recently updated DH supply temperature design guidelines would require customers upgrading their systems to a DHN to gain maximal efficiency gains during the heating season. High DH legacy temperatures result in smaller customer HE requirements.

5 Experiment: changes to mean pressure level in DHN

Unifying DHNs in Helsinki has been under discussion for a long time in Helen Oy. Now after the existing network has been able to run with the TUORE optimization system it is possible to make models on how the network will behave under different conditions. According to collected data, it would be possible to run the DHN as a unified system without hydraulically separating the networks for 90 % of the year with existing security margins. They haven’t been considered together for a while and likely are too cautious. HEs increase heat requirement to meet city’s demand as part of generated heat is lost in the return. Before testing Helsinki DHN in practice, the expectation was that under high load situations the current system constraints may become a limiting factor. Unifying networks might require updating PPs automation and network management software, warnings, limits, restrictions, locks and safety margins. Additional hardware in the field to support network pressure monitoring is likely required. (Helen Oy, 2024, internal presentation)

5.1 The experiment plan

Before the tests, the DHN was simulated with network simulation software Termis that can simulate network flow, pressure, and temperature in different parts of the network in different production and load situations independently of the DHN´s production system to reveal potential risk areas and situations in the DHN that can prevent leaks and underheating areas of network (T. Korhonen, personal conversation, 17.1.2024). The first experiment is made to ensure that DHN, PPs and other equipment in DHN can technically handle a unified network's conditions. It is followed later by the second experiment that tests DHNs capability to function as a unified DHN in more demanding heat load conditions. According to the results of the simulation, Jakomäki district in Helsinki was identified to be the most challenging area to manage from a network perspective. It is an uplands area in the eastern part of DHN and compared with its neighboring areas, the return pressure risks going below local static pressure. According to simulations and recent data the mean pressure in the DHN was set according to recent peak demand situations. Risks to a DHN infrastructure are minimized during the test by planning and preparations in close co-operation with operational and maintenance personnel. Additional human resources were prepared in case of leaks or other unforeseen problems with the network appearing during the test. The test interruption conditions were discussed and agreed during the planning phase in case problems with the DHN or production assets would emerge.

5.2 First experiment: rising pressure levels in the heating network

The first experiment was planned for late fall to have as many PPs and HOBs operating as possible before the heating season. The goal of this experiment is to ensure a DHN and PPs capability to function and hold the new pressure. The test pressure was set according to last year’s maximum load requirements. Potential problems with PPs and DHN leaks would be easier to handle and locate when DHNs were separated hydraulically, and heat demand was still low. The mean pressure of the main network would be increased gradually to meet the calculated common pressure during the first test week. At the same time, the eastern part of the network’s pressure was lowered to the same pressure. After the targeted pressure level was reached it was kept for a few days and returned to original value. During the experiment, new water intake to the network was monitored closely. Changes in DHNs water consumption are likely to come from new leaks in the network or enlargement of old ones.

During fall 2023, the outside temperature was significantly higher than normally at a similar time of year. High temperatures raised some concerns for experiment validity during normal operating conditions as lower heat demand reduced controlling assets contribution to the network and made it harder to respond to unpredicted events.

Predicted risks contained a possible reduction of pressure difference in the network as mean pressure raise increased supply and return pressures. As the margin between highest pressure in the DHN and its maximum design pressure decreases, surpassing automation warnings and being forced to limit pressure values becomes more probable. There are protective system limits below the DHN design pressure limits to prevent running the system over its safe operating values, and in turn prevent the abrupt shutdown of production assets, which would occur if the pressure hit protection limits. The low production could result in the concentration of production and saturate the transfer capacity of some areas. Automation restrictions would start to protect the system and limit the ability to control and manipulate the system. The supply pressure could increase close to the design limit as elevated mean pressure increased supply pressure.

