LAPPEENRANTA-LAHTI UNIVERSITY OF TECHNOLOGY LUT
School of Energy Systems
Master’s Degree Programme in Energy Technology

Henri Nykänen

District heat production methods: Case Keitele

Examiners: Professor Esa Vakkilainen
Doctor Ph.D Jussi Saari
Reviewer: Pertti Kovanen

ABSTRACT

Lappeenranta-Lahti University of Technology LUT

LUT School of Energy Systems

LUT Energy Technology

Henri Nykänen

District heat production methods: Case Keitele

Master’s thesis

2021

93 pages, 41 figures, 25 tables and 3 appendices

Examiner: Professor Ph.D. Esa Vakkilainen & Doctor Ph.D. Jussi Saari

Reviewer: Pertti Kovanen

Keywords: District heating, Heat production, Large-scale heat pumps, Ambient heat

In this master’s thesis was reviewed different heat production methods for the Keitele district heating network. Aim of this master’s thesis was to determine cost-effective ways to generate heat for supporting the selection of the future heat production method in Keitele.

Review was carried through with building different heat production models. Heat production models contained different base load production methods. Base load methods reviewed were combustion heat plants with woody biomass fuels, heat pumps, solar collectors, and purchased heat. The heat sources reviewed for heat pumps were ambient waters, ambient air, and geothermal energy. Their suitability and properties as a heat source were examined and geothermal and ambient air was selected in modeled systems.

Cost-effectiveness was reviewed by comparing systems levelized cost of heat. The most cost-effective heat production method turned out to be purchased heat, forest chip boiler and solar collectors. For heat pump-based heat production economic competitiveness requires that heat pumps are moved into tax category II. If tax category two is considered a hybrid system with pellet boiler and ambient air heat pump is also competitive.

As a result of this master’s thesis, there was presented costs of different heat production methods and recommended heat production method was presented. Reasons for the selected heat production method were presented including adaptability for future development on energy markets and technical suitability in Keitele was analyzed.

TIIVISTELMÄ

Lappeenrannan-Lahden teknillinen yliopisto LUT

LUT School of Energy Systems

LUT Energiatekniikka

Henri Nykänen

Kaukolämmön tuotantotavat: Kohde Keitele

Diplomityö 2021

93 sivua, 41 kuvaa, 25 taulukkoa ja 3 liitettä

Tarkastaja: Professori Esa Vakkilainen & TkT Jussi Saari

Ohjaaja: Pertti Kovanen

Hakusanat: Kaukolämpö, Lämmöntuotanto, Suuret lämpöpumput, Ympäristön lämpö

Tässä diplomityössä tarkasteltiin eri kaukolämmön tuotantomuotojen taloudellista kannattavuutta Keiteleen kaukolämpöverkossa. Tämän diplomityön tavoitteena oli tarkastella kustannustehokkaita lämmöntuotanto menetelmiä, joita voidaan käyttää Keiteleen tulevan lämmöntuotanto menetelmän valinnassa.

Tarkastelu tehtiin rakentamalla erilaisia lämmöntuotanto malleja. Lämmöntuotanto mallit koostuivat eri peruskuorman tuotantomuodoista. Peruskuorman tuotantomuotoja, joita työssä tarkasteltiin, olivat puuta polttoaineena käyttävät lämpölaitokset, lämpöpumput, aurinkokeräimet sekä ostettava lämpöenergia. Tarkasteltuja lämpöpumppujen lämmönlähteitä olivat vesistö, ulkoilma sekä geoterminen energia. Lämmönlähteiden soveltuvuuden ja ominaisuuksien tarkastelun jälkeen soveltuvimmiksi lämmönlähteiksi valikoitu geoterminen energia ja ulkoilma.

Kustannustehokkuutta arvioitiin vertailemalla eri lämmöntuotantomuotojen (LCOH) omakustannehintoja. Kustannustehokkaimmaksi lämmöntuotantomuodoksi osoittautui ostettavan lämmön, hakekattilan sekä aurinkokeräimiin perustuva järjestelmä. Lämpöpumppuihin perustuvan lämmöntuotannon kilpailukyvyn ehtona lämpöpumppujen siirtyminen veroluokkaan II. Jos veroluokka muutos huomioidaan, on pelletti kattilan ja ulkoilmaa lämmönlähteenä käyttävä lämpöpumppu on kilpailukykyinen vaihtoehto.

