

Benefits of increasing flexibility in a Low-Temperature District Heating and Cooling Area Network - Case: Aalto Works District

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Abstract

The heating sector is responsible for a major part of total greenhouse gas emissions in Europe and Finland. To achieve the ambitious emission reduction goals, the heating industry has to be able to more efficiently utilize renewable low grade heat sources. By lowering the supply temperature of a district heating network, heat pumps are more efficiently able to produce heat from these types of sources.

This thesis studies the benefits of introducing flexibility to a low-temperature district heating and cooling area network using a pilot project called Aalto Works District as a case study. In the study, the system is modeled inside a larger district heating system model in a tool called MONA. The model is simulated with different scenarios that introduce different types of flexibility to the network.

The results of this case study indicate that by introducing some form of heat accumulation into the low-temperature heating network results in most value created in terms of reduced operational costs. The study identifies that further research on the subject is required before definitive conclusions can be made on the exact monetary value created.

Keywords low-temperature, district heating, flexibility

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Lämmityksestä aiheutuvat päästöt ovat iso osa Euroopan ja Suomen kokonaispäästöjä. Päästövähennystavoitteet saavuttaakseen on lämmöntuotantoteollisuuden kyettävä hyödyntämään huonompilaatuisia uusiutuvia lämmönlähteitä. Näitä lämmönlähteitä on mahdollista hyödyntää tehokkaammin lämpöpumppujen avulla laskemalla kaukolämpöverkon menolämpötilaa.

Tässä diplomityössä tutkitaan, millaisia hyötyjä on mahdollista saavuttaa lisäämällä joustavuutta alueelliseen matalalämpöiseen kaukolämpö- ja kylmäverkkoon käyttämällä Aalto Works -kortteli -nimistä hanketta esimerkkitapauksena. Diplomityössä systeemi mallinnetaan osaksi suurempaa kaukolämpöverkkoa MONA-työkalulla. Mallia simuloidaan ajamalla sillä erilaisia skenaarioita, joissa verkkoon on lisätty erilaisia joustavuutta tarjoavia vaihtoehtoja.

Tutkimuksen tulokset osoittavat, että lisäämällä joustavuutta lämpöakun muodossa matalalämpöiseen kaukolämpö- ja kylmäverkkoon saavutetaan suurin arvo pienentyneiden käyttökustannusten muodossa. Tutkimuksessa tunnistetaan tarve jatkotutkimukselle ennen kuin lopullisia johtopäätöksiä rahallisesta lisäarvonluonnista voidaan vetää.

Avainsanat matalalämpöinen, kaukolämpö, joustavuus

Esipuhe

Näiden kansien väliin oli helppo maaduttaa kaikki se, mitä niiltä sadoilta luennoilta, kotitehtävistä, tentteihin pänttäämisestä ja työelämästä on lähes seitsemän opiskeluvuoden ajalta jäänyt päähän. Sen sijaan kaiken muun tapahtuneen maaduttaminen yhteen esipuheeseen tuntuu maadottomalta ja suorastaan vähättelevältä.

Nämä sanat lienevät kuitenkin ainoat, jotka tästä teoksesta tullaan milloinkaan ääneen lukemaan. Lienee siis tullut aika kiittää mukana kulkeneita ihmisiä, joita ilman tuskin istuisin nyt tässä, hiljalleen puhki kuluneessa Ikean toimistotuolissa, jonka vanhempani hankkivat minulle ensimmäistä kertaa Teekkarikylään Servin Maijan tielle muuttaessani.

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Eikä syyttä,

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Iuvenis in Aeternum!

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Symbols and abbreviations

Symbols

ρ	density
c	cost
c_p	specific heat capacity
D	demand
n	number of units
P	power
Q	thermal energy
t	temperature
V	volume
W	work

Operators

Δt	change in temperature
$\Sigma(f(x))$	Sum of function $f(x)$
$f(x)$	function f as a function of x

Abbreviations

ASHP	air-source heat pump
ATWHP	air to water heat pump
AWD	Aalto Works District
CHC	combined heating and cooling
CHP	combined heat and power
COP	coefficient of performance
DC	district cooling
DH	district heating
DHW	domestic hot water
DSHP	dual-source heat pump
DSR	demand-side response
ECI	energy cost index
EER	energy efficiency rating
FRED	framework for energy dynamics
GAMS	general algebraic modelling system
GHG	green house gas
GSHP	ground source heat pump
GWHP	groundwater heat pump
HOB	heat only boiler
HP	heat pump
LP	linear program
LTDH	low-temperature district heating
MILP	mixed-integer linear program
MTDH	medium temperature district heating
PE	polyethylene
PU	polyurethane
WTWHP	water to water heat pump

1 Introduction

1.1 Background

The ongoing effort to achieve local and global goals of greenhouse gas (GHG) emission reduction has set a wide trend in Europe for energy companies to set goals to discontinue the use of fossil fuels and transition towards renewable energy sources. (Lucia & Ericson 2014). In 2016 it was reported that household heating was responsible for 30 % of Finland's GHG emissions (Mattinen et al. 2016). Only as late as in 2019 renewable energy sources bypassed fossil fuels as the main thermal energy source in heating, while the market share of district heating is continuing to increase to date. (OSF 2020). 46 % of the entire heating market in Finland is covered by district heating, with a share of 60 % of new locations choosing district heating (DH) (Hillamo 2019).

To achieve the ambitious GHG emission reduction targets, DH production needs to be able to move away from combustion technologies towards completely CO₂ free production. Without combustion, the high supply temperatures that are commonly used in DH networks are hard to achieve efficiently, while at the same time the energy efficiency of buildings has increased by a substantial amount, resulting in lowered heat demand and a relative increase in network heat losses. (Köfinger et al. 2016). By lowering the supply temperature of the DH network, it is possible to reduce the heat losses while making it more effective to utilize a larger variety of heat sources efficiently using heat pumps (Kazjonovs et al. 2014; Dongellini et al. 2015).

Fortum is constructing a pilot low-temperature district heating (LTDH) and cooling area network in Espoo, Finland in the campus area of Aalto University called Aalto Works District (AWD). The plan for the AWD network is to begin testing and production in early 2021. This thesis was done as an assignment for Fortum and is the first academic case study performed on the subject. The heating and cooling networks are connected to five buildings, of which one contains a helium production unit that requires constant cooling. The condensed heat from the cooling network is utilized in the heating network with a dual-source heat pump, that can produce additional heat to the LTDH network using air as a heat source. The goal of this study is to find out what benefits can be achieved from introducing different types of flexibility in a local LTDH network using the AWD pilot as a case example.

1.2 Approach and purpose

The study is conducted by first modelling local heating and cooling demand based on historical data and other available resources. The production units of the network along with the demand are modeled into a mixed-integer linear optimization program

(MILP), which simulates the network. The simulation is run with different scenarios that utilize different levels and types of flexibility within the network to find out which scenario has the most value creation potential.

The model is created inside Espoo DH network model with a MILP programming tool created by Fortum called MONA. MONA has a graphical user interface and several user-friendly features that fit the requirements of modelling for a DH business, making the modelling more approachable and user-friendly compared to conventional text-based modelling. The MILP model minimizes the production costs of the AWD network alongside the Espoo DH network, to which the AWD model is connected to.

The main purpose of the study is to find out is it possible to increase the value creation of an area energy network approach by adding flexibility to the network and if, what type of flexibility? The study aims also to create a general outlook on AWD operation that is yet to start. The pilot is one-of-a-kind in the world and no available data on the subject exists. Therefore it is interesting to proactively study any additional possible value creation for the case in question and for any similar future types of local LTDH networks.

1.3 Limitations and scope of the study

Since there is no existing data on the production of the network, the model has to be based mainly on theoretical assumptions. Due to the nature of heat pump-based production, the hourly variance of production costs and heat demand, the simulation has to be done in an hourly resolution. This requires massive amounts of computational power and exponentially increasing time of optimization when increasing the time frame. When wanting to run multiple scenarios, the time frame of simulation is limited by the need for run times of optimizations to stay reasonable. Therefore no exact monetary value creation from flexibility solutions can be concluded. The study is able only to highlight the possibilities in value creation and give estimates towards the value created.

The scope of the study is focused on the base scenario, three flexibility scenarios, and a combination of the three scenarios. Other types of flexibility, such as demand-side response has been left out of the study since the result would represent other s of flexibility with just specific constraints, but with an increased need for assumptions. The study also simplifies the simulation of domestic house water usage since there is no available data on the buildings regarding that, and it does not contribute towards highlighting the possibilities in value creation in introducing flexibility.

1.4 Structure

This thesis consists of six sections. The second section covers existing research and theory on the subject. The evolution towards LTDH is briefly discussed along with its benefits and challenges. Existing LTDH networks and the function of heat pumps are also studied. The aim is to create a background on which to build the study of the upcoming research.

The third section begins by describing the Aalto Works District case with its different solutions and components. The section continues by taking a look at the tools used in the modelling and simulation, especially the MONA tool. After describing the tool, the functionality and modelling choices of the model and the model itself are studied. Finally, different inputs scenarios are discussed.

The fourth section presents the results of the simulation. The results of each scenario are represented independently and the differences between each scenario in comparison to the base scenario and other scenarios are highlighted. The fifth scenario consists of a sensitivity analysis of the most prominent scenario, along with an overall analysis on the results. The relevance of the study and future research is also discussed.

Finally, the sixth section draws the entire study together, drawing final conclusions and key findings of the study.

2 Background

2.1 From Steam to Low-Temperature District Heating

Access to warm water and the ability to heat buildings is crucial in many parts of the world. At the center of today's discussion is how to provide it as economically and ecologically as feasible. Some parties consider the key being an increase in household efficiencies to mitigate or even nullify the requirement of additional heating or even making buildings 'plus energy houses' with low-energy building technologies and solar thermal energy production. Others consider that the key is utilizing excess heat from industrial processes and using renewable electricity with large-scale heat pumps to be able to provide the needed heat. The latter option requires at least some grade of centralized heat production and distribution. (Lund, Möller, Bathiesen & Dyrelund 2010)

District heating (DH) is an efficient way to distribute and utilize heat from available heat sources to where it is needed. The benefits of DH are most evident in urban regions with a high energy density, since DH usually requires heavy investment in infrastructure. More than 70 % of the European population live in cities and the percentage is expected to increase to more than 80 % in the next 30 years. There should therefore be a growing demand for DH as well, with expected growth to up to 20 % of the entire European heating market in 2050, it being around 10 % in 2010. (Connolly et al. 2013)

Initially, in the late 19th-century district heating network utilized steam as a heat carrier. These networks are considered the 1st generation of DH. Some of these networks are still in use in old districts in places like New York and Paris. Slowly these systems were replaced by the 2nd generation, in which steam was replaced by pressurized hot water with supply temperatures of over 100 °C. Many of these networks remain operational to this date. In buildings from that time, space heating was mostly accomplished by using radiators, which needed a supply temperature of around 80 °C. Therefore DH networks with lower supply temperature were developed – the 3rd generation DH or medium temperature district heating (MTDH). The 3rd generation still utilizes pressured hot water as a heat carrier, but temperatures are now dropped below 100 °C. These types of networks suffer from large amounts of distribution heat losses, usually varying in a range of 10 – 30 %. The network piping requires the usage of high temperature sustaining materials such as steel and they can only exploit heat from high-temperature sources, most typically combustion. Over time the energy efficiency of buildings has increased drastically, decreasing DH demand resulting in an increase in relative distribution losses and lowering the overall cost-effectiveness of DH networks. (Köfinger et al. 2016)

One way to tackle the aforementioned decreases in relative effectiveness and demand is to further lower the supply temperature of the DH network. Since most newer

building types require relatively low-temperatures for space temperature control, usually around 23 °C for most building types, it is possible to significantly reduce the supply temperature (Schmidt et al. 2017). Domestic water on the other hand has to be at a high enough temperature level so that the low-temperature district heating (LTDH) network does not provide a suitable growth-environment for the harmful legionella bacteria, which grows at around 20 to 50 °C (Li & Svendsen 2012). The problem of legionella bacteria can be handled in multiple ways - some existing solutions are discussed in 2.4. This 4th generation of DH, the LTDH is not specified, but the supply temperature in discussions varies from around 45 °C to 60 °C depending on the source (Connoly et al. 2013; Köfinger et al. 2016; Li & Svendsen 2012; Schmidt et al. 2017).

2.2 Benefits of Low-Temperature District Heating

2.2.1 Heat sources

While the heat in most 3rd generation and older DH networks is commonly produced mostly with combined heat and power (CHP) plants and heat only boilers (HOB) due to their need for high supply temperatures, LTDH can utilize effectively a much larger variety of heat sources other than conventional combustion due to the lowered supply temperature required. These heat sources consist of utilizing renewable energy both directly from renewable heat sources, such as solar thermal collectors and indirectly using renewable electricity.

One prominent candidate for this type of heat source is waste heat from different sources that are not currently utilized. One such source is data centers, which consist of multiple powerful computers and other devices, that use electrical power to perform computational operations and as a byproduct produce heat. The number of data centers is rapidly growing globally with an estimated coverage of 1.1 – 1.5 % of the world’s electricity consumption (Koomey 2011). Although most of the consumed electricity is converted into heat, it is rarely utilized. The heat is usually considered low-quality since the temperatures are below 85 °C, but with LTDH it could be utilized to its full extent. According to Wahlroos et al (2017), by utilizing the waste heat from data centers the operational costs of simulated DH systems dropped by 0.6 % - 7.3 %. (Wahlroos et al 2017)

Other types of low-grade waste heat sources that could be utilized include a variety of industrial sources. Especially energy-intensive industries, such as smelters and cement plants produce a lot of excess heat that could well be utilized in LTDH, thereby also increasing the thermal effectiveness of said manufacturing units. In a study by Fang et al. (2013), a city in Northern China was able to significantly reduce their CO₂ and SO₂ emissions at the same time reducing their operating costs to less than half of the status quo. (Fang et al 2013)

Due to the extensively lowered supply temperature, heat sources that might not intuitively be considered heat sources can be utilized effectively. Heat pumps are able to recover heat from low-temperature sources to be utilized in LTDH. These lower-temperature sources are usually groundwater and air. Industry scale groundwater heat pumps (GWHP) and air to water heat pumps (ATWHP) become a viable option when the difference of the heat source temperature and the DH network supply temperature is low enough. The coefficient of performance (COP) shown in equation 1 equals to the useful heat supplied by the system divided by the work required to be put into the system, usually electricity. COP of heat pumps is usually most affected by the required difference of heat source and target temperature – the bigger the difference the more work needed, which results in a lower COP. Therefore when using LTDH it is possible to utilize very low source temperatures. (Kazjonovs et al 2014; Dongellini et al 2015) Heat pumps are further discussed later.

$$COP = \frac{Q_{out}}{W_{in}} \quad (1)$$

2.2.2 Heat losses

When wanting to operate a DH network that is connected to modern low-energy buildings, network losses become a major factor in cost-effectiveness. There are three ways to reduce heat losses. First, the insulation on the DH network piping can be improved and so reducing operational costs. However, this would heavily increase investment and installation costs, and could not be applied to existing networks without a complete overhaul. A DH network is already an investment-heavy business as it is. A second way to decrease heat losses in a DH network would be to redesign the network pipes to have smaller nominal diameters resulting in higher permissible pressure drops. The smaller diameter results in a smaller area that is in contact with the surrounding ground resulting in smaller heat transferred. According to Dalla et al. (2011), this method could have potential, but would again need the entire DH network to be rebuilt when considering existing DH networks. (Dalla et al. 2011) The third option is to achieve lower heat losses by reducing the temperature of the water in the network. By decreasing the temperature difference of the water and the surrounding soil, less energy would be passively transferred from the water to the soil according to the second law of thermodynamics. Compared to existing MTDH networks, an LTDH system can reduce network heat losses by up to 75 % possibly resulting in a significant reduction in operational cost. (Li et al. 2014) A lower temperature is also possible to be applied in some forms to existing DH networks without having to build the entire network again (Hynynen 2018).

2.2.3 Plastic piping

Another major factor that contributes to cost-effectiveness is the investment costs. The predominant piping system in 3rd generation DH has been a steel pipe with polyurethane (PU) insulation and polyethylene (PE) outer casing. This type of piping has been proven to work well, but is very expensive to build, and has a couple of weak points: the steel can rust and PU can lose some of its insulating properties once it comes in contact with water. Therefore the contractors need to be careful and have a certain amount of expertise in building DH networks. (Korsman et al. 2008) The materials used are also heavy and expensive resulting in high investment costs and relatively high heat losses. Therefore additional measures need to be taken when considering LTDH network piping. (Olsen et al. 2008)

The lowered supply temperature allows usage of materials of which would suffer from a decreased performance or be unable to withstand MTDH temperatures. Plastics and composites in combination with other materials could offer a flexible pipe, that is easier and cheaper to install, with lower heat losses. Olsen et al. (2008) compared two types of DH pipes for a low-temperature network. They found out, that a flexible twin-pipe called “Aluflex”, containing aluminum and cross-linked PE had lower heat losses compared to their steel counterparts. According to Fortum’s own study, the local contractors and piping suppliers could not offer a competitive price to the AWD network. This could very well be subject to change in the future once a larger demand for such technology exists.

2.2.4 Benefits to customer

In addition to multiple possibilities for utility suppliers to benefit from transitioning to LTDH, customers also have benefited from having their estate heated with LTDH. Although the difference between MTDH and LTDH might not be as evident for the customer, LTDH remains to be superior in the reliability of delivery compared to other solutions such as local production. The benefit of not having to worry about the optimal operation of heating systems, malfunctions, or availability of fuel. The possibility of utilizing renewable energy should also create value for the customer. Utilizing renewable energy means, in many parts of the world, that the heat can be produced with domestic resources, not having to resort to foreign fossil fuel supplies which further creates stability both in price and security of supply. A well-designed LTDH should be able to bring down costs for the utility supplier and therefore for the customer as well. (Li & Wang 2014)

2.3 Challenges of low-temperature district heating

2.3.1 Reduced system design margin

In most conventional DH systems, the network is designed and operated in a manner that is based on experience and a large safety margin. The supply temperature is maintained at a high level and is backed up with a reserve capacity of heat production so that the system can tolerate major malfunctions of a single or even multiple large production units in extreme situations such as peak demand hours without compromising the reliability of the heat delivery to end-users. (Li & Wang 2014)

In comparison with the 3rd generation, LTDH ends up having a lower system design margin in order to mitigate and control investment costs and heat losses. This raises the need to more accurately design the network based on extensive simulation modelling, sophisticated optimization, and knowledge gained from previous projects globally. Li and Wang (2014) mention that this type of design could include reducing storage tank capacities and installing booster pumps at street level to reduce dimensions of the distribution network. Additionally, it could be possible to lower the supply temperature of the network to an ultra-low level, at around 30 – 40 °C, and have the heat boosted up to DH customers with micro-heat pump units. (Li & Wang 2014)

2.3.2 Long term behavior of plastic piping

PE foam that can be used to insulate plastic piping suffers from drastic performance deterioration in wet conditions, even when the material itself seems to remain intact, whereas PU foam may start degrading in the same conditions. Therefore in order to reach optimum performance, the piping should remain in dry conditions. Even though the piping remains dry from the outside, water can diffuse through the inner pipe to the insulation layer causing water condensation in the foam cells. This process happens very slowly, and according to Korsman et al. (2008) takes up to 30 years even in the worst-case scenario. (Korsman et al. 2008)

Another major threat to the entire DH system is the diffusion of oxygen through the plastic piping material. The diffusion of oxygen into steel and copper components of the system, such as radiators, couplings, and heat exchangers results in increased corrosion of said components and thereby shortened lifespan and increased maintenance costs. The diffusion can be reduced with a coating on the pipe, which reduces but does not completely block the diffusion. The key is therefore to maintain high water quality and minimize the presence of both air and salts in the corrosion vulnerable parts of the system since corrosion is strongly increased in the presence of those factors. (Korsman et al. 2008)

2.3.3 Need for two-way heat market

In conventional DH, the heat provider produces and distributes the heat to all customers. To be able to achieve maximum potential for LTDH, for example, to make it possible for the LTDH network to utilize excess heat from customers cooling systems, a new type of heat market could be applied. In this type of heat market, the customers would become producer-consumers, or ‘prosumers’. This means that each customer would have the possibility to both buy and sell heat from and to the LTDH network. At its most simple, a two-way heat market could make it possible for consumers that need cooling to be able to sell the excess heat produced in the cooling process, while at the same time the network operator may distribute it onwards with a profit. This could be possible with the LTDH network due to low supply and return temperatures. (Hynynen 2018; Lyytikäinen 2015)

A two-way heat market could be conducted in multiple different ways. Fortum and Stockholm city co-owned DH provider Stockholm Exergi (former Fortum Värme) and Fortum in Finland have an Open District Heating market, where they are committed to buying any heat produced with renewable technology that is supplied into their DH network. The pricing varies depending on outdoor temperature and whether the heat is supplied to the return or supply side of the network. Both companies provide different types of pricing contracts. (Fortum (N/D); Stockholm Exergi (N/D)).

Another type of market is district cooling or combined cooling and heating, where the network operator provides cooling as a product that the customer pays for and then utilizes the heat produced in the cooling process in the heating network. This way the customer does not directly act as a ‘prosumer’ in the way that they’re not directly compensated for the heat they provide but should benefit indirectly with lowered prices resulting from the lowered operation costs for the network operator.

Other existing projects in two-way district heating include Skanssi in Turku Finland, which is discussed later, As Oy Tampereen Pohjolankatu 18-20, which implements five heat sinks, a solar heat collector, exhaust air heat pump, heat recovery from wastewater, and from which the heat is utilized locally if needed and the excess is sold to the local DH network. (Hynynen 2018)

Overall, some form of two-way heat market between the LTDH network operator and the customers may greatly benefit both parties making it possible to utilize waste heat from various sources and possibly even reducing some need for peak demand production units.

2.3.4 Transition to LTDH

Even though the technology for LTDH is already valid and viable, DH is a very investment-heavy business, as already mentioned above. Existing DH networks have

been developed over the years and in many cases slowly expanded to their current extent. A transition from conventional DH to completely LTDH would require heavy investments, which is not feasible while existing solutions operate at a reasonable profit level. On the other hand, new DH networks and parts of them will be built in the future and perhaps they will lean more towards an LTDH technology, while the utilized technologies themselves are continuously developed further.

2.4 Existing low-temperature district heating

There are multiple case studies on existing LTDH networks. Case studies on LTDH have taken place in countries such as Denmark, United Kingdom, Belgium, Sweden, Germany, Canada, Norway, and Finland, with Denmark having the most available data on different examples. In the following part, five examples are taken into closer focus due to relevance to this study and availability of their data. Here Each LTDH network is shortly described, along with their unique characteristics and findings of case studies. The main characteristics of all studied networks are compiled into Table 1.