During the test, automation problems were encountered with production assets, but operating personnel were able to work around them and manage the network without incident when they could not be fixed outright. After the test problems encountered during the test were identified and fixed by operation and maintenance staff during and after the test. Encountered challenges were mainly automation and maintenance related issues. A few problems were noticed with the compatibility of old automation systems' set values and the new higher pressure and pressure difference demand of the DHN. Automation settings require closer inspection after the tests to address found problems.

5.3 Second experiment connecting networks together

The second experiment was planned for early winter and expected to have moderate heat demand in late November to test a unified network in winter conditions. Weather and temperature during the test affect customers' heat demand from the DHN and limit when experiment is possible to do safely. The weather during the test was significantly colder than expected as the first cold period of the winter hit the Helsinki region and provided good data on united network behavior in winter conditions. Preparation for the second test focused on better communication and co-operation between different participants. Maintenance partners were taken in while planning process requirements and were well-informed before the test. Additional resources were reserved well in advance to ensure sufficient personnel to do required instrumentation manipulation to directly connect networks while having adequate reserves to handle possible leaks and other problems.

The stated worry in the project group was the possibility for a major leakage in the DHN due to increased mean pressure breaking older pipelines during or after the test. This was classified during the planning phase as highly unlikely, but it was noted that making changes to an old network, built over many decades, introduces the risks of unknowns that are hard to predict. The test made it possible to find a previously incorrectly marked valve in the maintenance system, which didn’t show up as closed for the operator. It was causing problems with pressure difference control at the end of the distribution line area. The area had been operated with only a bypass valve for a while, and the opened valve also made it easier to control adjacent areas as a result. During the test, the maintenance department reported an increased amount of strainer work due to deposits in pipelines getting loose and getting caught in strainers along the line. Some leaks were reported during the test but it was unclear how many of them were the fault of the test and how many were caused by older events in the DHN as the reasons for found leakages were reported being due to local corrosion and material fatigue in old DHN pipelines, that couldn’t be the result of the short test, and were not major in scale. The DHN did not have an increase in new water demand that would suggest that new leaks appeared because of the test. Pipeline deposit release into DH flow due to the change of pressure was not properly considered before the test, so that monitoring would have been increased sufficiently. This decreased water quality inside the lines and caused additional work after the fact.

The most limiting challenge during the test was pressure limits in the old DHN in the central city. The need to increase flow was limited by maximal pressure after increasing pressure during the test. Solution to this offered by the production optimization system was to raise the outflow temperature from a power plant but due to operator suggestion the average pressure was lowered. This enabled more flow in the network without rising heat losses like the temperature increase would have resulted in. According to the previous simulations, done before the thesis project, this was a more energy-efficient solution.

6 Discussion

The previously held expectations about the feasibility of connecting the DHNs seemed to be correct, and a more detailed feasibility study can be started. Unified DHN is important for further development towards new industry standards defining lower transfer temperatures (Finnish energy, 2021). Higher efficiency in distributed generation, higher waste energy utilization and better RES utilization towards 4GDH and more flexible DHN make future development work possible. Static mean pressure control is required to be further investigated in future and possible alternatives for more flexible controls provide a topic for future development work.

6.1 DHN benefits and risks

After DHN experiments SWOT workshop was organized to identify the potential positive aspects and downsides of network unification from different points of view in DHN development. Workshop group consisted of a wide array of shareholders and people from DHN design, development, life cycle management and production planning. The goal of the broad participant list was to enable all aspects of DHN unification to be considered during the early phase between the project and prevent expensive and time-consuming changes in the implementation phase of the project. Participants were provided with pre-questions to consider before the workshop that were collected at the beginning of the workshop and the identified aspects were discussed and collected into SWOT-matrix (Figure 27) after the event. The workshop was held online in teams to be able to be organized at short notice considering the large participant number with busy calendars.

During the workshop Helsinki DHN unification was considered to give better energy efficiency, DHN flexibility in operability and future development, lower losses in limited investment requirements. Possibilities for reduced visibility on the DHN during operations without additional investments was considered a downside as increase of DHN water intake will not tell area to suspect of leak like with separated DHNs. Increased inertia in the DHN before operator’s actions manifest, will force a change on how the DHN will be operated, and cultural changes are never easy to do in large organizations as increased inertia of one DHN increase demand for DHN operator to learn new way to manage the changed DHN.