Diplomityön tuloksina selvitettiin eri lämmöntuotantomuotojen kustannukset sekä suositeltu lämmöntuotantomuoto esiteltiin. Perustelut suosittelun lämmöntuotantomuodon valinnasta esiteltiin sisältäen soveltuvuuden ja mukautumisen tulevaisuuden energiamarkkinoiden kehitykseen sekä teknisen soveltuvuuden Keiteleen kaukolämpöverkkoon.

ACKNOWLEDGEMENTS

Two years at Lappeenranta, what a journey.

I am glad that I choose to extend my student life and did it in LUT. Overall university offered enthusiastic and international working environment with professional teachers and warm-hearted student community. Unfortunately, half of my stay in Lappeenranta was spent under exceptional circumstances due to global pandemic. Despite of that I managed to enjoy student life at its finest and got to meet and spend time with awesome people. But like all everything comes to an end, now we all head to our own paths, for all of us it is forward.

For this master's thesis I must thank Markku Viisanen from Rejlers Finland Oy for searching this wonderful subject. From Savon Voima Oyj representors Aki, Kari, Juha and Valtteri I want to thank for attending on meetings and encouraging. For Pertti Kovanen my reviewer, now its 100 % complete. For Esa Vakkilainen I want to thank for guidance for this thesis and interesting lessons about steam boilers and stuff.

Last but not the least, thanks for my family for supporting me through my entire studies.

30.5.2021 Mikkeli
Henri Nykänen

TABLE OF CONTENT

SYMBOLS AND ABBREVIATIONS

Roman

T	Temperature	[°C]

Greek

η	Efficiency

Subindex

F	Annual fuel costs
El	Annual electricity costs
p	Annual purchased heat cost
inv,a	Annualized investment cost
O&M	Annual operation and maintenance costs
0	Maximum efficiency
1	Linear loss factor
2	Quadratic loss factor
m	System mean temperature
a	Ambient temperature

Abbreviations

CHP	Combined Heat and Power
DH	District Heat
4GDH	4th Generation District Heat
AHP	Absorption Heat Pump
EHP	Electricity Heat Pump
GHP	Gas driven Heat Pump
LCOH	Levelized Cost of Heat
LULUCF	Land Use, Land Use Change and Forestry
GWP	Greenhouse Warming Potential
SMR	Small modular nuclear reactor

1 Introduction

Buildings space heating consists of one-fourth of Finland's total annual energy consumption. Space heating demand is high because of cold weather. Roughly half of buildings heat demand is covered with district heating. District heating is a service provided by heat provider companies. District heating is produced with different methods containing methods as combustion of fossil fuels like coal and mineral oils, or biofuels like wood or agricultural residues or heat pumps utilizing various heat sources. Heat sources heat pumps consist of ambient sources, geothermal heat, waste heat. (Energiateollisuus ry, 2020)

The production cost of heat is an important factor for heat providers for main competitiveness in heating markets. Straightening climate policy requires the reduction of fossil fuels in heat production. This increases the demand for biomass fuels which is considered to increase biomass fuels price in the future. This lead district heating companies to search for alternative cost-effective ways for generating heat. (Pöyry Oy. 2020, 11)

Alternative carbon-neutral heat production methods are solar thermal, small modular nuclear reactors, geothermal energy, and heat pumps. Solar thermal is potential in large centralized systems where the cost of produced energy is lower. Small nuclear reactors could be a cost-efficiency way of producing heat, but commercial applications are currently not available. SMRs major obstacles are licensing challenges and safety requirements. Geothermal energy utilization requires the development of drilling techniques for decreasing investment costs. (Pöyry Oy. 2020, 47-49) Heat pumps are estimated to take an important role in future district heating production. Heat pumps can utilize heat sources that would conventionally be wasted. The potential of large-scale heat pumps in district heat production was estimated to be 3 to 4,2 TWh which presents 9 to 13 % of annual district heat demand. Heat pump energy coverage potential in individual district heating network properties. (Valor Partners, 2016, 44). Heat pump's cost-effectiveness is improving since the taxation category is suggested to change that decrease variable costs of operation. Also, the potential of utilizing electricity market fluctuation in production control is possible if enough other heat production capacity is available.

1.1 Thesis background

This master’s thesis is done for Rejlers Finland Oy customer Savon Voima Oyj. Savon Voima Oyj has intentions to sort out cost-efficient and carbon-neutral heat production methods to produce heat in the Keitele district heating network. Nowadays, heat consumed in the Keitele district heating network is mainly purchased from the local sawmill. Heat production reliability is guaranteed with Savon Voima Oyj operated peak- and reserve units.