2.4.1 Skanssi (Turku energia)

The city of Turku and Turku Energia, an energy company owned by the city of Turku, set out to build a brand new district in the middle of the DH network of Turku, focused on energy-efficient and sustainable building with a focus on low CO₂ energy. The district of Skanssi consists currently of a shopping center and four apartment buildings, with a projected population of around 5000 inhabitants in the future. Turku Energia decided to construct an LTDH area network in the district with a shunt pump connection to the DH network, which, at the time of writing, is the only source of heat to the area. (Lyytikäinen 2021)

The temperature of the network was decided to be a constant 65 °C, to tackle the issue of legionella bacteria in domestic hot water (DHW). The network has been operational since 2018, and due to the short time of operation and ongoing development of the area, no definitive study has been done on the area. The network is estimated to have losses less or equal to the Turku DH network, around 8 % or less. All of the plots are sold to the housing cooperatives with conditions to have reserves for different solutions in the buildings, such as heat pumps and solar collectors. The goal is to create a two-way heat market to the area and have active 'prosumers'. In the market, anyone can produce renewable heat and sell it to the network for a set price. This creates an incentive for housing cooperatives to invest in renewable energy solutions themselves. (Lyytikäinen 2021)

2.4.2 Aarhus (Lystrup), Denmark

The LTDH network in Aarhus, a suburban area in the city of Lystrup, Denmark has been operational since 2010. The LTDH network is connected to 40 low-energy houses and a communal building, all with DHW supply and space heating. (Dalla Rosa 2012; Olsen et al. 2014)

The LTDH network has a shunt connection to an MTDH system. Distribution is achieved by twin-pipes, of which 82 % are plastic pipes and the rest are made of steel. Small dimension piping was chosen and booster pumps were applied to raise the pressure locally. The DHW is only at 45 °C, which raises the concern for legionella, as mentioned in 2.1. The concern is dealt with the small volume approach of DHW, with only 3 liters in volume. Space heating uses a direct connection since the radiators are designed for 55 °C supply and 25 °C return temperature. The network also utilizes substations with 120 l storage tanks and substations with instant heat exchangers. The main characteristics of the network can be found in Table 1. (Olsen et al. 2014)

The main findings of Olsen et al. (2014) include, that a supply temperature of 50 °C is able to satisfy requirements for both DHW preparation and storage heater requirements. Olsen et al. also point out that the network losses are able to remain low despite relatively low heat demand in the network due to low-energy buildings. The heat losses are slightly lower in the area with network heat storage units than in the instantaneous heat exchangers. This, however, is reversed with the heat losses inside the heat storage units. Despite that, heat storage units offer some advantages due to lower peak pressure requirements.

2.4.3 Birmingham (Wednesbury), United Kingdom

North-West of Birmingham is a small, actively managed LTDH system of Wednesbury that has been in operation since 2015. The system provides heat to 24 dwellings and a laundry. The purpose of the network was to prove incorrect the assumptions of need for an over-sized and over-temperature network by applying smart control technology making them as reliable and more competitive than individual gas boilers. The heat is supplied with a single gas boiler and an ATWHP unit. The supply and demand are actively managed to mitigate any distribution constraints: all of the substations and thermostats are connected to the energy center so that they are able to be operated optimally. DHW is low-volume, with only 3 liters maximum at 42 °C. (Cosic 2017)

It turns out, that by active smart management of the consumption and supply, it is possible to achieve a reduction of up to 50 % in installed capacity in comparison to passive networks, while at the same time reducing the overheads and expertise required to operate networks, especially in a small-enough operating environment. It was also concluded, that many existing buildings are able to utilize LTDH, although

some work is required in transient space heating to be able to answer UK customer requirements.

2.4.4 Slough, United Kingdom

Slough is a small, experimental LTDH system that has been operating since 2010. The network that is located west of London supplies heat to 25 residents in 10 dwellings, a total of 845 m². The purpose of the network is to demonstrate renewable energy technologies for low-energy houses. The main characteristics of the network are displayed in table 1. It is possible to supply the heat with a combination of four different production units: a biomass boiler, a ground source heat pump (GSHP), ATWHP, and solar thermal panels. The grid is a single-temperature grid with steel twin pipes for main pipes and AluFlex twin pipes for service piping. The heating systems of each house are directly connected to the DH network without any internal heating systems and DHW is prepared instantly on-demand. (Burzynski et al. 2012)

Burzynski et al. (2012) demonstrate their main findings to be that the supply temperature of 50 °C to 55 °C is sufficient to satisfy the heat demand of the consumption points and that the return temperature was higher than expected, with an initial return temperature of 42 °C. After a number of corrective measures were implemented the return temperature was able to be lowered to a monthly average of 28 °C. It was concluded that the return temperature was sensitive to errors, especially in a small system such as Slough LTDH network. The corrected errors included lowering the DHW setting, restricting water flow through radiators, and other malfunctions and suboptimal settings.

2.4.5 Høje Taastrup (Sønderby), Denmark

Høje Taastrup is the biggest existing LTDH network in this listing, with 75 houses, all built in 1997-1998, connected to the network. The network was built in 2012 to replace an existing MTDH system that was only around 15 years old but had network heat losses of around 38 % to 44 %. The new LTDH system was connected to a larger MTDH network via shunt connection. The network ‘reuses’ heat from the return side of the main MTDH network as primary water in the LTDH network but can also mix water from the supply side to increase the temperature if needed. The system is able to operate with the return water from the MTWDH network at 81 % of the time. In the overhaul of the old MTDH network in the area, the substations in each house were replaced with new ones. The solution implements instantaneous DHW with the small-volume approach, with 3 liters max of DHW in supply pipes. (Olsen 2014 et al.; Christensen et al. 2011)

The main findings of this case study of Olsen et al. (2014) were, that LTDH could be directly applied to underfloor space heating systems in the existing housing by

only replacing the substations. The return temperature was notably high compared to the designed 25 – 30 °C but is expected to be improved by optimizing settings and/or replacing faulty components in consumer substations.

Table 1: Main characteristics of studied existing LTDH systems

Network	Country	Heated area (m ²)	Supply temp(°C) (Design / Meas)	Return temp(°C) (Design / Meas)	DHW temp. (°C)	Distrb. losses (%)
Skanssi (Turku)	FI	354 400 (proj.)	65 / 65	40 / 35 - 47	65	8
Aarhus (Lystrup)	DE	4115	55 / 52.1	30 / 33.7	45	17.9
Slough	UK	845	55 / 51.3	25 / 28	43	N/A
Birmingham (Wednesbury)	UK	1500	55 / 50 - 60	35 / 25 - 35	42	N/A
Høje Tastrup (Sønderby)	DE	11230	55 - 52 / 55	25 - 30 / 40.3	42	14.3

2.5 Heat pumps

2.5.1 Heat pump basics

A heat pump transfers thermal energy from a heat source to another medium that is called a heat reservoir or a heat sink. A heat pump is required when the desired direction of movement of thermal energy between two systems is opposite to the direction of spontaneous heat transfer. In a spontaneous heat transfer heat is trying to reach a temperature equilibrium between systems, as is stated in the 2nd law of thermodynamics. Therefore in a spontaneous heat transfer, a system with a higher temperature transfers heat to a system with a lower one. A heat pump reverses that process by applying work into the process, usually in the form of electrical power. (Hofman 2011)

A heat pump consists of four basic components: evaporator, compressor, condenser, and an expansion valve, where the four main processes of a heat pump take place respectively: evaporation, compression, condensation, and expansion. The thermodynamic cycle of a heat pump consisting of these processes is called the vapor-compression cycle, which is displayed in Figure 1 along with the components and relative pressure and energy levels after each stage of the process. (Hofman 2011)

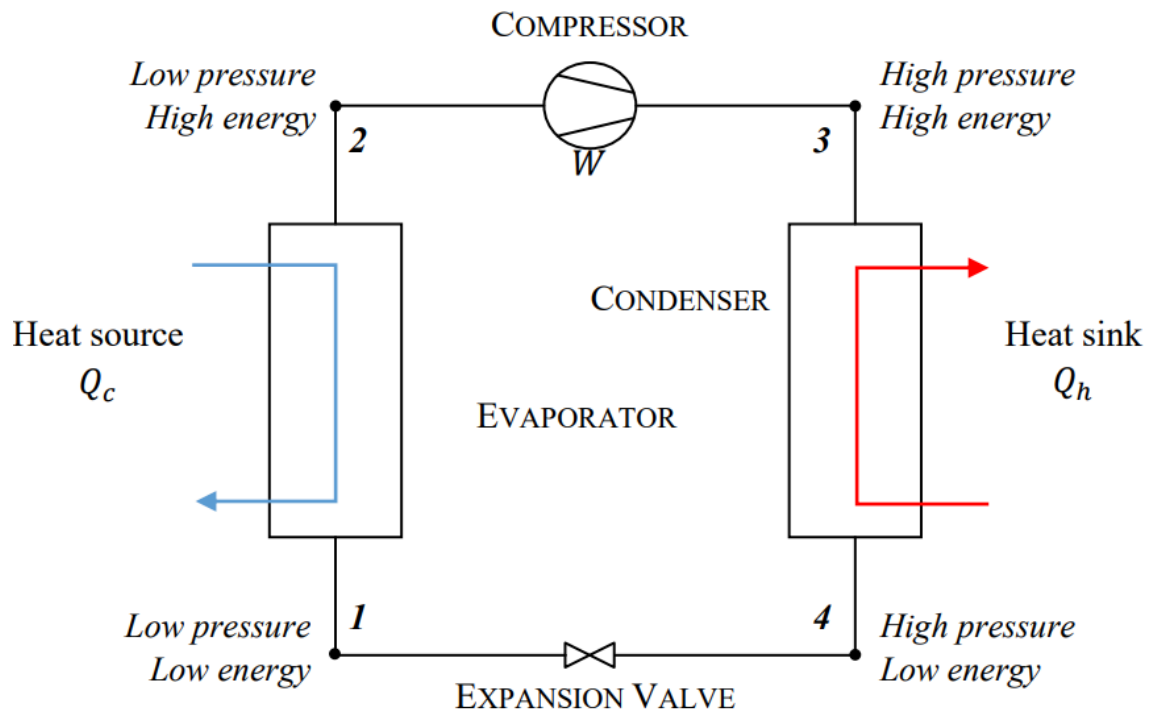


Figure 1: Vapor-compression cycle of a heat pump (Byrne 2013)

The operating principle is as follows: inside the Heat pump, there is a working fluid called the refrigerant. In the first stage of the process, at point 1 in figure 1, the refrigerant is a liquid fluid at a low temperature or a low energy level. In the evaporator, heat is transferred from the warmer heat source to the colder refrigerant which, as a result of the received thermal energy, changes state from liquid to gas resulting in low pressure and high thermal energy in point 2. In the compressor, the refrigerant is subjected to external work that increases its pressure resulting in high energy and high pressure in point 3. After point 3 the refrigerant moves on to the condenser, where the refrigerant, in turn, transfers its thermal energy to the heat sink, heating it and itself changing state back again to liquid form. After this, we have a high pressure, warm temperature liquid refrigerant at point number 4. Finally, the refrigerant moves onto the expansion valve, where the pressure of the liquid is dropped decreasing its temperature resulting again in low pressure and low-temperature refrigerant, from which point the cycle starts again. (Bryne 2013; Hofman 2011)

Heat pumps are often used to be able to utilize various types of low-grade thermal energy sources that are available at a low cost or no cost at all. By low-grade thermal energy source is meant that a heat source offers a notable amount of thermal energy but it is at a low temperature so it cannot be utilized without a heat pump. Most heat pumps can be divided into three categories depending on the source of the heat: air, ground, and water. Air source heat pumps utilize the thermal energy that is stored in the ambient air. Ground source heat pumps absorb the energy stored deep inside the ground. Water source heat pumps can effectively utilize waste heat from different processes that produce warm water, such as cooling processes and municipal sewage water. (Hofman 2011)

2.5.2 Dual-source heat pumps

When utilizing a single source of heat, GSHPs have been shown to be more efficient in heat production compared to air-source heat pumps (ASHP), as is demonstrated by Urchueguía et al. (2008). A GSHP, even though more efficient, requires larger investments compared to an ASHP. ASHP on the other hand offers lower investment costs but has increased operational costs. A reduction in both investment and operational costs would be beneficial for HP systems to be more adaptable and economically feasible solutions. In a heating-dominated solution, a GSHP can be combined with a solar thermal energy system to reduce costs as is shown by Bakarci et al. (2011). When it comes to a heating and cooling solution, a GSHP can be combined with a dry cooler or a cooling tower to provide an additional heat source/sink.

Hybrid systems that implement air and ground as heat sources/sinks have two advantages over other solutions: Firstly, the air heat exchanger is cheaper in comparison and the capacity of the ground source heat exchanger can be drastically reduced

bringing the costs down. Secondly, the operation of the system can be further optimized increasing the seasonable performance of the system. Having the dual-source available right at the heat pump will decrease the costs further and be much more compact than compared to a separate air source heat exchanger as is shown by Corberán et al. (2018). A dual-source principle can be applied to not only GSHP but water-to-water heat pump (WTWHP). A dual-source heat pump (DSHP) can use a cooling network in combination with ambient air as the dual heat sources, and a district heating network and air as two different heat sinks, as is done in the case of this study. With the solution, the heat from the cooling can be utilized in an LTDH network, and any additional heating can be produced with the air source.

2.5.3 Combined heating and cooling

Combined heating and cooling offers a substantial benefit over heating or cooling only. The performance of the HP is improved considerably if both heating and cooling energies are recovered at the same time, as Byrne et al. (2018) show. Ghouali et al. (2014) show that the more need for simultaneous heating and cooling there is, the better the overall performance and lowered costs there are. With these findings, we can also conclude that combining a constant need for cooling and utilizing the produced heat will result in significant benefits to all parties. Thereby a cooling network, that has a constant need for cooling such as different types of industrial processes, connected to a low-temperature district heating network may result in significant upsides compared to separate solutions. (Byrne et al. 2018; Ghouali et al. 2014)

3 Case description, research material and methods

3.1 Case: Aalto Works District

3.1.1 Introduction to Espoo district heating network and Aalto Works district

Espoo DH network is located in the municipalities of Espoo, Kirkkonummi, and Kauniainen and is currently owned and operated by Fortum. The network started from Tapiola, Espoo in 1953 making it the first DH network in Finland that is based on water circulation. Currently, the network covers an area of about 20 by 25 km and has around 840 km of total network length. The momentary heat demand varies from 70 MW summer loads to more than 800 MW loads in cold winters. (Kirjonen 2020) Espoo DH network drawn on a map can be seen in Figure 2.

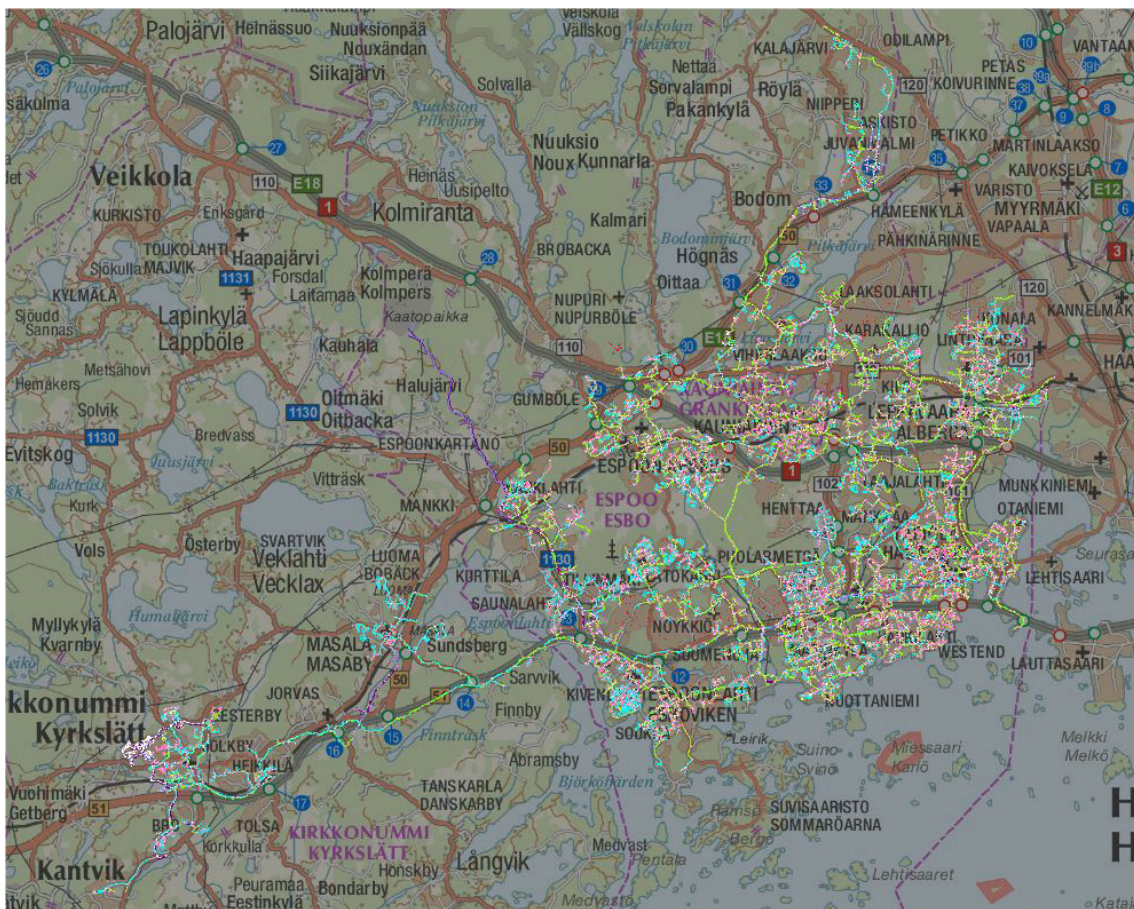


Figure 2: Espoo district heating network (Kirjonen 2020)

Aalto Works district (AWD) can be considered as a semi-independent sub-network

that is part of the Espoo DH network. AWD is located in the Aalto University campus area in Otaniemi, Espoo. AWD Consists of a low-temperature DH network, a district cooling (DC) network, heat production units, and, unlike most DH networks in Finland, the heat exchangers in each building are also owned and operated by the network operator. The network is built and operated by Fortum, but Fortum and Aalto University have agreed on research collaboration regarding the network. There are three existing gas-fired HOB's in Otaniemi in the area of the AWD with a capacity of $120 \text{ MW}_{\text{thermal}}$ with all of the boilers able to be run with light fuel oil as well. The AWD network construction is divided into two phases. The first phase is being built in late 2020 to early 2021 consists of constructing the 'backbone' of the AWD LTDH and DC networks, the heat production site, and connections to the phase 1 buildings. In the second phase, the network is further expanded into existing buildings, new buildings and energy renovated buildings in the area. This thesis focuses on phase 1 buildings because of the available consumption data. The technical concepts of the AWD are further discussed below.

3.1.2 Low-temperature district heating network

The purpose of the LTDH network is to provide space heating to five properties owned by Aalto University. The network is based on the circulation of water running through pipes that vary from DN125 to DN250 in size. The volume of the entire network is roughly 21 m^3 .

The heating of the LTDH is supplied with two DSHP units utilizing the cooling network and air as heat sources, and additional heating can be supplied from the Espoo DH network. The DH network connection comes into play usually on very cold days and during high electricity prices, when the heat pump production is expensive to produce.

Domestic hot water will not be supplied directly by the LTDH network. Due to existing connections to the Espoo DH network, the heat for the need of domestic hot water and its warm water circulation will be provided from heat from the LTDH network primed with heat from the DH network. Therefore there is no need to worry about the forming of legionella bacteria in the DHW circulation of the buildings.

The supply temperature of the LTDH follows the curve displayed in Figure 3. As can be seen, during temperatures below $0 \text{ }^\circ\text{C}$ the supply temperature remains at $+45 \text{ }^\circ\text{C}$, and at temperatures over $0 \text{ }^\circ\text{C}$, the supply temperature falls linearly down to $+35 \text{ }^\circ\text{C}$ at an outside temperature of $+20 \text{ }^\circ\text{C}$. The return temperature of the network is designed to remain at a constant of $+30 \text{ }^\circ\text{C}$.

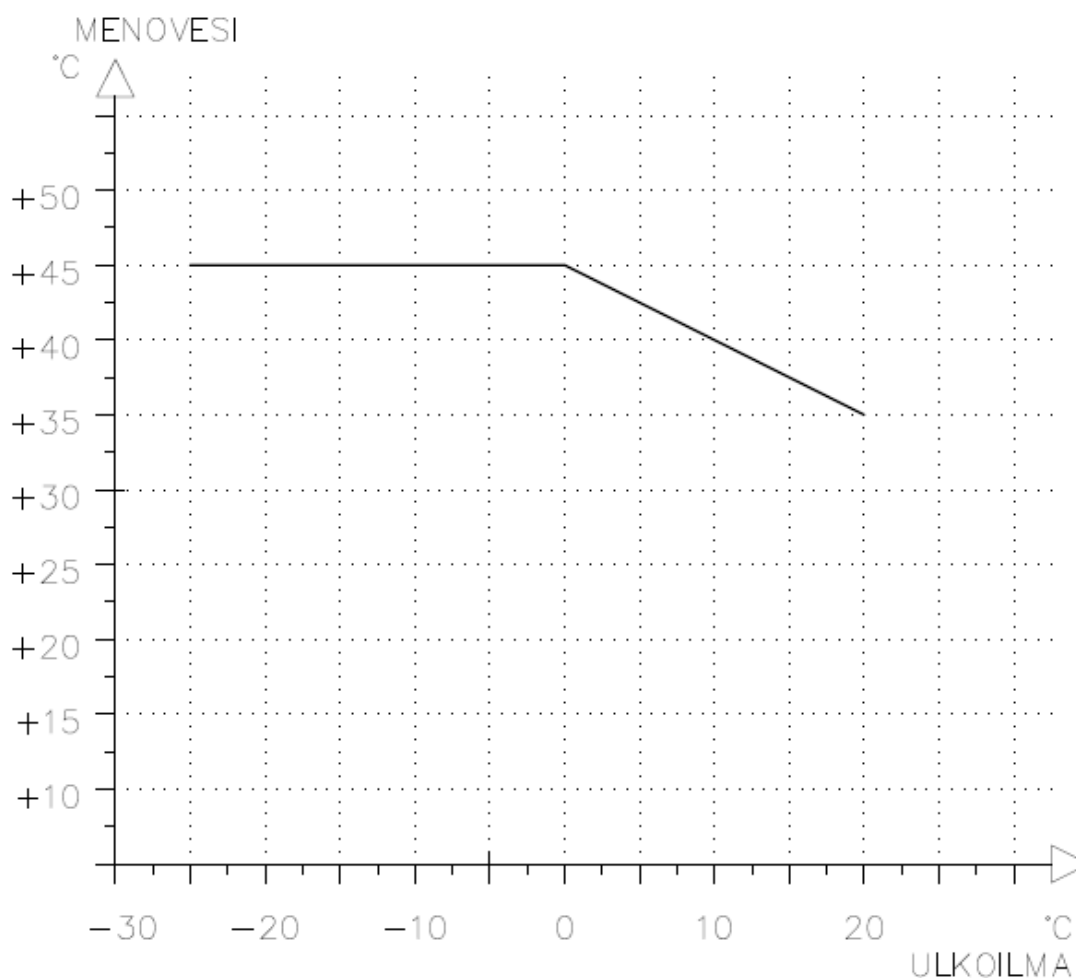


Figure 3: Supply temperature of the LTDH network as a function of outside temperature (Sweco, 2020A)

3.1.3 District cooling network

The district cooling network is built to provide indoor cooling for three of the five buildings that are heated with the LTDH network. In addition, there is a helium production unit connected that requires a constant amount of cooling both in winter and summertime.

The cooling network is based on water circulation through piping. Pipes vary from DN125 to DN250 like in the heating network. The cooling network is a bit larger in volume in comparison to the LTDH network with a total volume of 23 m³.

The cooling is provided with the DSHP with a combined heating and cooling (CHC) operation mode, that condenses the heat from the return side of the cooling network which then can be utilized in heating. The supply temperatures, which can be seen in Figure 4, vary from +10 °C during cold outside temperatures when cooling is not

needed as much, to $+8\text{ }^{\circ}\text{C}$ during warmer temperatures when cooling has a higher demand. The return temperature is designed to remain constant at $+16\text{ }^{\circ}\text{C}$.