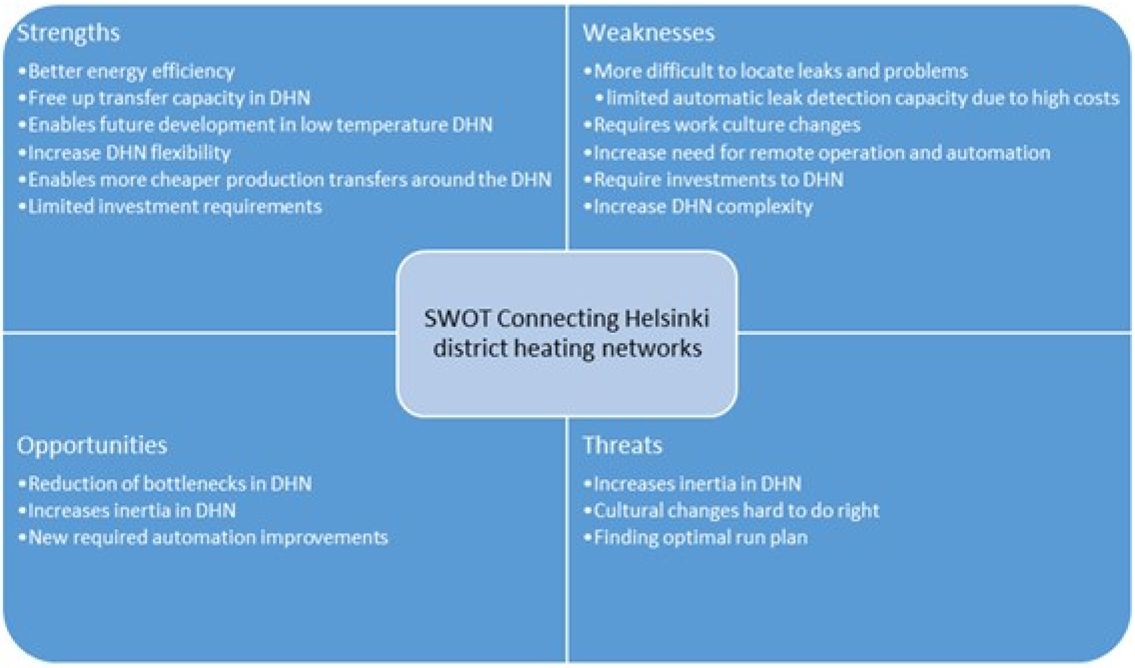


Figure 28 SWOT of connecting Helsinki DHNs

6.2 Developmental actions and future evaluations

After tests, the highest points of the DHN were identified from DHN data to prevent return pressure going below ambient pressure after DHNs are connected and the system gains more inertia from added mass. One of the known problems were the areas of high elevation in DHN topology. They were noticed to be much easier to manage during the test than before, and this affected DHN bottlenecks positively. The end of the network area had low pressure difference during the test due to a small connection pipeline and the incorrectly marked valve that reduced transfer capacity while consumption was large.

The information acquired during the experiments was used to contact industrial partners and suppliers about potential solutions to enable unified DHN for all customers and weather conditions. This can be mitigated with EPVs, that block the flow under set pressure, and increase mean pressure in a DHN (Figure 28). According to previous experience, they also require minimal maintenance. EPVs costs are dependent on the required number of units and the size of an individual valve. The cost of a valve unit increases significantly when larger, that requires on-site assembling, valve housing is needed instead of a smaller factory assembled one. A larger valve requires physically more space, on site assembly and demands more from controlling springs.