Heat purchase contract period with the sawmill is coming at the end. As competition for new contract Savon Voima Oyj has the intention to sort out costs of own heat production. Reviewed heat production methods consist of conventional combustion and non-combustion carbon-neutral production methods.

1.2 Thesis aim and outline

Master’s thesis aim is to review different heat production methods and estimate the cost of productions. Heat production methods cost is estimated with accuracy that they can be utilized to support the selection of future heat production methods for the Keitele district heating network. Reviewed heat production methods consist of conventional combustion technologies which are using carbon-neutral fuels. Non-combustion methods reviewed in the thesis consist of heat pumps utilizing geothermal, ambient water, and ambient air as heat sources. Regulations and limitations are reviewed for each heat source. Also, solar collectors are reviewed.

Heat production is reviewed with generating heat production models for six different cases.

- Combustion based production
- Combustion and heat pump-based production
- Combustion, heat pump, and solar-based production
- Heat pump-based heat production
- Purchased and heat pump-based heat production
- Purchased, combustion and solar-based heat production

1.3 Thesis structure

For reviewing this task thesis was structured with studying an overview of district heating's current state and prospects. This was done in Chapter 2. After determining bigger guidelines of district heating combustion and non-combustion-based heat production methods were reviewed in Chapters 3 - 4. After this studied district heating network was introduced in Chapter 5. Modeled heat production models are presented in Chapter 7. Modeled heat production models economic and environmental properties are compared, and recommended heat production method is presented in Chapter 8. Results are analyzed and in Chapter 9. The thesis summary is presented in Chapter 10.

2 District heat in Finland

District heating has a long history in Finland. DH is centralized heat production which consists of heat production units and a distribution network. DH's working principle is that heat is produced in heat production units and delivered to a customer with the distribution network. Customers can utilize heat for building space heating, domestic hot water, and industrial processes. The first commercial application was introduced in Helsinki Olympic Village in 1940 after this district heating was applied slowly to other cities. DH was first applied to city centers where heat demand per square meter was highest. This was economically most viable since the heat distribution network is the most costly component. (Koskelainen L et. all, 25-27). Today district heating is the most common space heating method for residential, commercial, and public buildings with a market share of 46 %. DH heat demand has been increasing annually because district heating networks are continuously expanding, and new customers are constantly joining. (Energiateollisuus ry, 2020). Annual DH demand is illustrated in Figure 1 where can be seen that annual heat demand has been increased from 5 TWh to 37 TWh from 1970 to 2019. (Energiateollisuus ry, 2021)

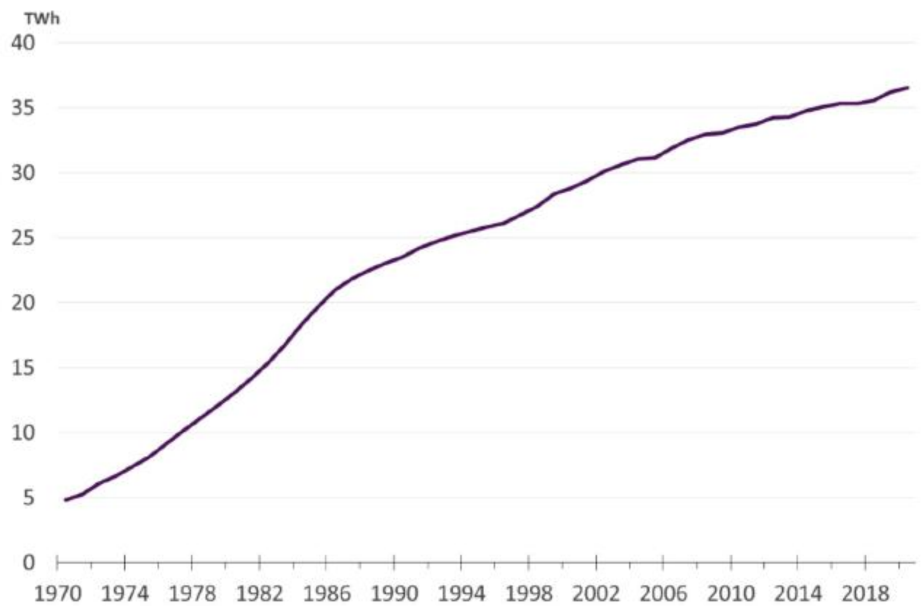

Figure 1 Temperature corrected district heat demand (Energiateollisuus ry, 2021)