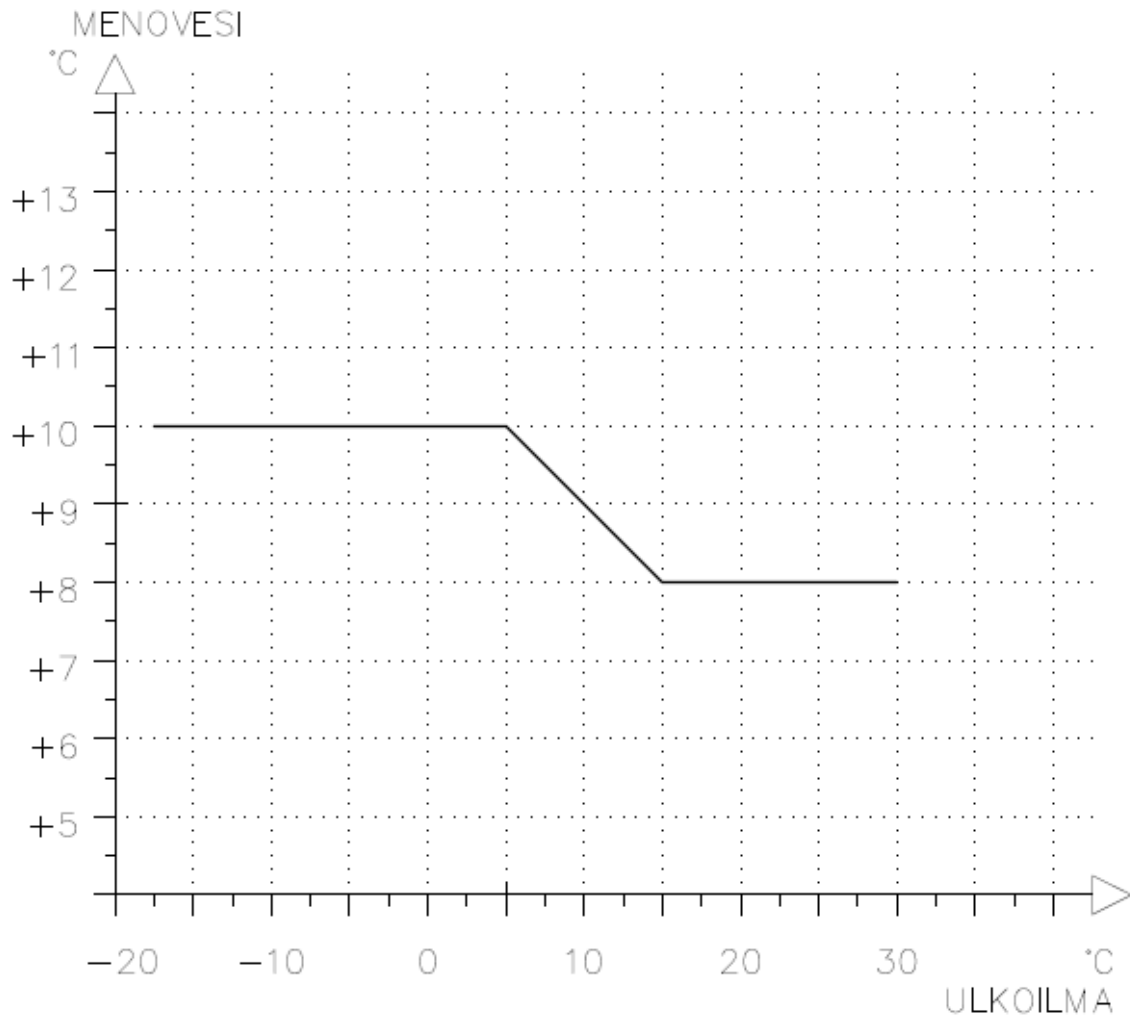


Figure 4: Supply temperature of the cooling network as a function of outside temperature (Sweco, 2020A))

3.1.4 Consumption points

There are a total of five consumption points connected to the LTDH network and the DC network in the first phase. These buildings consist mostly of office spaces and lecture halls that are used mostly during office hours. No residential dwellings are included.

One of the buildings has a helium production unit and other types of processes that are running around the clock. These processes require a steady amount of constant cooling of around 200 kW, which is a substantial amount of condensed heat produced when compared to the total heat demand of the AWD.

3.1.5 Dual-source heat pump units

There are two identical DSHP units installed in the AWD district. The heat pumps are deployed in the same site as the existing heating plant in Otaniemi. The function of the DSHP units is to produce the required cooling to the district cooling network and heat to the LTDH network with the condensing heat and provide additional heat using air as a heat source. If there is no need for cooling, the heat pump will continue to pump heat from surrounding air if demand for heat still exists. (Sweco 2020)

The heat pumps are installed to operate as a couple by the heat pump supplier and a controller is installed to ensure that the supply temperature of both the district heating and cooling water is achieved and the compressors of the pumps are operated optimally. The HP system is required to be scalable by up to double the power to be installed in phase 2. (Sweco 2020)

The heat pumps have three different operation modes. They are able to operate as a cooling-only unit by condensing the produced heat into the surrounding air, as a CHC HP where the condensed heat is pumped into the LTDH network and provide any additional heat required from the air source up to the installed capacity, or operate in a heating-only-mode, where the required heat is taken only from outside air without producing any cooling. The two HP units can also be simultaneously operated with different modes. For example, if there is a greater need for heating than there is for cooling, the other heat pump can utilize two heat sources (air and cooling network), while the other operates with heating-only mode. (Sweco 2020)

3.1.6 Connection to Espoo district heating network

All five consumption points have an existing connection to the Espoo DH network. Therefore the DH network acts as a tool for the security of supply during a possible malfunction of own heat pump (HP) based production, and during colder hours with high demand and inefficient production. There is in this case no need for a physical connection between the AWD LTDH network and the Espoo DH network. Though it is not in the scope of this study, it should be mentioned that in phase 2 of the AWD the consumption points will include new buildings with no existing connections. In a case where the consumption points have no direct connection to the DH network, it could be the most cost-effective to create a heat exchanger between the DH and LTDH network to provide additional heating when needed or rely only on local production.

Currently, it isn't included in the plans to have a possibility to transfer the heat from the LTDH network to the Espoo DH network but to leave a reservation for such technology. This can be achieved with a water-to-water heat pump. Such a heat pump would have to pump the heat from the LTDH supply temperature of 45 °C

to either return or supply side of the DH network. Pumping the heat to the return side, around 60 °C on average, would make the HP operate at a COP of around 3.3. Increasing the supply temperature of the HP up to the supply side of the DH network, up to 80 °C would decrease the COP of the HP to around 2. (Lintu 2020) While this decrease in COP is significant, it could be more beneficial considering the entire DH network not to heat the return side of the DH network in a larger scale with multiple HPs connected to the return side: the efficiency of CHP units decreases with the increase of the supply temperature due to boilers' reduced ability to condense heat. In this study, we will use a COP of 3.3 supposing the connection is created to the return side since the volume is small having little or no impact on the performance of Espoo DH network CHP units.

3.1.7 Energy storage option

There is no energy storage option going to be implemented in phase 1. Even though it is decided, the benefits of such a solution are a subject of interest in the study. In the Otaniemi HOB plant area, there is an oil container with a volume of 1500 m³ that can provide oil as a secondary fuel for the Otaniemi HOB and act as mandatory security of supply oil storage regulated by law. If the oil container would be refitted into a heat accumulator, it could increase the self-sufficiency of the AWD network and decrease operating costs. The capacity of the accumulator can be calculated as follows:

$$Q_{accumulator} = \Delta t * V_{accumulator} * c_{p,water} * \rho_{water} \quad (2)$$

Where, Δt is the temperature difference of the supply and return water, $V_{accumulator}$ is the volume of the accumulator, $c_{p,water}$ is the specific heat capacity of water, and ρ_{water} is the density of water. This gives us the thermal energy capacity of the accumulator in Joule. We can transform it into Watt-hours by multiplying it with 1/3600, which gives us then:

$$Q_{accumulator} = \Delta t * V_{accumulator} * c_{p,water} * \rho_{water} * \frac{1}{3600} \quad (3)$$

The regular operating supply temperature of the heat pump units is 45 °C and the maximum supply temperature of the ATWHP is around 60 °C and the return temperature is at a constant 30 °C. This gives us the temperature difference of 15 – 25 °C and with that, the capacity of the oil storage unit as a heat accumulator can vary from 26 to 52 MWh, which corresponds to 35 to 71 hours worth of heat with an average consumption of 730 kW, and even up to 8 to 17 hours worth of heating during highest heat demand hour during 2017 to 2019 of around 3.1 MW of thermal power.

3.1.8 Network flexibility

Besides a 'conventional' heat accumulator there is an additional way of providing flexibility that doesn't require any extra investment. The ATWHPs are able to pump heat to a higher temperature than the +45 °C of the supply network, all the way up to +60 °C. During low demand hours, it is possible to increase the temperature of the entire network, making the network act as an accumulator.

When considering the entire volume of the network to act as a battery, the capacity of the heat that can be accumulated to the network can be calculated with the same formula as the oil container heat accumulator. With this, we get the 21 m³ network to be able to accumulate an additional 365 kWh in the network itself. This is not a substantial capacity compared to the heat accumulator option, but should be noted that it is completely investment free and could possibly provide the flexibility that can decrease costs in hour-to-hour level operation if used optimally and therefore worth investigating.

3.2 Modelling with MONA

3.2.1 Initial Excel model

As a kind of proof-of-concept, the AWD LTDH consumption and production was modeled in Microsoft Excel and compared to Espoo DH network realized production costs based on historical hourly data on realized from 8th February 2017 to the end of the year 2019. The realized Energy Cost Index (ECI) (production cost of produced heat before VAT) from that period was fetched from FRED, the realized electricity spot prices from Nordpool's website (Nordpool N/D), the consumption data of the phase 1 consumption points from Fortum's own data storages and the ambient temperature data in Tapiola, which is close to Otaniemi, from the Finnish Meteorological Institute data bank (Finnish Meteorological Institute N/D). Modelling of the heat produced from cooling and additional heat from ATWHP is described more in detail in 3.3.2.

$$ECI = \frac{Costs}{Q_{ATW}}, \quad (4)$$

where Q_{ATW} is heat produced with the ATWHP. Costs are operational costs without VAT, and they consist of taxes (c_{tax}), transmission costs (c_{trans}), and electricity power price, which is Nordpool spot price in the model (c_{elspot}). Therefore we get:

$$\begin{aligned} & \frac{P_{ATW}}{Q_{ATW}} * (c_{tax} + c_{trans} + c_{elspot}) \\ &= \frac{P_{ATW}}{P_{AWT}} * COP_{ATW}(t) * (c_{tax} + c_{trans} + c_{elspot}), \end{aligned} \quad (5)$$

Where P_{ATW} is the electrical power used in the ATWHP unit and $COP_{ATW}(t)$ is the coefficient of performance for the air-source operation mode as a function of ambient temperature. Let's further note that:

$$c_{tax} + c_{trans} + c_{elspot} = c_{costs} \quad (6)$$

Now we can simplify to:

$$ECI_{ATW} = \frac{c_{costs}}{COP_{ATW}} \quad (7)$$

And likewise for the heat produced in the CHC process:

$$ECI_{CHC} = \frac{c_{costs}}{COP_{CHC}} \quad (8)$$

When the ECI of the Espoo DH network from the time period was known and the ECI of the DSHP production calculated, the production costs for the known demand volumes for the LTDH network were calculated so that the model would always prefer the cheapest option first. This meant that the required must-run CHC was first utilized. Then when the additional ASHP production was cheaper than the Espoo DH ECI, it would first utilize the entire available capacity of the HP before transferring heat from the DH network to the AWD LTDH network. The ASHP production was limited according to outside temperature as described in 3.3.2. but no limitation or cost to heat transfer to the AWD network from the Espoo DH network side were implemented. With those the AWD production was modeled for the time period resulting in production curve shown in Figure 5.

From the figure 5 we can see that heat from the Espoo DH network is utilized in the winter. For around half a year, there seems to be excess heat from heat recycling from the CHC network, that is not utilized at all. In addition, there are hours when the ATWHP has excess capacity that is cheaper than the production of the Espoo DH network, but it is not utilized. This is shown in Figure 6.

From the initial simulation, we get a self-sufficiency percentage of around 79 %, which exceeds the required 70 % by a fair percentage. This suggests that we are able to focus on optimizing the production costs of the LTDH by optimizing the usage of heat pumps. As can be seen from Figure 6, there is a lot of HP capacity that is unutilized, even when beneficial. By introducing flexibility in a form of heat storage, network flexibility, or a possibility to utilize the heat elsewhere we could increase the value creation of the LTDH network. It is important to note that this simulation does not give accurate results, but an indication towards where value could be created for the upcoming research later in the study.

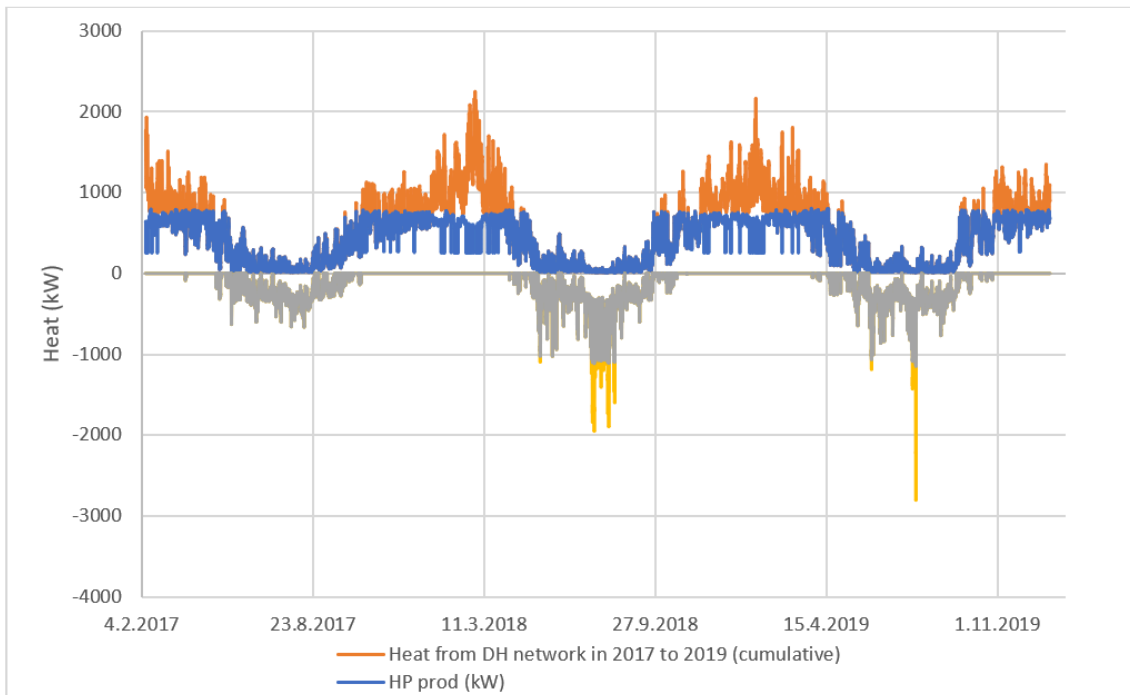


Figure 5: Excel simulated AWD Heat production and heat from DH network from 2017 to 2019

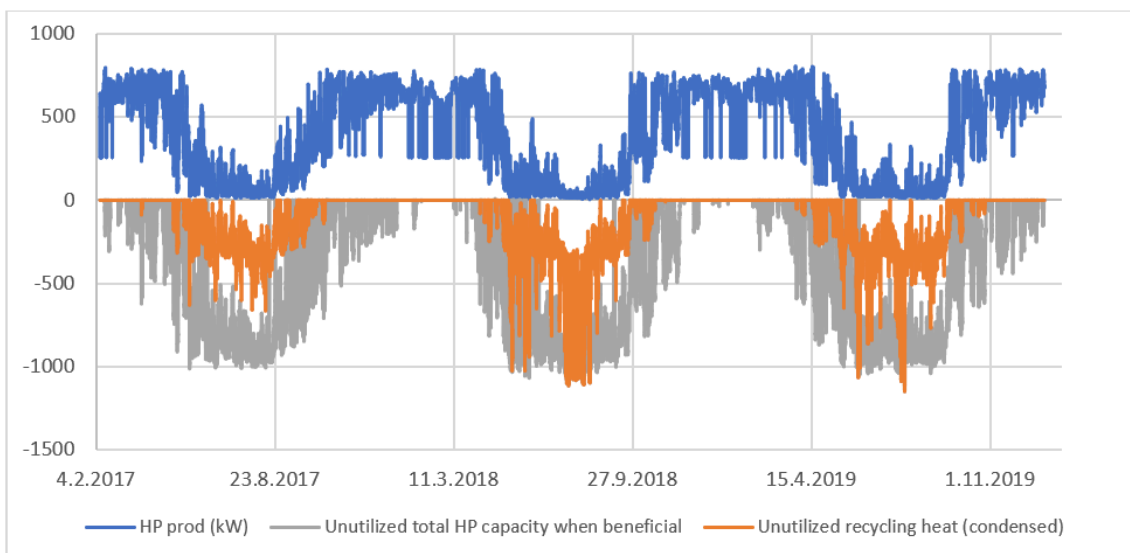


Figure 6: Excel simulated heat pump production and unutilized beneficial capacity

3.2.2 MONA in general

MONA is an in-house product created by Fortum that is developed to answer the need for efficient and accurate modelling of the district heating business. MONA makes it easier for people with expertise in the areas of energy systems but limited

knowledge on linear programming and optimization to create and understand complex optimization models without ever seeing or writing a single line of code. MONA has a drag 'n drop type of user interface that generates the model into GAMS (General Algebraic Modelling System) optimization program. GAMS is a modelling system designed for mathematical optimization, with which its possible to solve linear, non-linear, and mixed-integer linear optimization programs. GAMS is a natural choice for MONA as the optimization system since it is well-tailored to solve large-scale and complex optimization problems. Because of the graphical user interface, the models are more accessible and can be enhanced and edited by almost anyone with just a little bit of training on MONA's basic principles and operation. Due to its versatility, MONA can be utilized in a lot of different types of optimization and modelling scenarios in the DH business and systems. (Laakso J. 2020)

MONA models are most commonly used for short-term production optimization of Fortum's district heating systems. The MONA models are connected to a wider framework called FRED that is further discussed below. From FRED the model is given required inputs, such as weather, production, and electricity price forecasts. The MONA model then optimizes the production of the modeled assets to maximize economic value creation. The real-life assets' production is then planned and operated accordingly. Production model parameters and inputs are continuously being updated, improved and the optimization results validated to ensure ongoing development and adjustments to changes. (Laakso J. 2020)

MONA is equipped with a server-based version management system. All users can check out and check in models to be updated, or download them locally to their own devices if needed. MONA also has user component libraries, where it is possible to share more complex modeled components easily without having to always model each individual part of the system separately. When wanting to tinker with inputs and parameters, users are easily able to download up-to-date inputs from FRED and then adjust the parameters to their need locally, without having to affect the production model. (Laakso J. 2020)

In addition to short-term optimization, MONA is able to run longer time frame models. With MONA it is possible to calculate long-term forecasts and investment analyses for a scale of many years, with an hourly or daily resolution. MONA is being used to calculate financial mid-term and long-term forecasts for Finland and is being looked to expand into other heating business areas. In this thesis, MONA will be utilized to simulate and optimize the AWD heat production.

There are many benefits in expanding MONA models into system-level modelling, but mainly two: centralization and model quality. The models are created by experts as a collaborative effort resulting in a highly accurate model. The models are updated centrally and their performance is evaluated continuously by comparing their results to realized production. (Laakso J. 2020)

Centralization offers many benefits. A large company like Fortum benefits from

having all the modelling in a business area in one place. Since there are a number of people that need access to the modelling and its results they are readily available for anyone anywhere. Due to the server-based version management system, people are able to access up-to-date models with all the relevant data in hand and run the models locally on their computer or online in FRED. When all the calculations from short-term optimization to long-term forecasting and investment analysis are done with the same models, assumptions, and dynamics, the results are easily comparable and in line with each other. This also results that no parallel systems need to be maintained, making it more efficient. (Laakso J. 2020)

MONA models are built to optimize the production side of the DH system. The models include the power and heat production processes from fuel input to energy output. DH distribution network modelling is not supported – the heat consumer side is simplified as a single consumption vector, making the forecasts rather heat production forecasts than heat consumption forecasts. MONA supports currently hourly and daily resolutions in optimization schemes, of which the hourly is usually utilized in short to mid-term optimization – roughly with a time frame from less than a week to a month. The daily resolution is utilized in mid to long-term optimization, with time frames from a month to even tens of years. (Laakso J. 2020)

3.2.3 FRED in general

FRED stands for Framework for Energy Dynamics. It is a framework that is built as a microservice platform to be utilized in Fortum’s district heating and cooling business’ in different countries. FRED was developed by the Fortum City Solutions System Optimization System project in collaboration with different experts from the Fortum City Solutions division, Fortum eNext, and various developers from external agencies. The need to develop an in-house solution arose due to no existing commercial solutions being available to fit Fortum’s future vision and strategy. In the long term, the goal is that FRED would optimize and automatically operate the whole district heating and cooling system, including distribution networks, short and long term heat storages, the demand-side response of the entire consumer side, and of course the heating and cooling itself that are produced by utilizing heat pumps and renewable energy sources. The whole platform aims to minimize expenses and GHG emissions. Fred is currently in use in 6 countries: Finland, Estonia, Latvia, Lithuania, Poland, and Norway, some with multiple different DH systems utilizing it. (Laakso J. 2020)

As mentioned above, FRED is built as a microservice platform: there are currently multiple applications in use in FRED, and more are continuously developed. These applications include but are not limited to short and long term heat production planning, post-optimal comparison of realized DH production to evaluate the success of the production planning and execution, an analysis tool for creating and comparing ad hoc scenarios for different purposes such as sensitivity analysis of different produc-

tion interruptions and natural gas tariff-based energy and transmission purchases, an operations application for electricity spot bidding and solid fuel short term and long term delivery and logistics planning, and demand-side response optimization and execution for Espoo DH network with Fortum Spring and Leanheat. FRED also has tools for forecasting sales margins for short and long term and planning and timing maintenance breaks for production units.

FRED connects MONA models with all the parameters that are relevant to production optimization, such as DH production forecasts, electricity price forecasts, CO₂ pricing, and technical restrictions for production. The model is then run in MONA with the GAMS engine, and the results are then fed back into FRED, which then creates a predetermined type of report from the results. For example, in a short-term forecasting report, multiple graphs show past and future data on the weather, realized and forecasted production from the MONA optimization, electricity prices, heat accumulator operation, DSR (Demand-Side Response) plan, fuel consumptions and a lot more. An example of short-term production optimization and past realized production in Espoo can be seen in Figure 7.

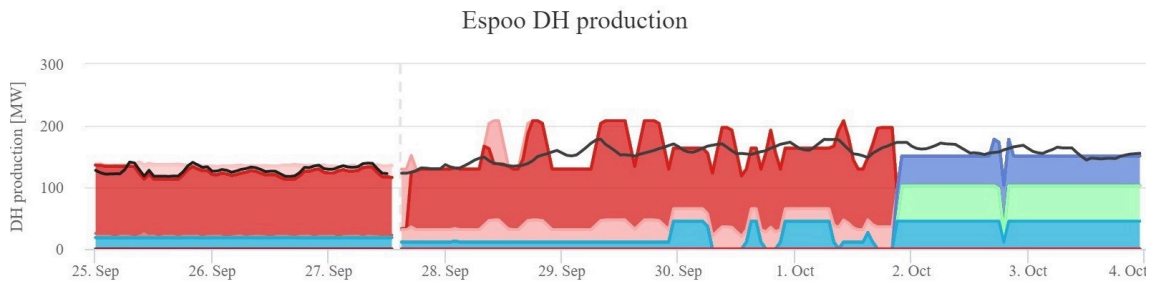


Figure 7: FRED realized (left) and forecasted (right) production in Espoo.

3.2.4 MONA modelling in practice

As mentioned above, MONA is operated using a graphical interface. The model is composed of pre-created user components from existing component libraries, with also the ability to edit the existing user components and create their own components. An example of a MONA model is displayed in Figure 8. The user components are modeled parts of the DH system. Typical user components include components such as fuel supply, a boiler and a turbine of a power plant, a heat pump, heat demand components, electricity and heat trading modules, heat storages, emission components, and an objective function component. The goal is that every DH system would be possible to be modeled with accuracy using only these existing user components. As mentioned above, if none of the existing components meet the requirements of the model, it is always possible to modify existing ones or create one totally from scratch. The component libraries are continuously developed and updated by MONA administrators and developers.