For future consideration, it was noted that higher mean pressure raises the DHN supply pressure at the same pressure differential and reduces the difference between design pressure and supply pressure. Low margin between supply and design pressure raises the risk of supply pressure measurement going over the notification-alarm-lockdown threshold of system automation as measurements have individual peaks from time to time. Dynamic pressure control might be necessary for a unified DHN according to preliminary discussions. The topic will be continued in a separate future master’s thesis on dynamic DH pressure management in Helen Oy. (Table 3) Better understanding about Helsinki DHN is necessary to enable more flexible control schemes and enable a more flexible way to manage network supply and pressure. Previous experience has been that controlling the network with measurements from network endpoints is enough to run the network with adequately trained staff in a static set pressure environment, and this has kept the number of measurement points limited. Measurement points have been expensive to implement before mobile connections due to the technical limitations of copper wires and limited amount of system inputs.

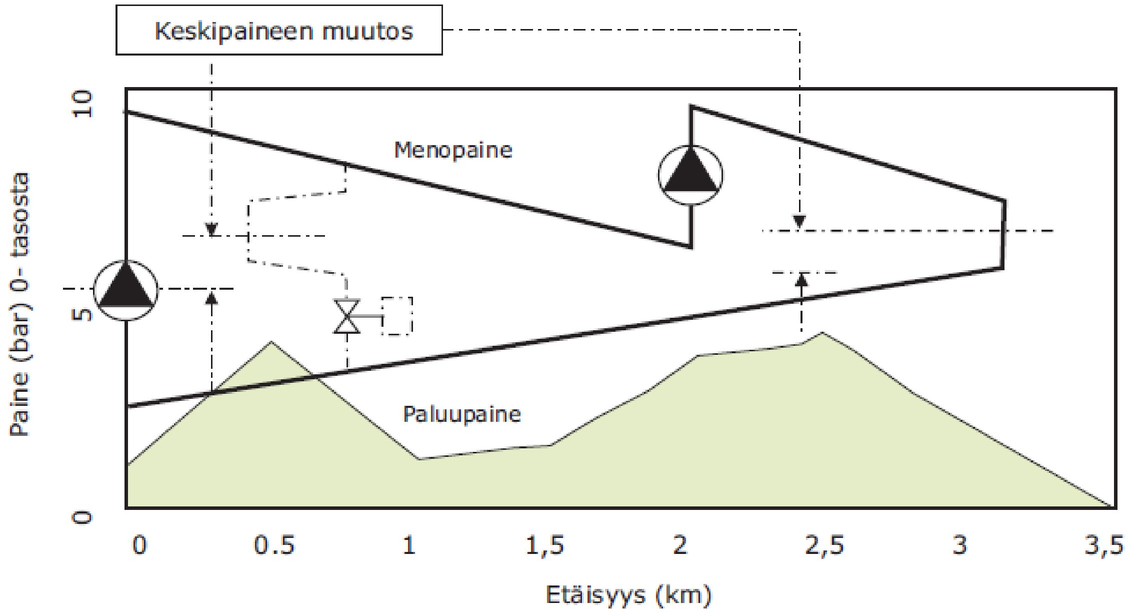


Figure 29 Average pressure in a DHN with multiple pumps and flow restriction in return flow (Koskelainen et al., 2006, p. 339)

Table 3 Future DH development steps after thesis

Task	Benefits	Equipment investment required	Profitable	Requirements
Network unification	Lower transfer losses	Yes	Significant yearly savings from energy production	Human resources, system update for production assets, additional measurement equipment and additional valves for the DHN
Increased pressure measurement on the DHN problem areas	Enables better control, network unification and more accurate future development	Yes	Requires investigation	Investments on measurement instrumentation
Return pressure control	Enable network unification	Yes	Requires investigation	EPV investments on identified risk areas
Summary on pressure limits and automation restrictions on existing system	Enable network unification	No	Requires investigation	Investigation on possible investment requirements.
Production automation control system limits and restriction update	Enable network unification, energy efficiency improvements	Maybe	Requires investigation	Requires time and human resources to update restrictions on production automation to be compatible with different pressure level of unified network
Lowering network temperature	Increased HP COP, lower transfer loses	Maybe	Requires investigation	Network unification
Remote control for the current DHN`s border valves	Increased control of the network, reduced labor requirement,	Yes	Requires investigation	Feasibility study for potential solutions, automation integration to current system, construction required
Dynamic DH mean pressure	Lower pumping costs, increase DHN flexibility	Maybe	Requires investigation	Remote automatic DHN pressure control and monitor

7 Conclusion

Following conclusions can be made based on experience gained by DHN tests.