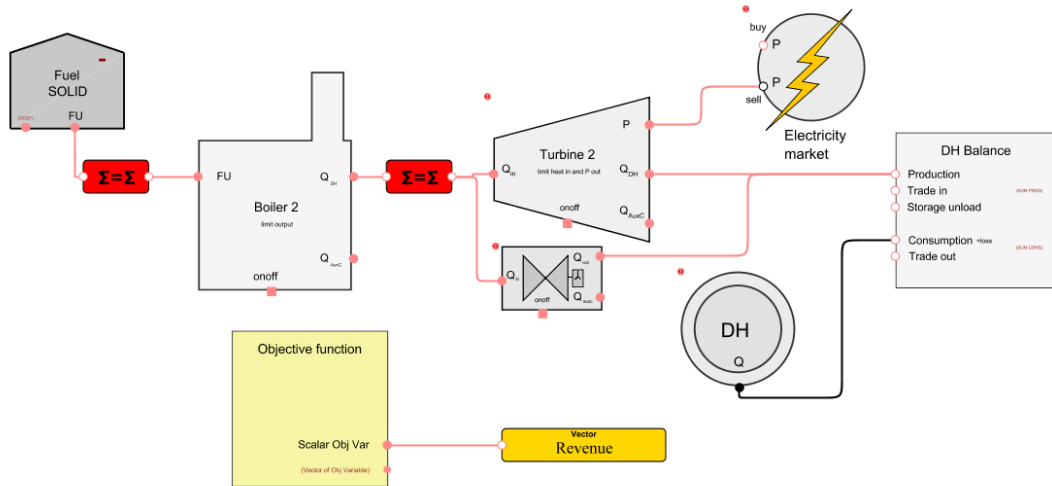


Figure 8: Example of a MONA model

Components are connected with lines that represent interactions between the components as can be seen in Figure 8. The connections can also include operators, such as arithmetic operators, comparison and logical operators, and equations. There are also expressions, which can be constant, get their values from a time-series or calculated from them, and global and local variables. Global variables are common throughout the entire model and they can be scalar or vector types of data, whereas local variables are active only in the part of the model in question but can be defined as an integer, binary, scalar, or vector type. In Figure 9 a snapshot of an inside of a gas turbine model is displayed. There can be seen both expressions (in blue) and variables (in red) and arithmetics between them. By using these different objects and operators it is possible to define any MILP or LP (linear program) just like writing it in code.

The models are run with input values, that can be downloaded from FRED or defined by the user. These values include all the parameters that the model needs such as financial information like power and fuel prices, heat demand, and technical specifications of different components. The data can be easily viewed and modified by the user in a tabular form.

The model created with the graphical interface along with the input model is converted into a text-based GAMS model and input file in MONA, which is then solved in the GAMS system. Results of the optimization are in text form, which is again converted into a graphical and tabular form in MONA for easier reviewing of the results. The GAMS is meant to only run in the backend of MONA. However, the text version of the model along with the other text-based files can be accessed by the user if need be.

Because of the graphical interface in MONA, the results can be easily reviewed. A user can select individual components, connections, variables parameters, and logical operators to see trend graphs on how the value of the object or connection behaved over the calculated steps. Additionally, it is possible to plot multiple variables into a single graph. The results can also be exported from the output table and analyzed in a different program, for example, Microsoft Excel if desired. All of this makes inspecting the model and its behavior fast and easy.

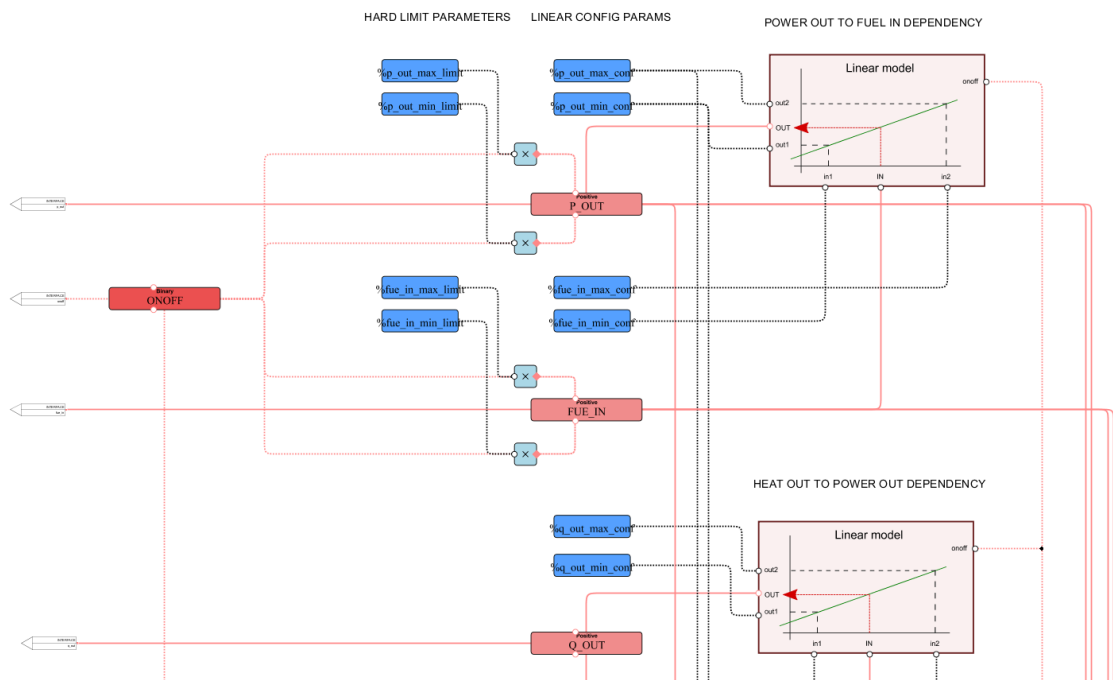


Figure 9: Example of a MONA model

3.2.5 AWD Heat demand modelling

To be able to run simulations of the AWD energy system, it is required to know the heating and cooling demand in the buildings connected to the energy grid. The Espoo model is based on heat production, therefore we need to be able to model both the heat demand and the effect the cooling has on heat production.

The Espoo heat production forecast model is based on a recurring neural network, that takes outside temperature, solar radiation, precipitation, and social aspect, such as weekday, time, possible holidays, as inputs. This model comes up with a single number that represents the required production of each hour of the day in the whole Espoo DH network area. Therefore the existing forecast cannot be applied to the AWD heat demand but there is a need to come up with a new demand model instead.

As it is not the main focus of this study, a simple heat and cooling demand model of the AWD is sufficient. According to Dotzauer (2002), heat demand can be modeled

according to historical data, based on outside temperature and the social component. The buildings in AWD have been connected to the Espoo DH network for a long time. Therefore there is hourly consumption data available for multiple years. By taking the hourly consumption data for three years provided by Fortum, from the start of 2017 to 2019 and combining each hour to the historical temperature data of the Tapiola, Espoo weather station from the Finnish Meteorological Institute website (N/D) we are able to plot Figure 10.

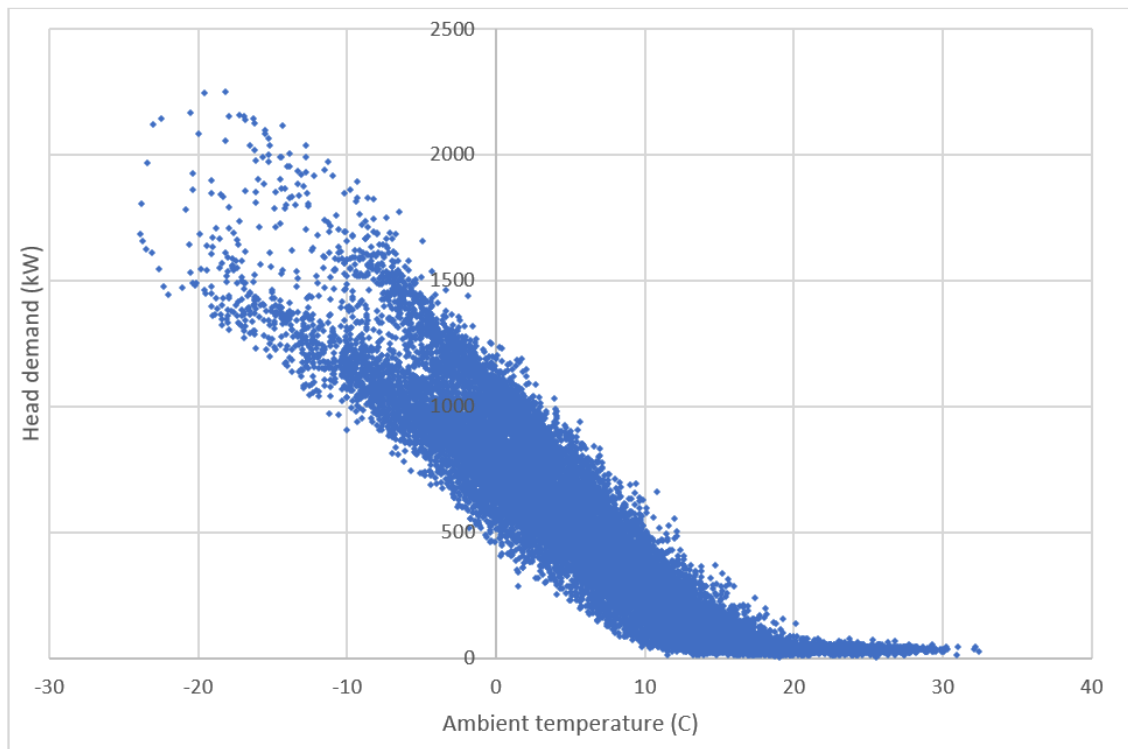


Figure 10: AWD building heat demand as a function of outside temperature

Even though Dotzauer (2002) states that: “It is obvious that the temperature dependence (of the DH network load) is non-linear.” (Dotzauer 2002) and can be modeled rather as a piecewise linear function, Figure 10 suggests that the load model could be divided into two different linear functions.

Firstly, there is the minimum demand. The minimum demand represents the continuous hot water circulation: The domestic water needs to be kept warm so that heated up water is available at all times. From the Figure we see that this minimum is achieved at around 20 °C. By further examining the data and Figure 10, we find that the demand at temperatures of 20 °C and above averages around 45 kW. Thereby it is sufficient to simplify that the demand is at a constant of 45 MW at outside temperatures of 20 °C and more.

Secondly, the heat demand at temperatures below 20 °Celsius seems to vary by up to almost 1000 kW within a recorded temperature level. According to Dotzauer

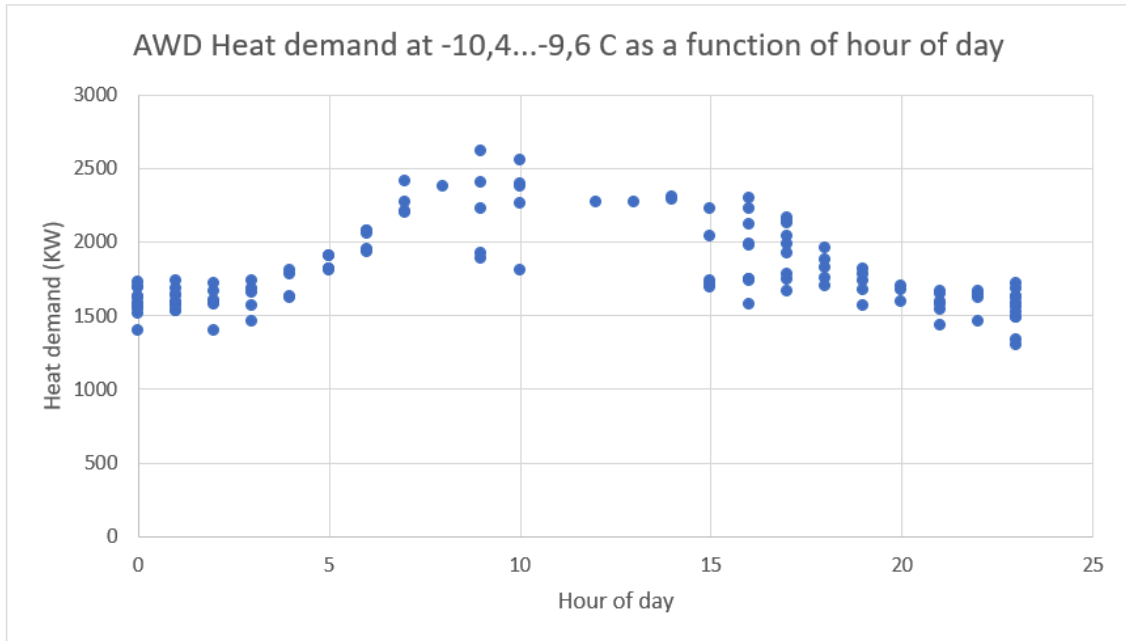


Figure 11: AWD heat demand at -10.4...-9.6 °C as a function of hour of day

(2002), this could be explained by the social component of heat demand. The social component takes into account the time of day, i.e. whether it is working hours or night, holidays, etc. By examining Figures 11, 12 and 13 we see that there is great variance within the time of day also in almost constant temperatures. The social component seems to clearly increase the demand during working hours, but the increase is not so dramatic and has such variance, that for the purposes of this study the demand can be simplified to consider only the outside temperature.

Further examining the AWD building heat demands at temperatures at below +20 Celsius we see that we can get an average heat demand at a certain temperature level by drawing a linear trend line from the measured heat demands. The trend line, which can be seen in Figure 14, gives us a linear function displayed in equation 9 where the average heat demand at a given temperature can be calculated. With the function we can form a function for AWD heat demand as follows:

$$D_{heat}(t) = \max \begin{cases} -66.128t + 1170.2 \\ 45 \end{cases} \quad (9)$$

3.2.6 Cooling demand modelling

The Espoo MONA model focuses solely on DH production simulation and optimization since district cooling in Espoo is very small in volume in comparison to heating

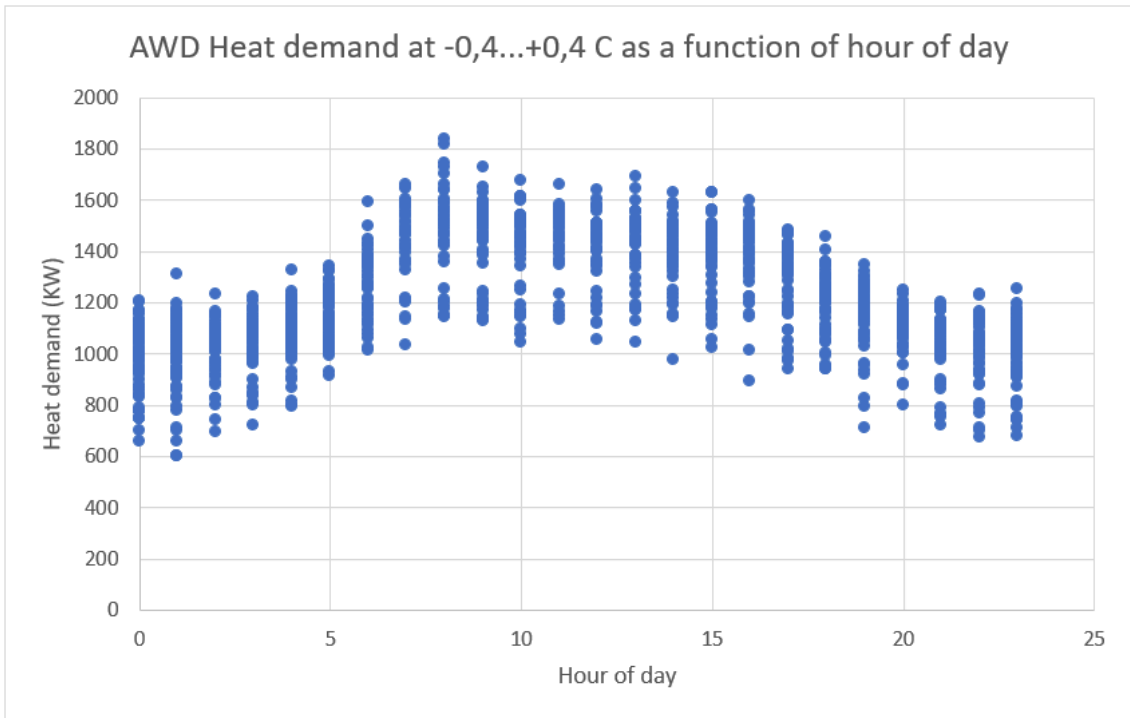


Figure 12: AWD heat demand at -0.4...+0.4 °C as a function of hour of day

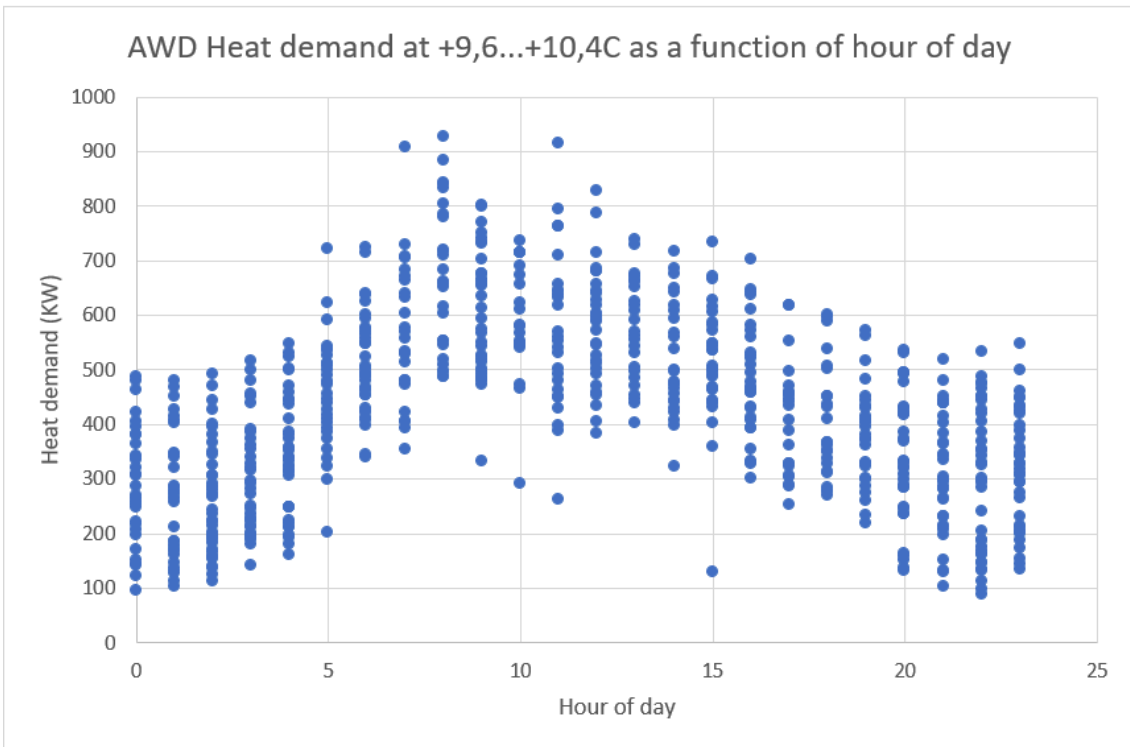


Figure 13: AWD heat demand at +9.6...+10.4 °C as a function of hour of day

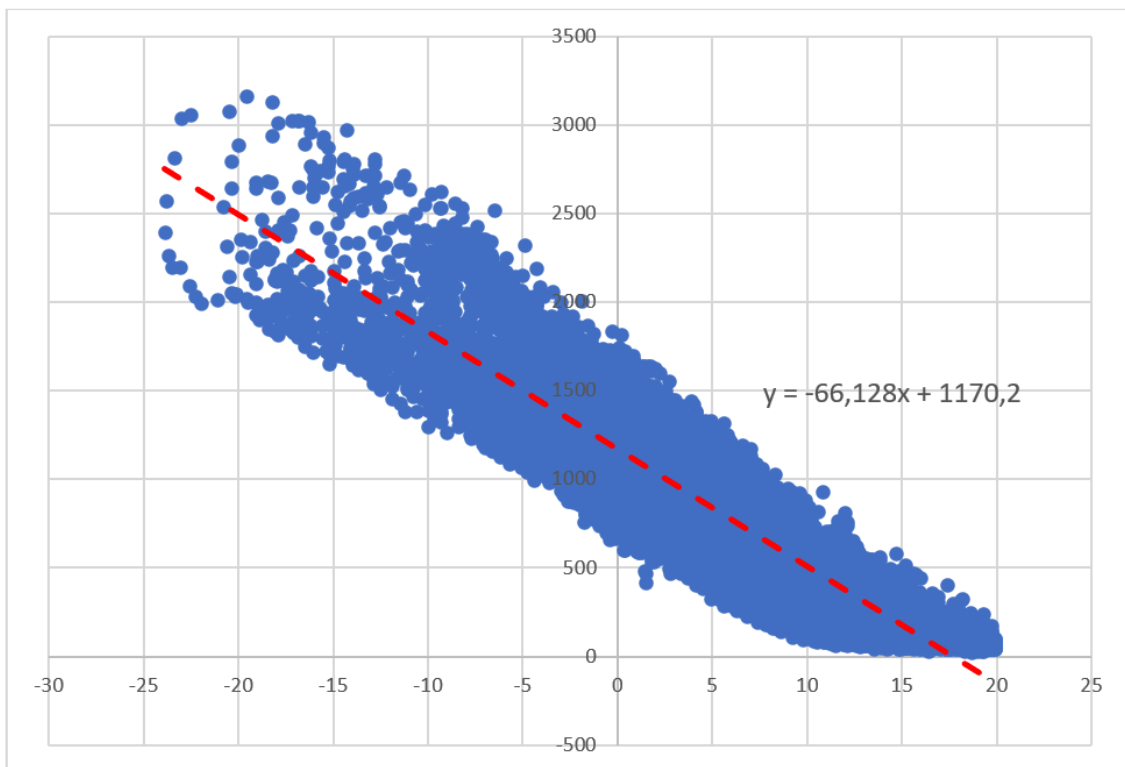


Figure 14: AWD heat demand trend curve at temperatures below +20 °C

making it uninteresting to optimize in its current extent. In AWD's case, the cooling demand is much more significant in comparison to heat and has a big impact on the functionality of the entire energy network and its optimal operation and therefore cannot be disregarded.

Fortunately, it is not necessary to model the cooling network as an individual network, but rather only model its impacts on the heating side. The heat from the return pipe in the cooling network is pumped from the water with the CHCHP so the produced condensing heat is a must-run type of production, and can be utilized in the heating side or condensed to air. The cooling produces heat with a COP of 3.45 which means that 1 kW of electrical power produces 3.45 kW of heat from the cooling network to be utilized (Lintu, 2020). More on the possibilities of the utilization produced heat below.

Since there is no existing cooling on the properties, except for the helium production unit, an assumption of the cooling demand has to be created. Sweco provided a theoretical duration curve for the cooling demand, which can be seen in Figure 15. The plotted cooling does not include the helium production unit and other constant processes, which have a total constant cooling demand of 200 kW, which has to be included in the final calculations.

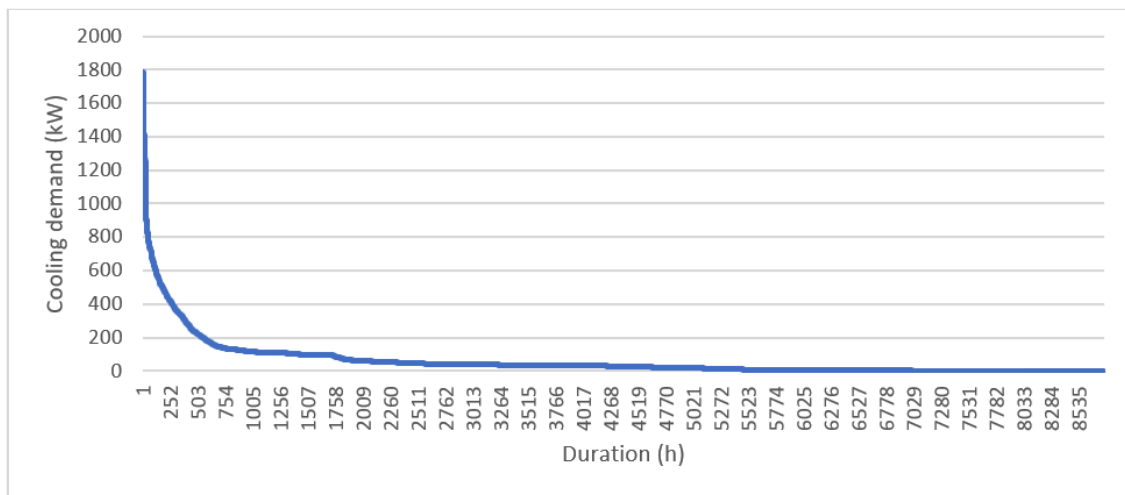


Figure 15: Aalto Works District cooling demand duration curve (Sweco 2020C)

With the cooling demand duration curve, we can create a temperature-dependent cooling demand curve, by creating a temperature duration curve from historical data from the Finnish Meteorological Institute data bank (Finnish Meteorological Institute N/D) for average temperatures for the past 5 years, and connecting those temperatures to each value of the duration curve, with the helium production added, we get the temperature dependence displayed in Figure 16.

The Figure seems unintuitive because of the the exponential growth at higher temperatures. This is supposedly because of the duration curve used in the method.

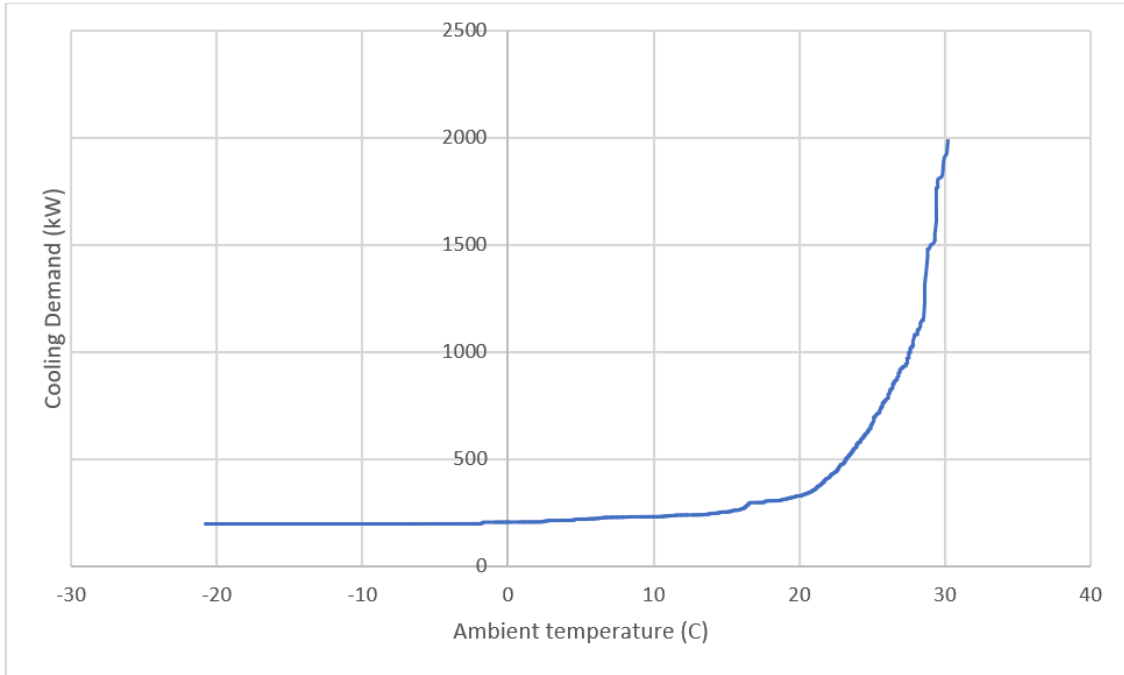


Figure 16: AWD Cooling demand as a function of ambient temperature

Since the highest cooling power the HP units can provide is 800 kW, which eliminates most of the exponential increase in demand, we can continue this figure for the sake of this research. Apart from that the cooling demand seems to imitate reality intuitively. Since room temperatures are usually around +20 °C there is little demand for additional cooling at temperatures below that. At temperatures roughly above +20 °C the demand for cooling seems to exponentially increase as discussed above. Similar to the heating demand, the cooling demand can be divided into a piecewise function. Firstly, the cooling demand in temperatures at 0 °C and below seem to be constant at 200 kW. Secondly, the demand from 0 °C to 20 °C seems to follow a somewhat linear dependency. By fitting a linear trend line to the data points we get the demand function depicted in Figure 17. Third, the demand from +20 °C above seems to increase exponentially. By fitting an exponential curve to the demand data points we get an exponential dependency function that gives feasible results in the scope of interest. The data and the exponential trend line functions are shown in Figure 18.

By combining the cooling demand functions with the restriction of maximum cooling capacity of 800 kW we can formulate an estimate for cooling production as a function of outside temperature:

$$Q_{cooling}(t) = \begin{cases} 200 & t \leq 0 \\ 4.674t + 200.08 & 0 \leq t \leq 20 \\ 12.2805 * e^{0.1588t} & 20 \leq t \\ 800 & t \geq 26 \end{cases} \quad (10)$$

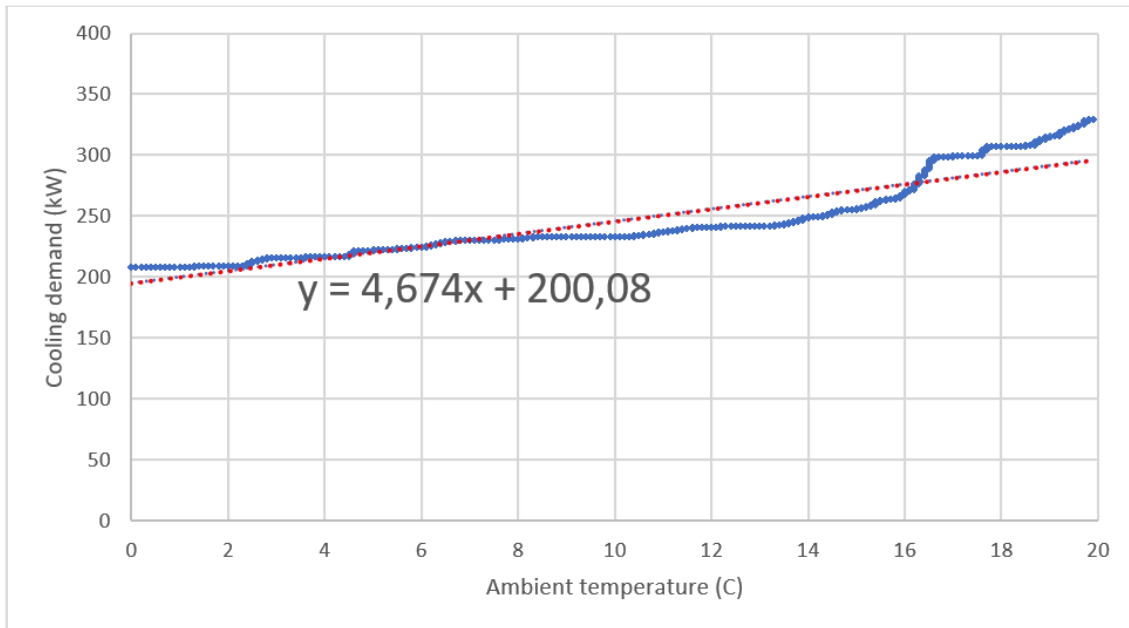


Figure 17: AWD Cooling demand at from 0 C to +20 C with trendline

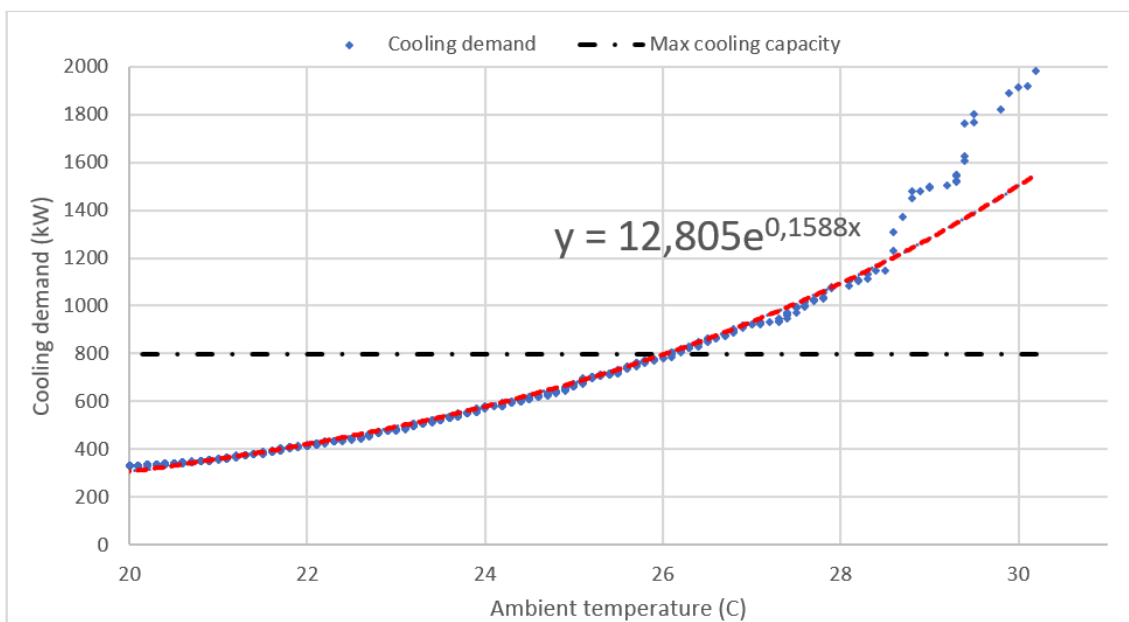


Figure 18: AWD Cooling demand at temperatures above +20 C

Where D_{cooling} is the cooling demand in kW, that produces heat with COP of 3.4 and t is the ambient temperature in centigrade.

3.3 AWD MONA model

3.3.1 AWD Linear program

In MONA the linear program is created with the graphical user interface. The model consists of 7 decision variables, all vector form. No other form of variables, integer or binary, were needed. The basic AW MONA model variables (without their constraints) can be formulated into a simplified linear program as follows:

$$\begin{aligned} \min \sum f(\hat{x}_{step}) \\ s.t. \\ Q_{ATW} + Q_{CHC} + Q_{\text{cond to air}} = Q_{\text{HP to AW}} \\ Q_{\text{HP to AW}} + Q_{\text{DH to AW}} = Q_{\text{AW demand}} \end{aligned}$$

Where $f(x)$ is the cost function with AWD costs added to Espoo DH network costs with the input values x at each step, Q_{ATW} is the heat produced with the air to water heat pump operation, Q_{CHC} is the total heat produced from the cooling, $Q_{\text{cond to air}}$ is the heat from cooling that is unutilized and condensed to air, $Q_{\text{HP to AW}}$ is the HP production that is utilized in the network, $Q_{\text{DH to AW}}$ is the heat from Espoo DH network used in consumption points, and $Q_{\text{AW demand}}$ is the heat demand in the network. From these six parameters, Q_{demand} and Q_{CHC} are parameters calculated from input data described earlier, $Q_{\text{cond to air}}$ is a negative vector variable, and the other three are positive vector variables. In addition to these, there are three more decision variables based on which scenario is simulated: $Q_{\text{HP to DH}}$, which is the heat pumped from AW network to Espoo DH network; Q_{accu} , which is heat charged or discharged to/from the heat accumulator and Q_{flex} , which is heat stored or discharged in network flexibility. With all these applied we get the following linear program:

$$\begin{aligned} \min \sum f(\hat{x}_{step}) \\ s.t. \\ Q_{ATW} + Q_{CHC} + Q_{\text{cond to air}} = Q_{\text{HP to AW}} + Q_{\text{HP to DH}} \\ Q_{\text{HP to AW}} + Q_{\text{DH to AW}} + Q_{\text{accu}} + Q_{\text{flex}} = Q_{\text{AW demand}} \\ -Q_{\text{accu}} - Q_{\text{flex}} \leq Q_{ATW} + Q_{CHC} \end{aligned}$$

The cost function $f(\hat{x}_{step})$ can be written as:

$$\begin{aligned} f(\hat{x}_{step}) = c_{ATW}(Q_{ATW}) + c_{CHC}(Q_{CHC} + Q_{\text{cond to air}}) + \\ c_{\text{HP to DH}}(Q_{\text{HP to DH}}) + c_{\text{ESP}}(Q_{\text{DH to AW}} + \hat{x}_{\text{ESP}}) \end{aligned}$$

where c_{ATW} is the cost function of the ATW heat production, c_{CHC} is the cost function

of the cooling heat production, $c_{\text{HP to DH}}$ is the cost of pumping heat from LTDH to DH network and c_{ESP} is cost function of Espoo DH production defined by the Espoo MONA model. The cost function of heat pump production is as follows:

$$c(Q_x) = \frac{Q}{\text{COP}} * (c_{el} + c_{trans} + c_{tax})$$

Where Q is the produced heat, COP is the coefficient of performance for the HP, c_{el} is the cost of electricity which for this case is the Finnish area spot price, c_{trans} is the transmission cost taken by local electricity transmission grid operator and c_{tax} is the electricity tax that is taxed from the consumed electricity. This applies to all HP processes in AWD, only the COP varies depending on which type of HP is in question: as described earlier the COP of the ATWHP process is according to Figure 19, COP of the CHC is 3.45 and 3.3 for pumping heat to the DH network. By applying the cost functions to the linear program we get:

$$\begin{aligned} & \min \sum f(\hat{x}_{step}) \\ & \quad \quad \quad s.t. \\ f(\hat{x}_{step}) &= \left(\frac{Q_{ATW}}{\text{COP}_{ATW}} + \frac{Q_{CHC} + Q_{\text{cond to air}}}{\text{COP}_{CHC}} + \frac{Q_{\text{HP to DH}}}{\text{COP}_{\text{HP to DH}}} \right) * (c_{el} + c_{trans} + c_{tax}) \\ & \quad \quad \quad Q_{ATW} + Q_{CHC} + Q_{\text{cond to air}} = Q_{\text{HP to AW}} + Q_{\text{HP to DH}} \\ & \quad \quad \quad Q_{\text{HP to AW}} + Q_{\text{DH to AW}} + Q_{\text{accu}} + Q_{\text{flex}} = Q_{\text{AW demand}} \\ & \quad \quad \quad Q_{\text{accu}} + Q_{\text{flex}} \leq Q_{ATW} + Q_{CHC} \end{aligned} \tag{11}$$

This linear program is only supposed to display the relations between different heat production and consumption variables and parameters used in MONA. It is not a complete linear program, since each production still has its own constraints. From the first row of the linear program constraints, we see that the goal is to minimize the total costs of the Espoo DH network and AWD. This is because AWD is owned and operated by Fortum, so the goal is to reach the global cost-optimum in the Espoo area, DH network included. The second row tells us that the heat from cooling, air-to-water and condensed to air has to be equal to the heat utilized in the AW LTDH network or pumped to Espoo DH network. The third row tells us that the sum of local utilized production, heat utilized from the DH network, the heat stored or discharged into the heat accumulator, and network flexibility has to be equal to the local demand. Finally, the fourth row tells us that the heat accumulator can only be charged with the HP units, and not from DH since DH is not directly connected to the network.

In MONA the model calculates the costs of utilizing each HP unit and adds those to a global objective vector which it is trying to minimize, called CONT_COSTS. This variable includes all the continuous costs of the Espoo DH system in addition to the costs of the AWD network. Connection to the CONT_COST objective vector can be seen in Figure 23

3.3.2 Heat pump model

The COP of the air-source mode as a function of ambient temperature was estimated by linear extrapolation from the table 2 by Sweco that shows the COP of an on/off scroll compressor ATWHP.

Table 2: COP of on/off scroll compressor Air to water heat pumps with R410 refrigerant. (Alilehto 2020)

COP		T_out				
T_amb		30	35	40	45	50
20		5,98	5,34	4,81	4,36	3,97
10		5,06	4,49	4,02	3,62	3,29
5		4,55	4,03	3,61	3,25	2,94
0		4,06	3,57	3,21	2,85	2,58
-3		3,79	3,33	2,92	2,62	2,41
-10		3,08	2,65	2,31	2,07	1,83
-100		0	0	0	0	0

Operating outside the ambient temperatures described in the table is possible for short periods of time. The ATWHP was assumed to not be able to operate below -10 °C, but to be still able to operate normally above 20 °C, since there is not much need for heat during the peak temperature hours.

With table 1 a simple linear model could be created for the COP as a function of ambient temperature. The graph of the function can be seen in Figure 19.

For the CHC process, a constant COP of 3.45 mentioned in 3.2.6 was used, since the temperature difference between the cooling return side and LTDH supply side remains constant.

The heat pump system was modeled into MONA as two separate production types: the heat recycling (CHC_HP_PROD in Figure 20) and into air-to-water heat pumping described above (ATW_HP_PROD in Figure 20). The basic principle of the model is that it calculates the maximum possible heat production for each hour from ambient temperature, subtracts the heat energy produced from the CHC network (CHC_HP_PROD in Figure 20), which is calculated from the CHC network modelling described in 3.2.6, from the maximum total HP production and sets that

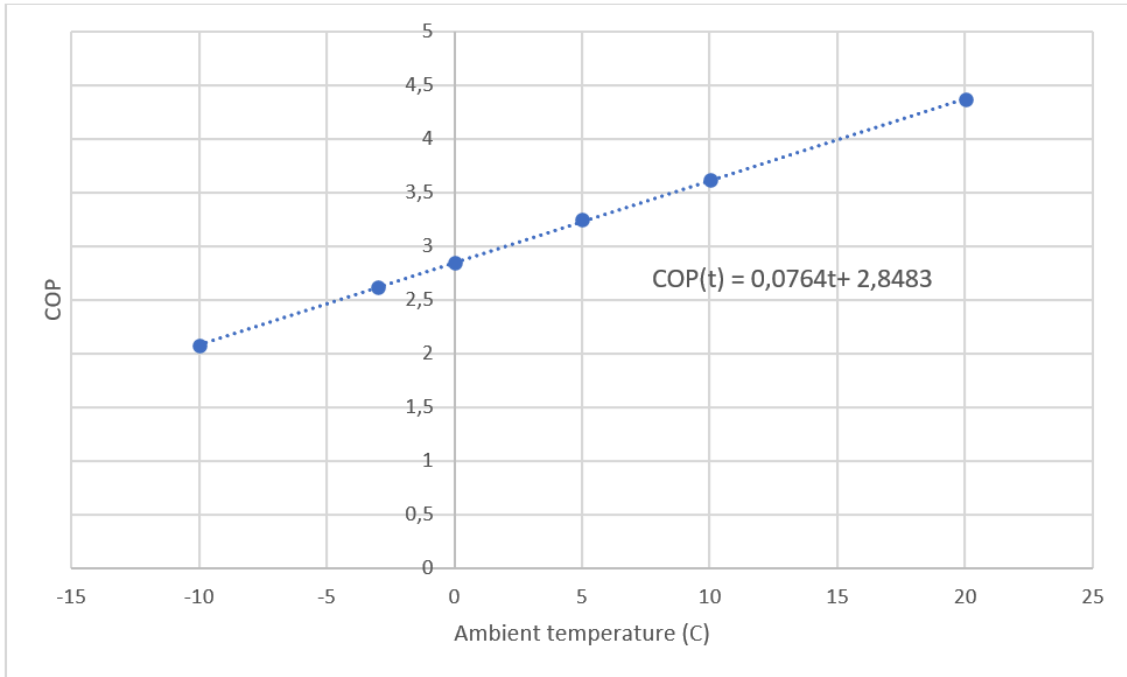


Figure 19: COP of an on/off scroll compressor heat pump with R410 refrigerant as a function of outside temperature

as the maximum value for the `ATW_HP_PROD` vector variable. As can be seen from the snapshot of the HP model in the AWD MONA model in Figure 20, there is only one other decision variable in the HP model called `CHC_HP_AUXC`. This represents the heat from the CHC process that cannot be utilized in the LTDH network and has to be condensed to air. The ATWHP is set not to work at below $-10\text{ }^{\circ}\text{C}$ and so the model utilizes only DH during those hours.

The maximum HP production is a linear function of outside temperature, that has been obtained by creating a linear function from performance points obtained from Swegon regarding the HP units in question. The function is as follows:

$$Q_{HP,max} = n \frac{13.359 * t_{amb} + 699.75}{500} \quad (12)$$

where t_{amb} is the ambient temperature and n is the number of hp units installed.

3.3.3 Demand and connection to DH network model

The heat demand model is simplified as a parameter, that receives it's values from the linear function described more in detail in 3.2.5. The demand is then set to equal to the sum of AWD own production used, heat from the DH network used and the heat pumped to the DH network from the AWD LTDH when available.

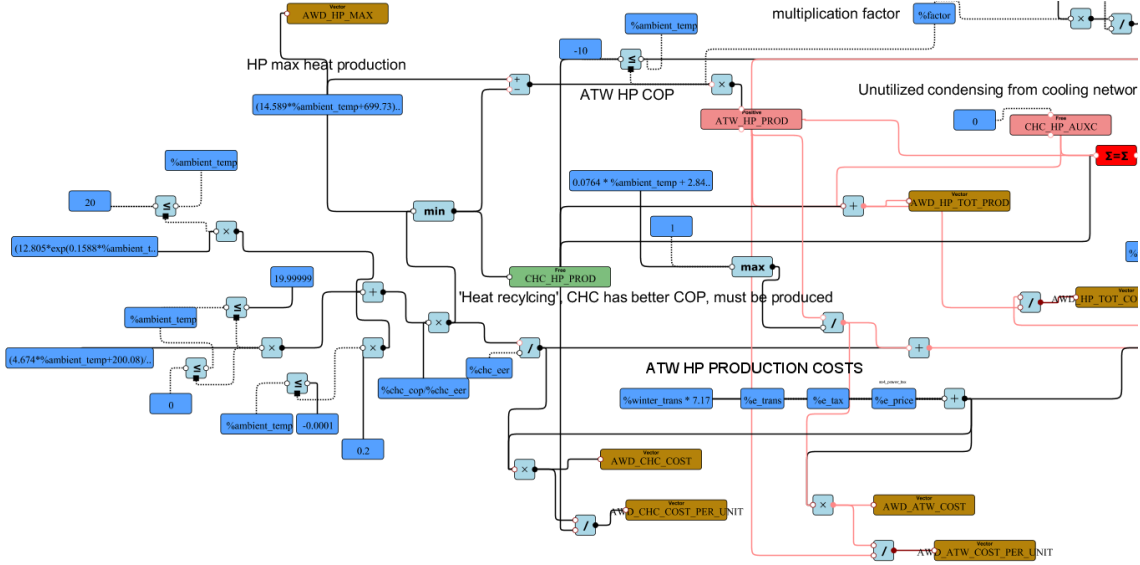


Figure 20: Snapshot of heat pump system model in AWD MONA model

The heat pumped from the AWD LTDH is modeled as a positive vector variable without an upper limit. A cost, however, for pumping heat to DH network is introduced, which is equal to the sum of electricity spot-price, transmission fees, and electricity taxes for every MW of electricity consumed in the process. The HP is connected to the return side of the Espoo DH network and has a constant COP of 3.3 (Lintu 2020). The cost of pumping heat to the DH network for each hour is, therefore:

$$c_{AW\ to\ DH} = \frac{Q_{AW\ to\ DH}}{COP_{AW\ to\ DH}} * c_{costs} \quad (13)$$

where c_{costs} are the costs described in equation 6. The model can also take in an unlimited amount of heat from the Espoo DH network without any additional cost. As mentioned earlier, the model uses a constant of 0.025 MW or 25 kW of DH due to hot water circulation. This is the only domestic water modelling in the MONA model and does not fully correspond to reality. A snapshot of the demand model, demand and production balancing, and connections to Espoo DH network can be seen from Figure 21. The AWD LTDH network is connected to the Espoo MONA model by connecting the model into the Espoo DH Balance unit via Trade-in (for pumping heat to DH network) and Trade-out (for utilizing heat from DH network) gates, as can be seen in Figure 22.