- Helsinki DHN is technically capable of operating under common pressure and as a unified network.
- Helsinki DHN assets require an update to system automation warning-limit-lock values to ensure operability in all conditions.
- Unified DHN reduced existing problems in DHN management and made heat management easier in currently more challenging areas.
- Return flow in high elevation areas require additional protective EPV valves to ensure adequate minimal pressure in DHN.
- More measurements in the DHN are required for better system control and management in the future.

Technical viability of common DHN pressure level over DHNs and production assets needed to be confirmed experimentally before larger changes to the system assets in large could be planned and implemented in a sustainable manner. These experiments are described in this thesis along following actions to enable the reduction of existing bottlenecks in the DHN in following development projects towards more efficient DHN. During tests known bottlenecks were easier to manage as transmit capacity was larger between DHNs. From a previous experience, one of the known problems were the areas of high elevation in DHN topology. These developments follow previous DH and DHN development during the last century to increase energy efficiency by utilizing low-cost under-utilized heat sources and increase heat transfer efficiency. Unifying Helsinki DHNs and reducing losses from HEs follow this development and provide the ability to reduce transfer losses in the future. Reducing required production to fulfill customer demand along with lower returning DHN flow temperature that helps with HP production efficiency, costs and emissions of the DHN provided by heating service.

A need was recognized to update the pressure settings and safety margins of DHNs production sites together. DHN would require new equipment to cope with pressure change and to get knowledge about needed pressure levels in different scenarios as set mean pressure level sets return pressure level. Better understanding about the Helsinki DHN is necessary to enable more flexible control schemes and enable a more flexible way to manage network supply and pressure. A possibility to manage a mean pressure level dynamically in a small range became more feasible with added information. More dynamic pressure control schemes require more visibility on the DHN, which can be done more economically today than when DHN was built due to the technological advancement and reduced costs of additional measurements on the DHN. At this point, the possibility to reduce energy consumption from the losses in the network would provide significant reduction in costs according to preliminary estimations.

8 Summary

Helen Oy aims to be a carbon neutral company by 2030, stop coal usage in DH generation and focus investments to RES production along with increasing flexibility. The company has a goal to stop all burning-based energy production by 2040. Energy sector requires more flexibility in RES integration and biomass is seen as a transitory fuel as electrification of heat generation gets more widespread with HPs and electric boilers along with potential synergies with future electro fuels and waste heat reuse in the heating sector. TES is a crucial part of a diversified energy portfolio and allows better utilization of increased energy market volatility. DHN can be part of this TES service and reducing the usage of the most expensive energy source provides value for the society and environment. (Helen Oy intra, 2024)

The thesis discusses DH development in scientific and industry literature and describes Helsinki DHN structure now and during its early years. It considers how the literature on generational DHN development fits to the visions of DHN in future to increase efficiency and reduce losses and emissions of the energy sector.

The thesis finds a significant energy saving potential from the DHN unification and it is followed by an internal feasibility study on required investments and provided savings. DHN development will be continued in a future master thesis on dynamic DHN pressure control to enable more flexibility for the system.

The thesis also investigates the possibility of connecting Helsinki DHN to a single hydraulic network. During investigation practical tests were conducted with DHN to evaluate feasibility of the concept. Connected DHN allows higher DHN efficiency and heat transfer enabling removal of exchangers between main and east network. HEs increase temperature in return flow and this produced heat cannot be used for serving customers. Required extra heat production needed to meet customer demand in DHN increases transfer losses and emissions of DH generation. Lowered DH return temperature will increase efficiency of HP production in DHN.

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