The system has a set minimum self-sufficiency requirement of 70 %, as is agreed between ACRE (Aalto University Campus and Real Estate) and Fortum. The model ensures self-sufficiency by requiring that the sum of own production utilized in the network divided by the sum of consumption over time is greater or equal to the

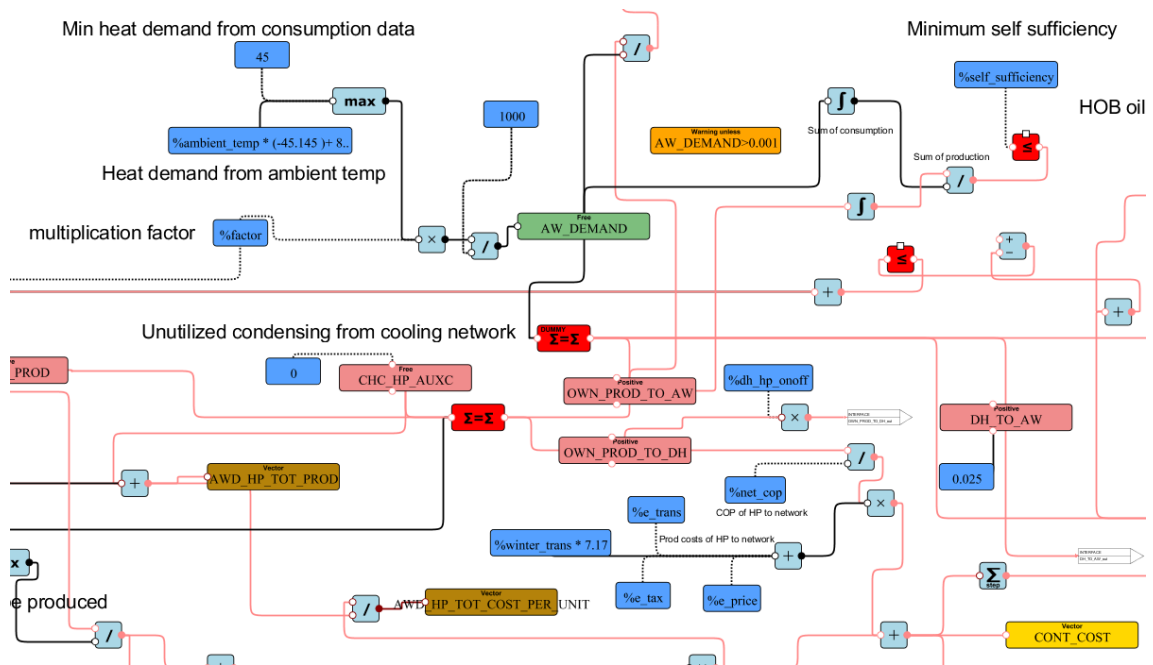


Figure 21: Snapshot of heat balancing, demand, connections to Espoo DH network and self-sufficiency requirement in AWD MONA model

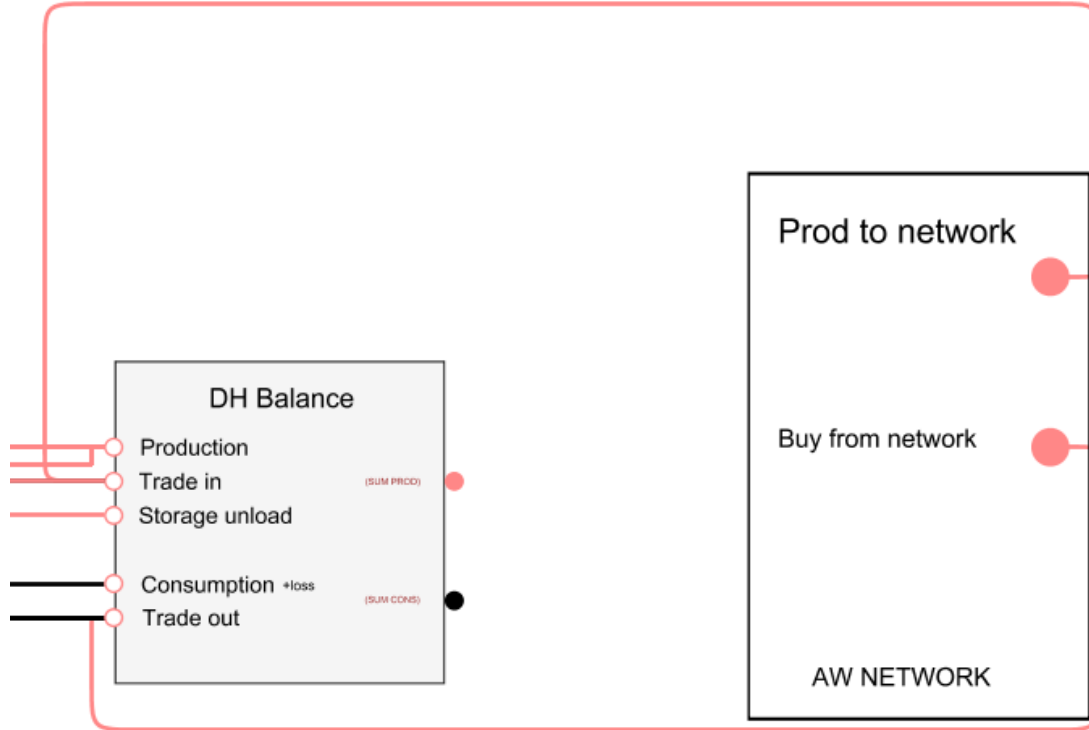


Figure 22: Snapshot of AWD MONA model connection to Espoo MONA model DH balance block

minimum self-sufficiency requirement, which is 70 % in this case. This can also be seen in the right-hand top corner in Figure 21.

3.3.4 Heat storage and network flexibility as a heat storage modelling

The AWD model has two different storages, the HOB oil tank heat storage, and network flexibility modeled as a heat storage. Both of these storages are based on the same user component, Heat storage, and only differ in given parameters. The heat storages are connected to the demand balance equality, so the following applies:

$$Q_{HP\ production} + Q_{DHtoAW} + Q_{storage} = Q_{demand} \quad (14)$$

If the heat storage is charged with heat, it will result in a negative heat energy component in the equation. There is also an additional restriction: because the DH network is not directly connected to the LTDH network rather than just the consumption points, the charging of the accumulators is limited as follows:

$$Q_{storage} \leq Q_{HP\ production} \quad (15)$$

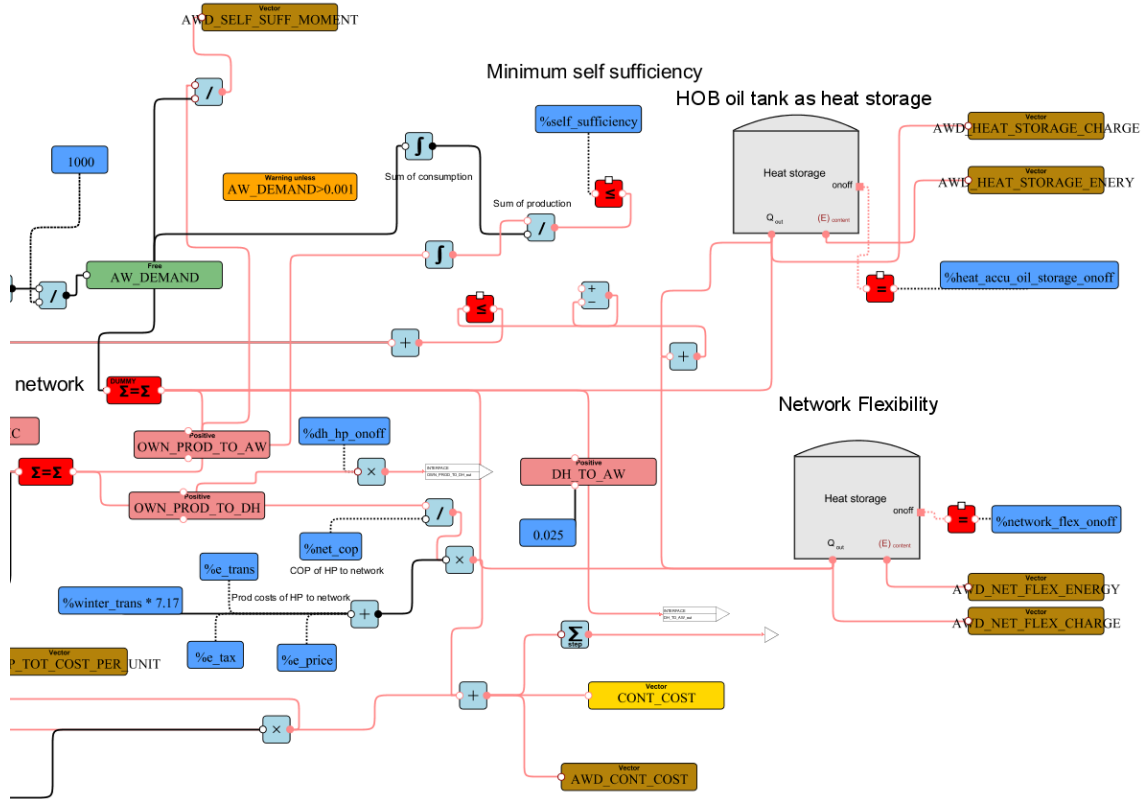


Figure 23: Snapshot of heat storage connection to charge limitation and demand balance equation in AWD MONA model

Since the hourly demand for heat and the local production volumes are reasonably small, there it is not required to limit the maximum charge and discharge of the storages any further. They are only given artificial limitations that are not the limiting factor in any case.

There are no additional costs introduced to charging or discharging heat into the HOB oil tank or network flexibility. In reality, increasing the supply temperature to store energy in the network will decrease the COP of both CHC and ATW processes. For the purposes of the study, it was decided to first see the results of the network flexibility charging without effects on the COP and then decide whether or not it is reasonable to study the option further. The capacities of the storage options are as described earlier, 26 MWh for the HOB oil tank and 360 kWh for the network flexibility. The temperature increase option in the HOB oil tank is insignificant as can be seen later in the study.

A snapshot of the heat storages and their connection to the demand balance can be seen in Figure 23. In the figure, we see the two different heat storage units labeled respectively connected to both the limitation equation and the demand balance.

3.3.5 Model inputs and outputs

The Espoo MONA model together with the AWD model has 323 input parameters, of which most are time-series parameters, meaning that they have a specified value for each step or hour of calculation. This makes a total of more than 19 000 input values over the course of one month.

The AWD model itself has roughly 10 unique input parameters. In addition to those, it utilizes three input parameters directly from the Espoo model. The three parameters from the Espoo model are electricity tax price, Espoo temperature forecast / realized temperature, and realized / forecast electricity spot price. Forecasts are replaced with realized values once they are available. Unique input parameters include parameters such as CHC heat pump and AWD to network HP COP and EER (energy efficiency rating) parameters, on-off parameters for different scenario components, electricity transmission price, and winter electricity transmission price increase parameter. There is also a parameter called ‘factor’, which if set to something else than 1 multiplies the production and consumption of the AWD network by the factor set, if there is interest to study effects of an increasing number of similar solutions around the Espoo area and benefits of applying some of the solutions in the scenario.

Much like input parameters, output parameters include a large number of different parameters for the Espoo MONA model and AWD model combined – a total of 690 resulting in over 40 000 output values. To access the data of interest from the results, additional post-processing parameters are introduced to the model, and desired output parameters are ‘locked’ so that it is possible to view only the locked output parameters if needed. In Figures 20, 21 and 23 the post-processing variables have a brown background color. With these post-processing parameters, it is possible to store data from any part of the model. What we are most interested in, are the usage of components, such as HP units and storage units, costs of the AWD network, and total costs of Espoo DH network among other parameters. The entire AWD MONA model can be seen in Figure 24.

3.4 Modeled scenarios

The optimization was done on five different scenarios based on different options to increase flexibility in the network: base, network flexibility, heat storage, HP to DH, and All on scenarios. The base scenario is based on the planned solution, where no flexibility is introduced. The scenario acts as a point of reference to the other scenarios and is used to quantify the benefits of each solution.

In the network flexibility scenario the LTDH network itself is used as heat storage by increasing the supply temperature. As mentioned in 3.3.4, the reduced performance of the HP units was not taken into account, since the capacity of the ‘storage’ is

minimal and it is more reasonable to find out the effects of the storage of that size before modelling it more in detail. Due to the small capacity of the storage, no restrictions to maximum charge or discharge were introduced.

In the heat storage scenario the oil tank of the Espoo HOB plant was modeled to be repurposed as a heat accumulator. No additional costs were introduced to the charging or discharging of the accumulator, and since the restriction of only being able to charge the accumulator with the local production, no additional restrictions to charging or discharging rate needed to be introduced.

In HP to DH scenario a HP unit was modeled to be able to pump heat from the LTDH network to the Espoo DH network return side, thereby producing ‘conventional DH’ from the LTDH. Since the purpose was to study how much value that type of investment would produce, no capacity restrictions were introduced. The HP unit was modeled after a generic HP unit based on data from the Swegon Prochill program to be able to apply costs to the process with the COP of the unit.

In all on scenario, all of the above were applied. Therefore there was a minor increase in heat storage capacity compared to the heat storage scenario in the form of network flexibility, along with the possibility to utilize the heat in the Espoo DH network with an additional cost of pumping the heat from LTDH up to the return temperature of the DH network. It was also possible in theory to store heat into the heat accumulator and later pump it into the DH network.

3.5 Chosen simulation time frame and resolution

It can be assumed that in general, a smaller resolution of calculation provides more accurate results. By accepting this we can decide that as small-as-possible a resolution is desired. Due to the nature of the hourly varying electricity price resulting in hourly varying production costs, a resolution of 1 hour was chosen: The model would not be able to provide any additional information on a smaller resolution since the provided input data is hourly based, and a bigger resolution would result in too vague results and not provide interesting results.

Laakso (2020) shows us, that increasing the calculation time frame results in exponential growth in computing time. Therefore an hourly resolution required a short-enough time frame to be able to be computed in a reasonable time with reasonable equipment, at the same time giving the desired result. A time frame of one month divided into two periods was chosen so that the requirements were met. The chosen month was from the 1st of March 2020 at 00:00 to 1st of April 2020 at 00:00, the first period being from 1.3.2020 at 00:00 to 15.3.2020 at 00:00. In the second half, the sliding time window method was applied for Heat storage and All on scenarios, to achieve more optimal results for heat storage usage, as suggested by Fang and Lahdelma (2015). The overlap was done so that the second half began from 14.3.2020

at 00:00 and the initial level of energy storage in the second half set to the storage level at that time in the first half. The exact time was chosen because of multiple factors, such as availability of accurate data and large variance in both electricity spot prices and outdoor temperatures resulting in varying production capabilities and costs to highlight the possible achieved benefits, and also relevance to future production costs in Espoo DH network due to cost factors such as fuel pricing. The ambient temperature and Nordpool electricity spot prices used can be seen from Figure 25.

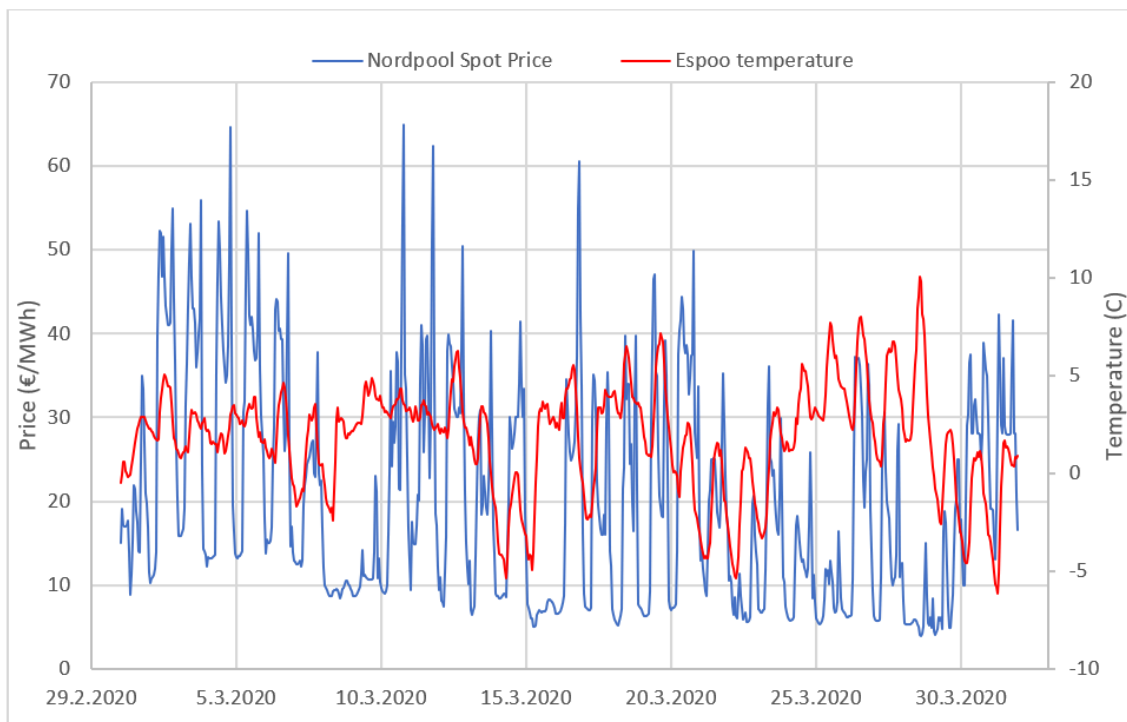


Figure 25: Historical Nordpool Spot prices and ambient temperature used in simulation

4 Results

4.1 Base scenario

In the base scenario, no flexibility was introduced to the LTDH system. Results of the base scenario act as a benchmark to other scenarios with different types of flexibility. The LTDH system was able to achieve self-sufficiency of around 89.1 % which is more than sufficient compared to the required 70 %. This is calculated simply by summing up the entire production of the HP units and dividing it by the total demand of the AWD consumption points. The production curve that can be seen in Figure 26 shows, that additional heat from DH is mostly used during peak hours.

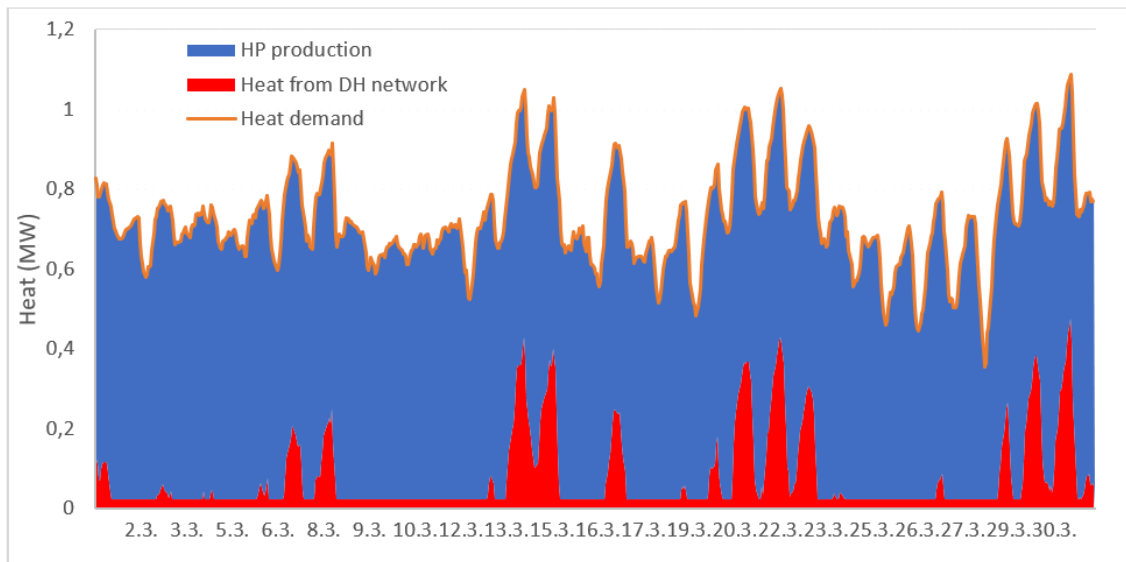


Figure 26: Base scenario heat production in AWD LTDH network

The indicative cost of heat produced with HP units compared to the Espoo DH network costs is displayed in Figure 27. As can be seen from the figures, the HP production is significantly cheaper most of the time. In addition, from Figure 28 we can further examine that the capacity of the HP units are not utilized entirely most of the time. More in detail, the utilization of the HP capacity is at 89.5 % over the course of this period. This further supports the hypothesis that introducing additional flexibility to production may decrease overall operational costs of the LTDH network. Key numbers of each scenario compared to the base scenario can be seen from table 3.

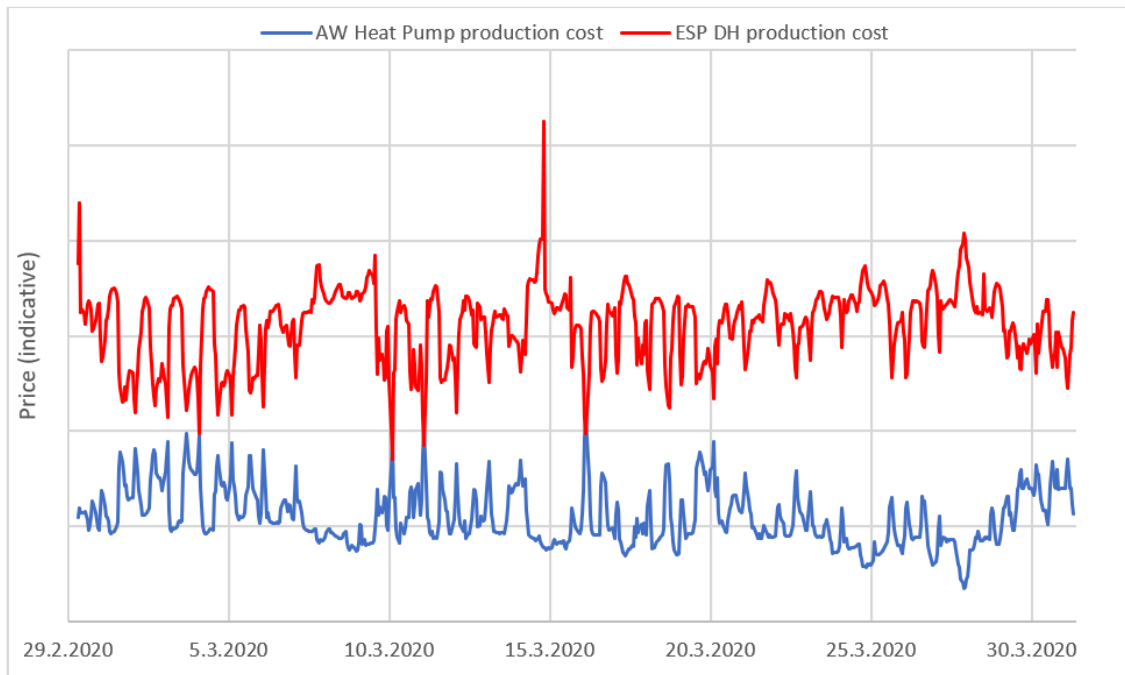


Figure 27: Heat pump heat production costs and Espoo DH production costs in base scenario

4.2 Network flexibility scenario

In the network flexibility scenario, flexibility was introduced to the system by being able to store heat in the LTDH network itself by momentarily increasing the temperature of the network. The system was able to increase its self-sufficiency by around 0.8 % compared to the base scenario, up to 89.9 %. This can be seen from Figure 29. In the figure, when the heat production exceeding the heat demand it implies that the system is ‘charging’ the network and when the heat production is less than heat demand, the system is discharging the network. The change in network charge level is displayed in more detail in Figure 30.

The HP utilization was also increased by roughly 0.8 % up to 90.2 % of maximum capacity. The utilization of the HP capacity throughout the whole month is displayed in Figure 31. From the figure we see, that the heat pump is ramped up and down much more frequently than in the base scenario.

By taking into focus a shorter period from the results in Figure 32 and also plotting power price along with the production and capacity curves, we can see that the system is able to utilize cheaper hours by producing additional heat and reducing production during higher electrical power price hours, which results in decreased production costs. Overall the heat production costs were decreased by roughly 0.68 €/MWh for the heat consumed in the AWD. This equals to about 370 € over the course of one month. This is roughly a 4 % decrease in operational costs, making it

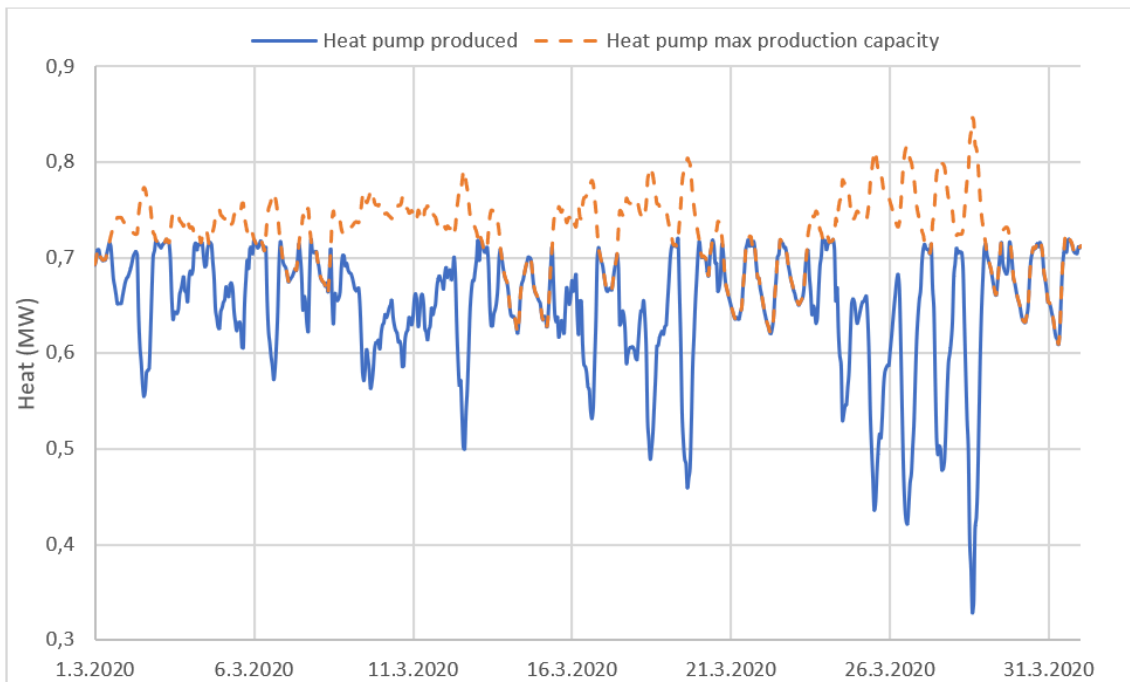


Figure 28: Heat pump produced and maximum possible production capacity in base scenario

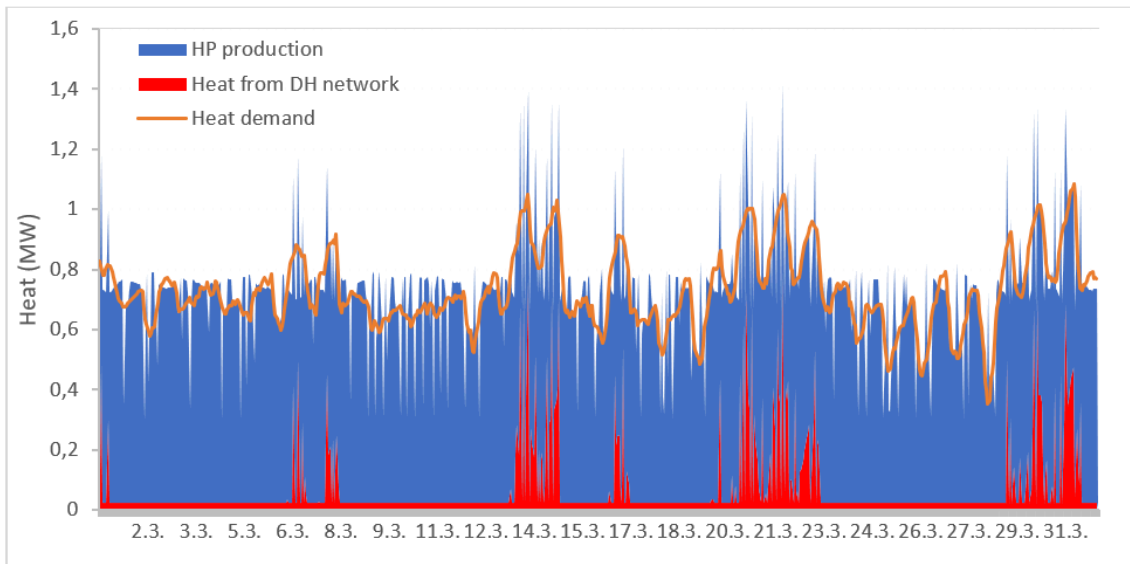


Figure 29: Network flexibility scenario heat production

non-remarkable in the volumes of the AWD network.

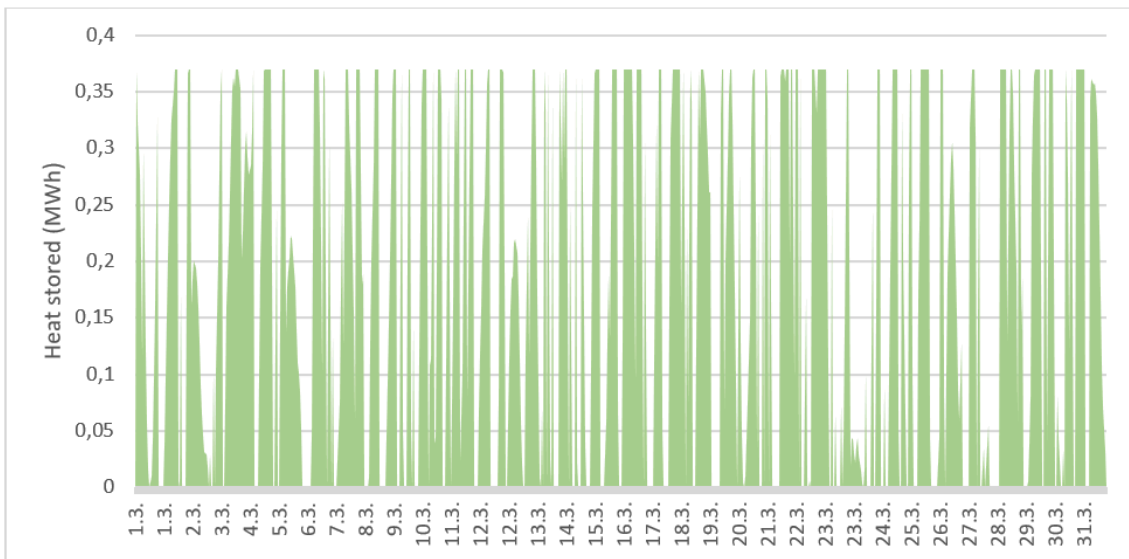


Figure 30: AWD network stored energy in network flexibility scenario

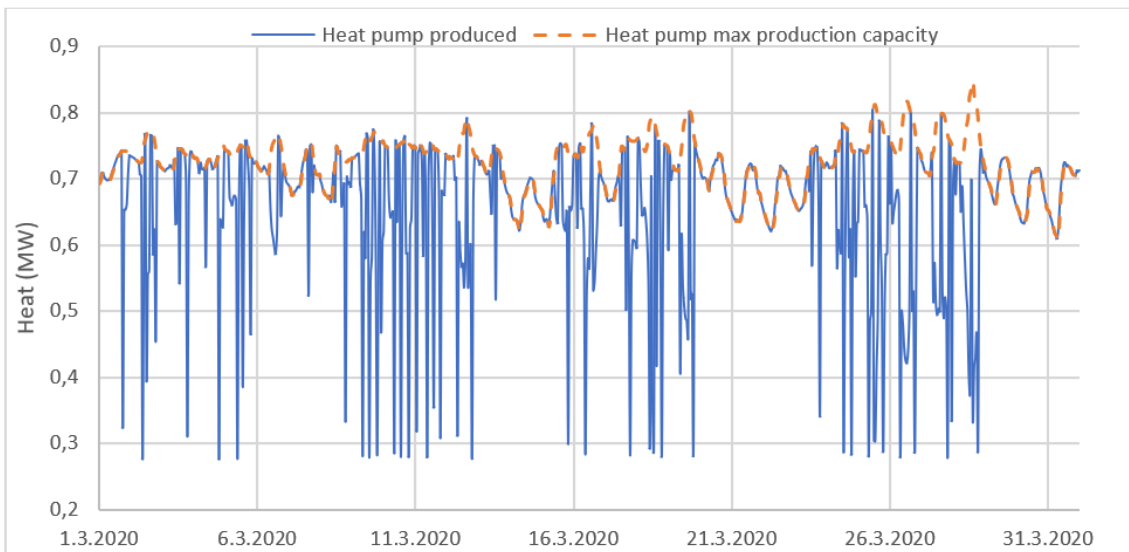


Figure 31: Heat pump capacity utilization in network flexibility scenario

4.3 Heat storage scenario

In the heat storage scenario, an oil container was modeled to be repurposed as a heat accumulator. The capacity of the storage was considerably large compared to the overall heat consumption of the LTDH system. With the heat storage, the need for additional DH was diminished, save the need because of domestic water usage. As can be seen in Figures 33 and 34, DH is actually used to make it possible to utilize the heat pumps as efficiently as possible, and accumulate the HP production into the heat pump by supplying the consumption points with DH instead of heat from the AWD LTDH network. Figure 34 shows us, that the total capacity of 26

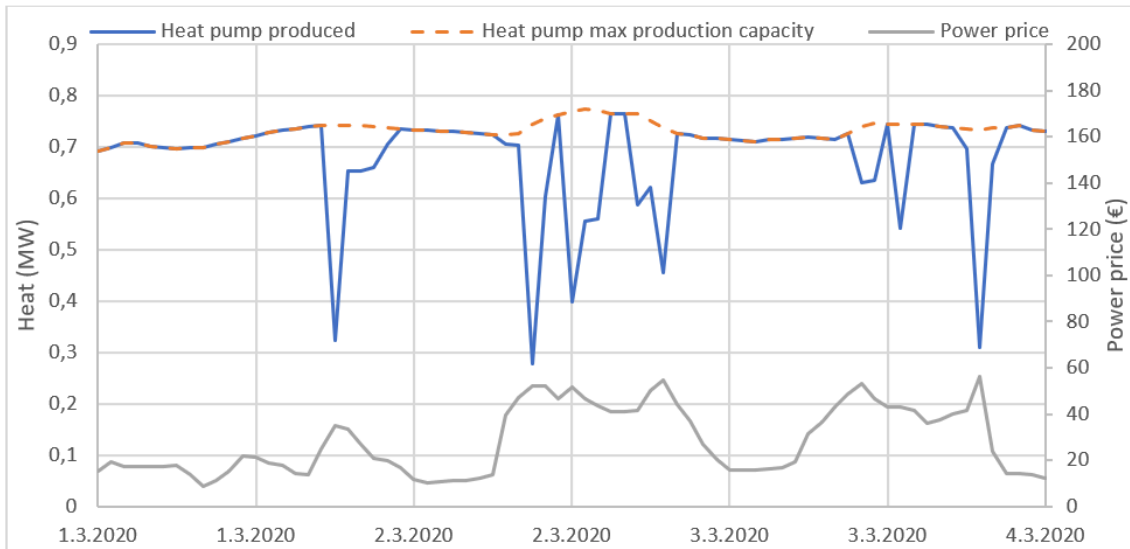


Figure 32: Heat pump production, capacity, and electricity spot price in network flexibility scenario from 1.3.2020 to 4.3.2020

MWh of the heat accumulator is never fully utilized – therefore, in this case, the heat storage scenario can be considered to also be a scenario of ‘infinite flexibility’. The self-sufficiency of the LTDH was increased by over 6.8 % up to 95.1 %.

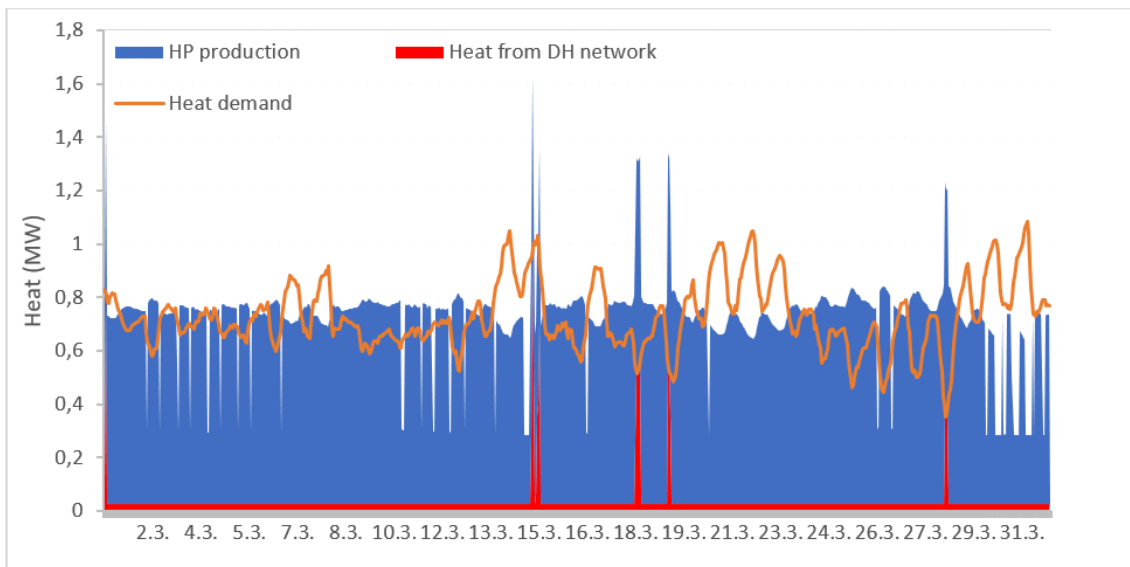


Figure 33: Heat storage scenario heat production over time

The HP utilization in the heat storage scenario was also increased by almost 6.8 % up to 95.6 %. This can be seen in Figures 35 and 36. Similar to the network flexibility scenario, the system is able to avoid high electricity prices, only even more efficiently than in the previous scenario. Due to the increased flexibility, the overall costs were reduced significantly, up to -2.18 €/MWh of heat produced, which

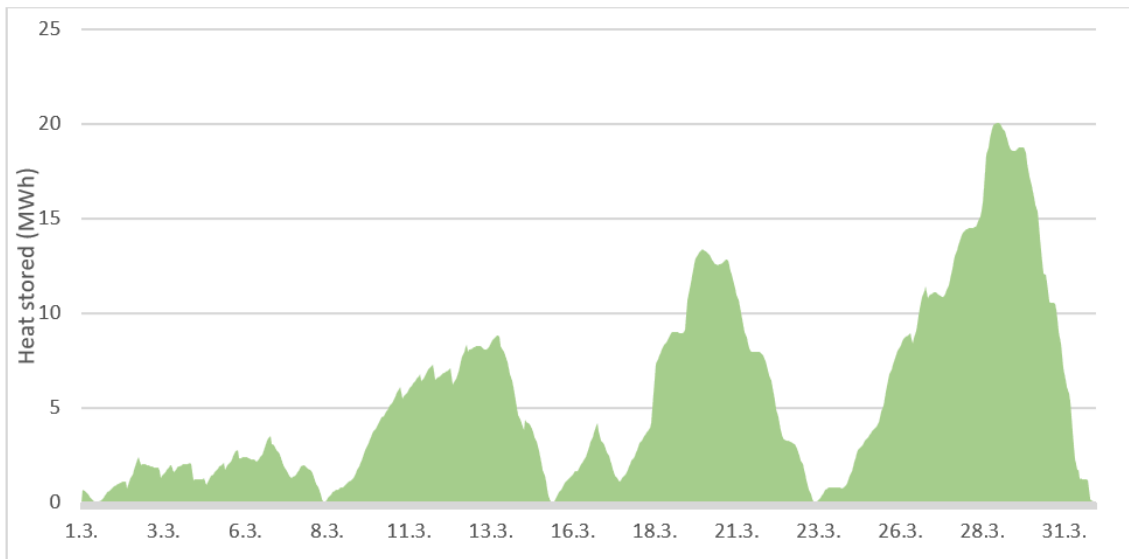


Figure 34: Heat storage scenario accumulated heat energy over time

accounts for almost 1200 € in a month for the AWD network, or by almost 15 %.

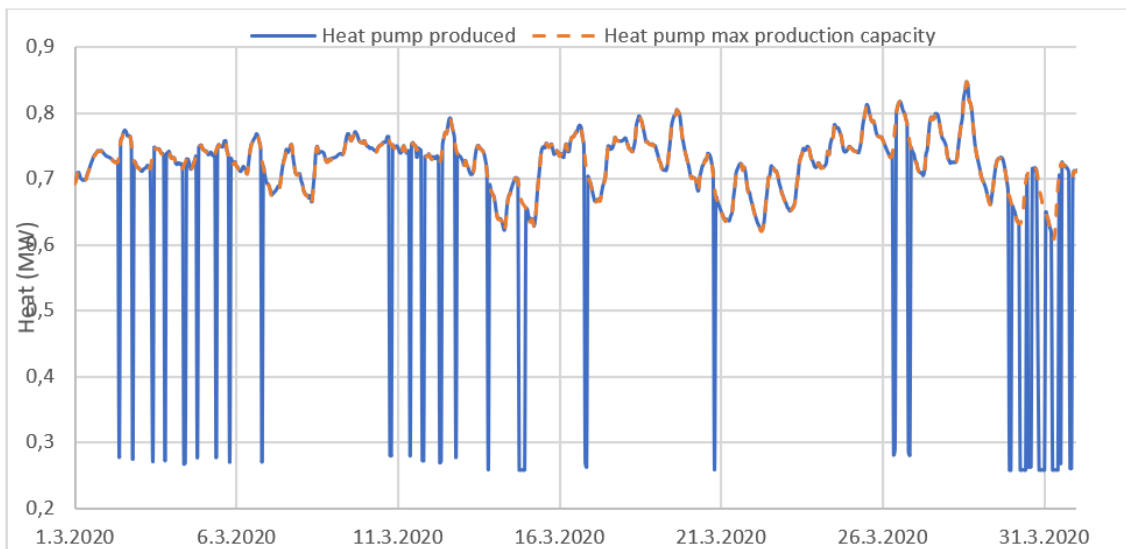


Figure 35: Heat pump capacity utilization in heat storage scenario

4.4 HP to DH scenario

In HP to DH scenario a heat pump was installed to make it possible to transfer heat from the LTDH network to the Espoo DH network. Since there was no capacity limit introduced for the heat transfer with the heat pump (other than the limits of the AWD network itself). Therefore we could say that the AWD model had unlimited flexibility, but only one way and this time with a cost. In the production curve in

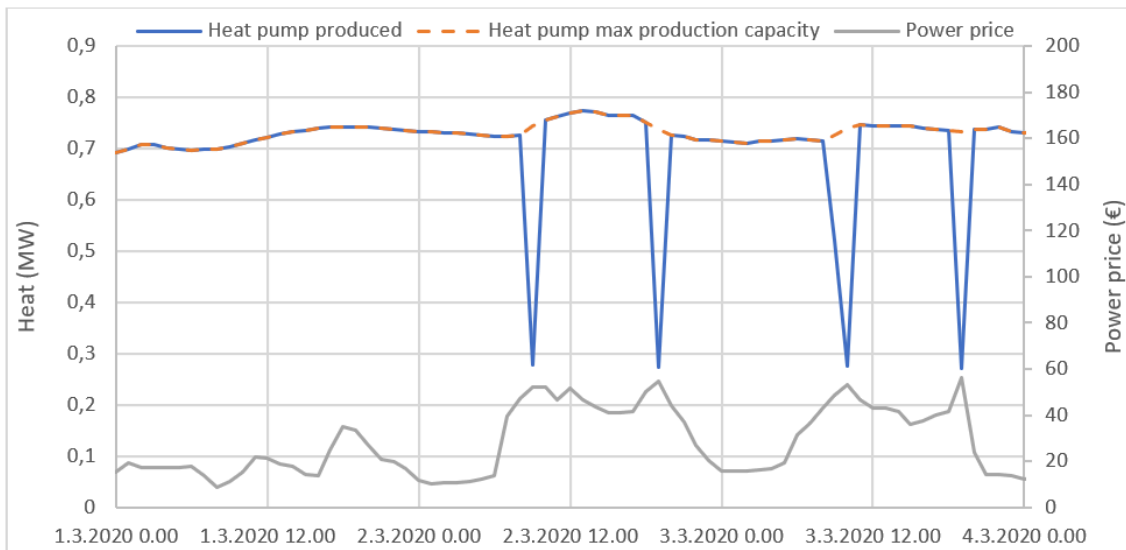


Figure 36: Heat pump production, capacity and electricity spot price in heat storage scenario from 1.3.2020 to 4.3.2020

Figure 37 the production exceeding the demand represents heat that is pumped to the DH network. The two-step heating to DH temperatures proved not to be feasible at all times, since the full capacity of the HP is not utilized at all times as can be seen from Figure 38. The self-sufficiency of the AWD network ended up being 95.2 % when accounting for all the heat produced with the HP units, including heat pumped to the DH network. HP utilization was roughly equal to the heat storage scenario with a utilization percentage of 95.6 %. Figure 39 shows the heat pumped to the DH network over the period of one month.

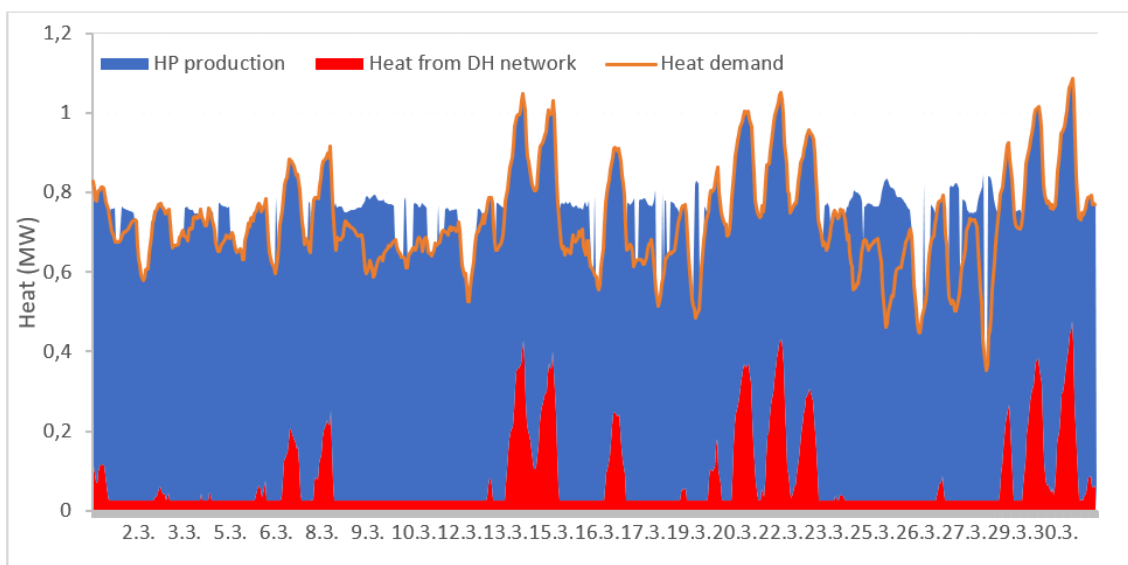


Figure 37: HP to DH scenario heat production over time

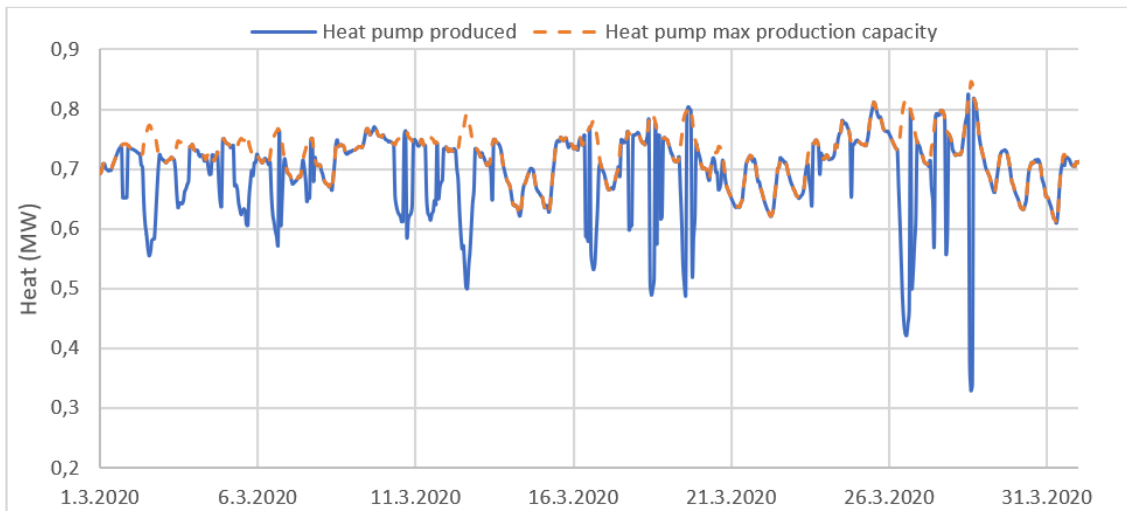


Figure 38: Heat pump capacity utilization in HP to DH scenario

Overall this investment provided a decrease of only 0.44 €/MWh in AWD LTDH system, when the decreased production costs in Espoo DH network were considered.

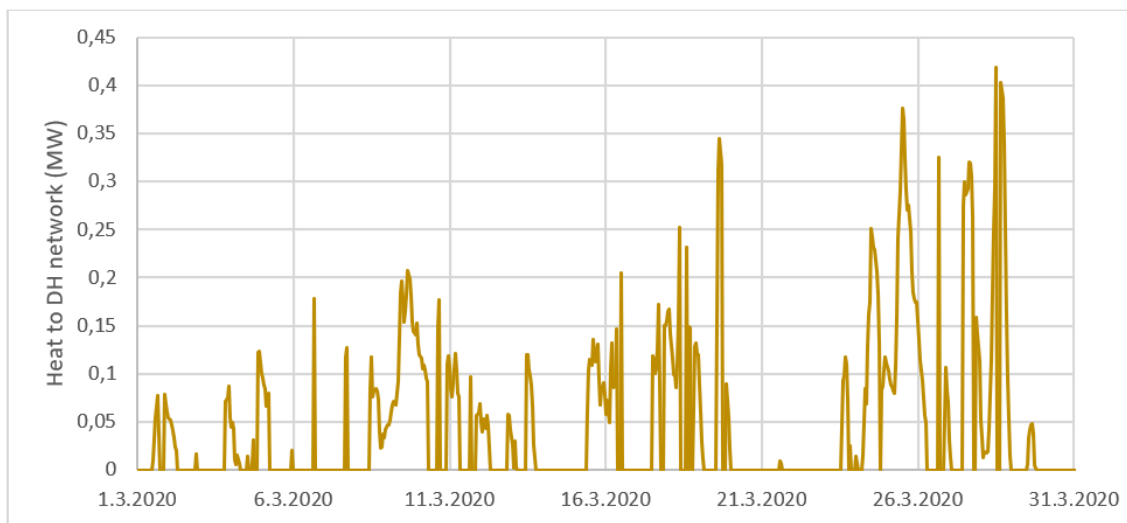


Figure 39: Heat pumped to DH network in HP to DH

4.5 All on scenario

In the last scenario, all of the scenarios above were introduced together. As can be seen from Figure 40, the network was using DH even more aggressively to be able to store heat produced in the HP units to energy storage. From Figure 41 we see that the system was able to reach 100 % utilization of the HP system, with the self-sufficiency of 99.5 %.

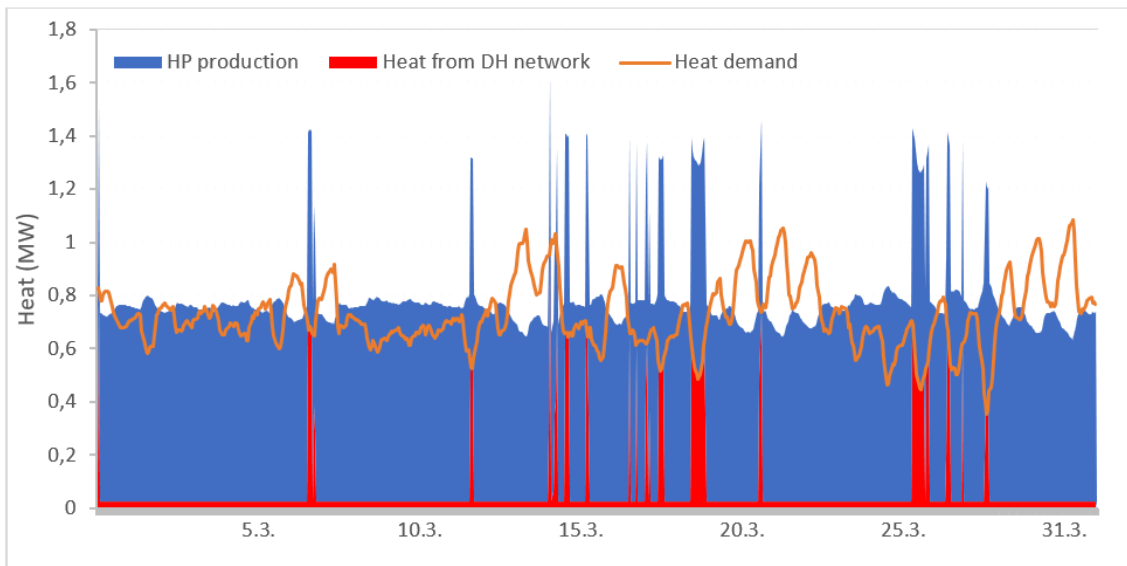


Figure 40: All on scenario heat production over time

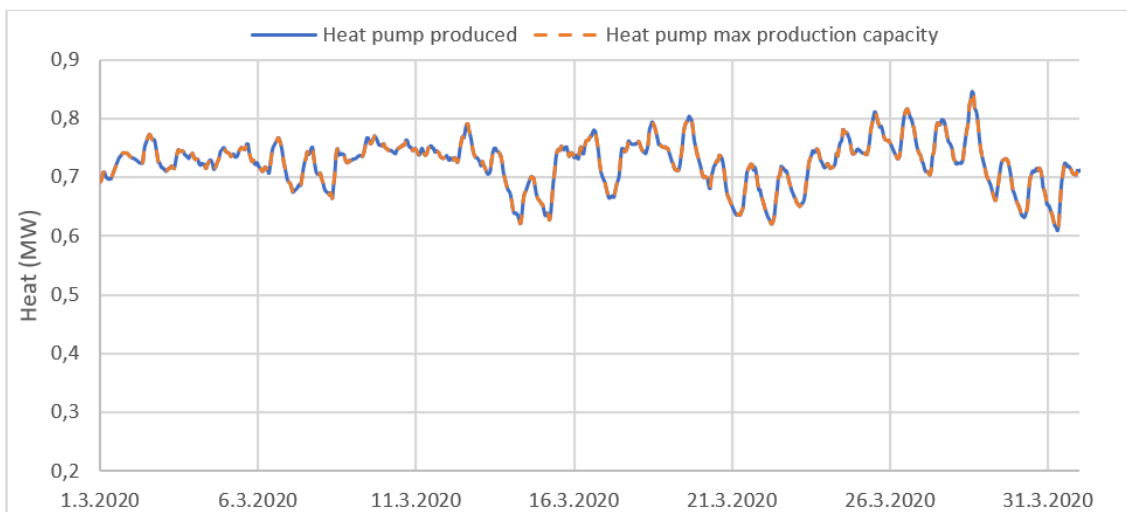


Figure 41: Heat pump capacity utilization in All on scenario

In the all on scenario, the available storage capacity was not fully utilized, even though the utilized capacity was slightly higher than in heat storage scenario. This can be seen in Figure 42. Heat pumps to DH were utilized less than in heat pump scenario, which can be seen when comparing Figures 39 and 43.

The overall production costs were reduced by a notable margin, by around 2.43 €/MWh. This equals to around 1315 € in this case. When comparing this to the heat storage scenario, additional reduction was only 0.25 €/MWh with the introduction of the HP, since the increase of flexibility was insignificant because the capacity of the heat storage was not fully utilized.

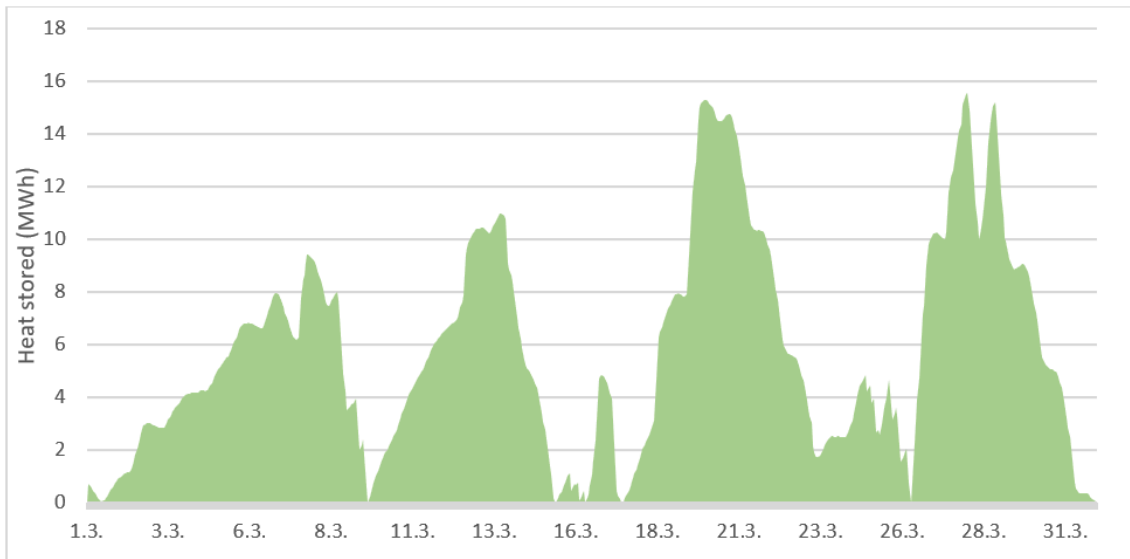


Figure 42: Heat stored in heat storage and network flexibility in All on scenario

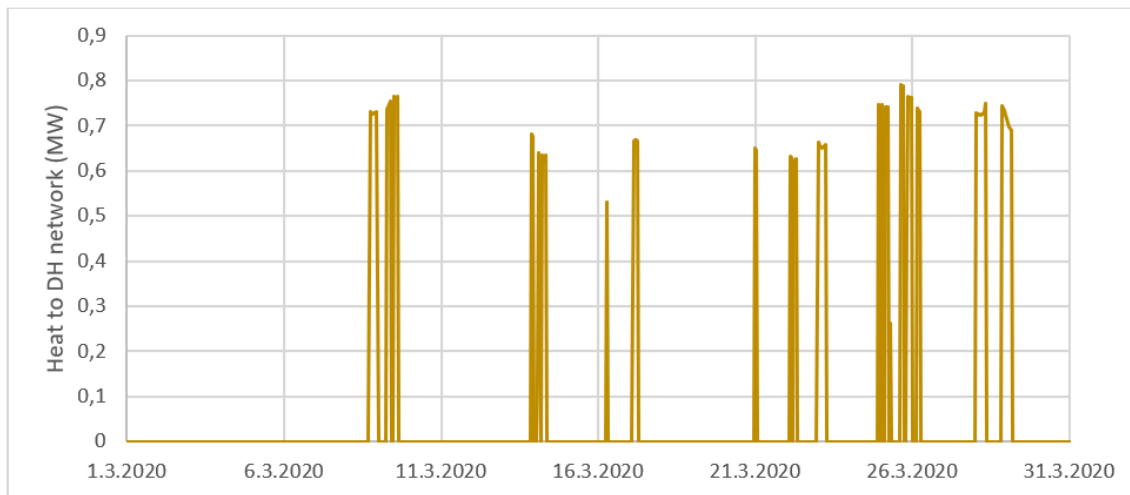


Figure 43: Heat pumped to DH network in All on scenario

4.6 Computation time

The first half of the computation was 336 steps long, and the second half 432 steps long with the sliding time window overlap applied. One step equals to one-hour simulation. As discussed in 3.5 this resulted in a considerably longer time of execution for the second half. When performed with an Intel Core i5-8350U CPU, running at 1.7 GHz with 8 cores and 8GB of RAM, the calculation times were roughly 1 to 5 minutes for the first half and from 20 to 29 minutes for the second half, depending on the scenario.

Table 3: Scenario key results and comparison to base scenario

Scenario	Self sufficiency	Self suff. Increase compared to base	HP utilization	HP utilization change compared to base	Heat cost compared to base (€/MWh)
Base	89,1 %	0,0 %	89,5 %	0,0 %	0
Network flex	89,8 %	0,8 %	90,2 %	0,8 %	-0,68
Heat storage	95,1 %	6,8 %	95,6 %	6,8 %	-2,18
DH heat pump	95,2 %	6,9 %	95,6 %	6,9 %	-0,44
All on	99,5 %	11,8 %	100 %	11,8 %	-2,43

5 Analysis and discussion

5.1 Heat storage capacity sensitivity analysis

By increasing the flexibility by a substantial amount with the oil storage unit, the value created in decreased production costs is significant. When further inspecting Figure 34, we see that a smaller capacity could be more efficiently utilized in this scenario, when the optimization scope is around two weeks. Performing a simple sensitivity analysis for storage capacity by running the simulation again at different heat storage capacity levels from 1 MWh to 20 MWh we can plot out Figure 44 and include the analysis for network flexibility (0.37 MWh). Figure 44 shows the value created as decreased production costs at the storage capacity levels.

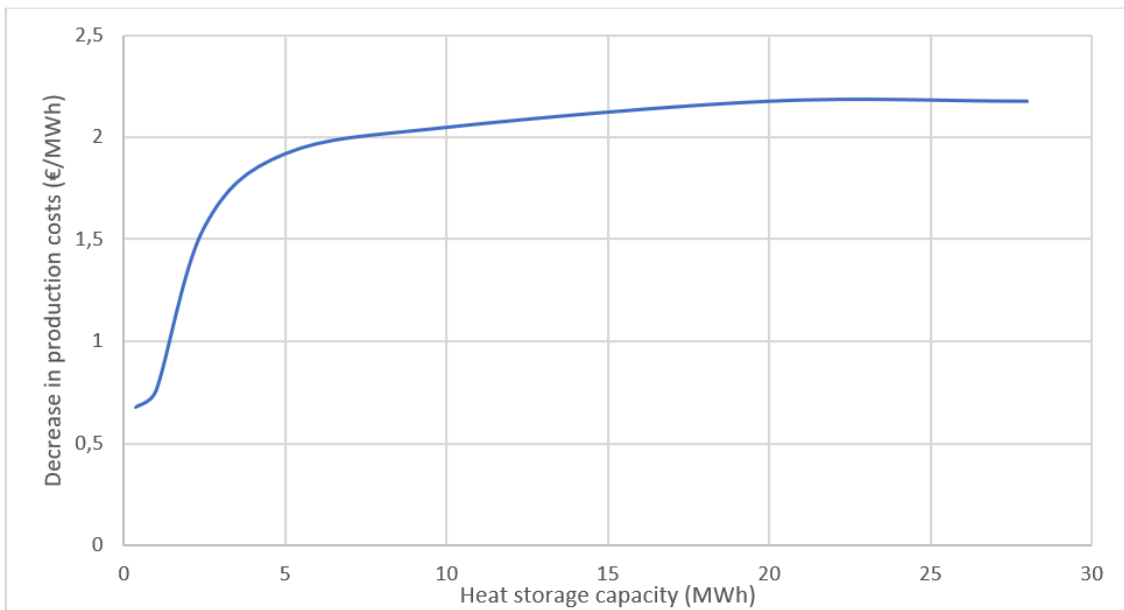


Figure 44: Decrease in heat production costs as a function of heat storage capacity

From Figure 44 we can see that the steepest climb in decreased production costs is from around 0.5 MWh up to 3 MWh. If we assume that the investment cost in increasing storage capacity is roughly linear, can deduce that the most value per investment is between 2.5 and 4 MWh.

For example, if we take into consideration Schmidt et al. (2011) estimate for heat storage of 50 – 200 €/m³ of water equivalent, which in our case corresponds to around 3000 to 12000 €/MWh of capacity and use an average of 7500 €/MWh, a water storage of 4 MWh, as discussed earlier, would require an investment of 30000 €. From the figure, we can estimate that 4 MWh would result in a 1.85 €/MWh decrease in production costs in the simulation adding up to around 1000€ in total value created in a month. That would mean, that the payback time before the investment would

start to create profit would equal to roughly 30 months of similar operation. If we assume 3 months in a year of similar type of varying in production and no value created in other months, it will result in a payback time of 10 years. This, of course, is only a rough estimate and in reality value would be created throughout the year. A more delicate analysis would be required to make any decisive conclusions and is outside the scope of this study.

5.2 Analysis

The base scenario without any flexibility easily fulfills the requirement for 70 % self-sufficiency in the time frame of the simulation. Furthermore, the capacity of the HP is utilized almost 90 %. This implies that while heat from Espoo DH network is ‘free to use’, meaning that no additional cost to heat taken from the network is introduced, existing plan to AWD network provides more value creation in production in comparison to conventional DH and therefore creates a solid base for operation as it is.

The network, while providing some flexibility, doesn’t seem to impact all that much when it comes to value creation by decreasing costs. While in reality ‘charging’ the network would result in a decrease in the HP unit performance, the value created without introducing the costs or any other constraints into the equation was minimal and would most likely diminish when introducing them. In Figure 30 we can see that the network is constantly heated up and cooled down, which although in theory is possible, does not seem like an efficient way to operate a network and with some minimal dummy costs applied in the model would most likely reduce the usage of the flexibility.

By providing flexibility with a possibility to ‘sell’ the heat to the DH network, next to no additional value is created in this simulation, as can be concluded from the ‘HP to DH’ and ‘All on’ scenarios. An HP unit would be a more investment-heavy option in providing flexibility compared to a heat storage, especially if the heat storage is a water tank. This option may prove to be more beneficial during low local demand and low electricity prices, for example during summertime, but will require further simulation and study to be able to come up with any conclusions.

From Figure 44 we see that for this type of LTDH network there is a possibility to find an optimal capacity for flexibility when wanting to optimize in a certain timeframe. For this case, the optimum may lie somewhere between 2.5 and 5 MWh, but would require an in-depth study considering the utilization during all seasons to conclude definitively.

5.3 Discussion

Based on the results of the simulation, providing a sufficient capacity of two-way flexibility either in the form of a thermal energy storage unit or some other form of flexibility can be concluded to be the most efficient way to increase value production in the time frame of the study. The sufficient capacity is dependent on the investment costs required to achieve such flexibility and the utilization of the flexibility. As analyzed shortly in 5.1 a simple thermal storage results in considerable value creation, even when taking into account the investment costs of said option in the example. This raises the question, what if the optimization time frame would be a longer period of time? How much capacity would a seasonal storage require, and how could it best be utilized? How much more value would it create? Optimization of operating a seasonal storage would rely heavily on forecasts and therefore also increase risks involved, since no forecasting is perfect. Along with monetary value creation, a heat storage would increase the security of supply for an independent LTDH network, being able to provide accumulated heat for the network even when unable to operate local production in malfunction situations or low-temperatures.

The simulation provides a rough estimate based on a simple consumption model that is based on historical data. The purpose of the study is not to accurately predict the hourly consumption of the area, nor to give exact monetary results. Some rough estimates had to be made to make the study possible without any actual production data and the performance of the HP units rely on numbers from the HP suppliers, which don't always completely work as well in reality. However, the study shows conclusively, that it is possible to create value by providing flexibility to an LTDH area network and that it should be considered both when wanting to maximize self-sufficiency and increase monetary value creation.

5.4 Further research

This study proves a solid base for future research on the topic and could be applied in general to any LTDH network with a similar production structure and possibilities. Further subjects for study in an area LTDH network as is the case in the AWD network are endless. For this study, further research on optimal thermal storage technology options for LTDH and other possible flexibility is required, one of which being a demand-side response control of the network. Questions raised above on the optimal capacity and utilization of a thermal storage should be studied further. To complete such a study, the simulation should be completed in a longer time frame, maybe simulating a whole year production, but as discussed in 3.5 an hourly resolution would still be required. This would mean either a significant increase in computation power or a simplified model, that perhaps instead of optimizing the entire DH network alongside the LTDH network, would only take some information about the Espoo DH network as input data, such as hourly production costs, which

would make the model drastically lighter and thereby faster to simulate. The applying the sliding time window method with reasonable time frames could also make possible to simulate a whole year of production with the selected flexibility scenario.

Other questions left unanswered include what requirements would have to be made to justify an HP unit that would transfer heat from an LTDH network to an MTDH network? For example, if a cooling network would provide more heat to be utilized in an LTDH network, or the taxation of HP production where a subject of change in the future. Overall an LTDH area network as a part of a DH system may provide many opportunities and subjects for study.

6 Conclusions

Heat production is responsible for a major part of greenhouse gas emissions globally and in Finland. To reduce emissions, new renewable thermal energy sources have to be utilized, while maintaining a profitable business. Heat pumps can be used to efficiently utilize low-grade renewable heat sources, while the supply temperature of the district heating network can be lowered significantly.

This study investigates additional value creation achieved by introducing flexibility in this type of low-temperature district heating network by studying a pilot project, Aalto Works District (AWD) by Fortum as a case example. AWD is a one-of-a-kind pilot project consisting of a low-temperature district heating and cooling network that utilizes condensing heat from the cooling network in the heating network with a dual-source heat pump, that uses ambient air as an additional heat source. The study is conducted by creating a theoretical model of the heating and cooling demand in the network and the heat pump units. The model is created inside a mixed-integer linear programming tool called MONA. The production is simulated based on historical data in a time frame of one month in five different scenarios that introduce different types of flexibility.

The results of the study are promising. The study identifies that a simple heat storage unit is most efficiently able to create value in reduced operational costs, increased self-sufficiency, and utilization rate of the heat pump system. The study identifies the level of storage that may be most optimal for the case in question.

However, the study is not able to give any conclusive answers. More in-depth simulation on the heat storage scenario for a longer period of time is required to be able to conclude what type of value the flexibility may offer throughout the different seasons. The thesis is also unable to answer on the most beneficial way to operate such a heat storage – if it would be more beneficial to utilize some of the capacity as e.g. a seasonal storage.

The thesis created a solid foundation for future research and is able to achieve its goal in providing the benefit of flexibility in an LTDH network and highlighting the type of flexibility which is able to create the most additional value. If the study is conducted further, it may act as a base for any similar future projects and increase their value creation and help make decarbonized heat production more feasible in the future.

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