2.1 Heat production

In Finland DH is produced mostly with combined heat and power production. CHP includes production where useful heat and power are generated simultaneously. Depending on technical solutions overall efficiency varies from 80 – 90 %. Power to heat ratio in district production units is typically 0,5. Gas combined cycle power plants can achieve power to heat ratios over one, therefore more power is generated than heat. Combined gas cycle power plants utilize steam and gas turbines in power generation. (Koreneff et all, 6-7). CHP production requires higher investment costs compared to heat only production. Therefore, CHP has applied places where heat demand is relatively high to achieve economic viability (Koskelainen et. all, 27). DH is available in 174 municipalities in Finland there are many DH networks with lower heat demand where heat only units are utilized. Alternative heat generation methods are heat only production with heat only units and heat recovery utilization. (Energiateollisuus ry, 2020)

CHP share in DH production has declined from 75 % to 67 % from 2008 to 2019. CHP production's economical attractiveness has been impacted because of cheap wind power electricity available in the electricity market (Rämä. M. 2020). CHP weak competitiveness is estimated to be caused by an increasing amount of heat pumps, limited availability of biofuels, and increased price of emission allowances (Koreneff et all, 40). Therefore, some CHP units at end of technical life have been replaced with heat only production units. (Energy authority of Finland). Also, the ban of coal in energy use is a reason for large units to close at some point before 2029. This is one key point of Finland's national energy plan to be carbon neutral in the year 2035 (Government of Finland). This adds pressure towards the carbon-neutral DH industry in Finland.

DH demand was 36,6 TWh in 2019 where CHP share was 66,6 %. Heat pump and heat recovery share in district heating supply was 10,5 %. Heat only combustion production was covering the remaining portion. Shares of district heating primary energy sources can be seen in Table 1. There can be seen that consumption of fossil fuels has decreased and biofuels increased from 2010 to 2020. In 2020 renewable sources portion was the first time over half of DH production. (Energiateollisuus ry, 2020) District heating production with biofuels and renewable sources are efficient ways to decrease Finland's carbon dioxide emissions. Carbon dioxide emissions are zero when biomass is used in combustion. Biomass is considered to recycle carbon dioxide released from burning during its growing period. (Vakkilainen E. 2017, 21)

Table 1 District heating heat supply shares in 2020 and 2010 (Energiateollisuus ry, 2021)

	2020 %	2010 %
Coal	11	20
Natural gas	14	30
Peat	14	19
Heat recovery	11	3
Other biofuels	8	2
Industrial wood residues	13	7
Forest fuelwood	22	10
Other	6	2
Oil	1	7

2.2 Heat distribution with transmission pipes

In Finland, district heat is distributed from heat producers to consumers with a two-pipe system. The two-pipe system consists of one supply and one return transmission pipe. Transmission pipes are insulated and installed underground. These pipes are filled with treated water which is pumped through the district heat system to transport heat. The pressure of water is required to be high enough to prevent boiling. Supply pipe is used to deliver warm water from heat producer to customer and return pipe is used to deliver cooled water from a customer back to heat producer (Koskelainen et al., 338). The temperature of supply water is related to the outside temperature. This is illustrated in Figure 2. There can be seen that supply water temperature varies between 75 °C and 120 °C. Also, heat consumers may require certain supply temperatures for an industrial process for example. Therefore, a district heat network may have other limiting factors for supply temperature than the outside temperature. (Mäkelä & Tuunanen)

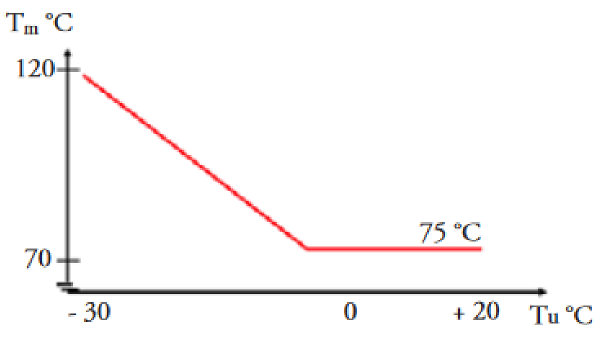

Figure 2 Supply water temperature in different outside temperatures (Mäkelä & Tuunanen)

Transmission pipes and all other metal parts in a district heating system are dimensioned with operating pressure of 16 bars and operating temperature of 120 °C. The technical lifetime of estimated lifetime transmission pipes are depending on supply temperature. With constant supply temperature transmission pipes are estimated to have a technical lifetime of over 50 years. In Finland, some district heating networks have a lifetime up to 70 - 100 years (Mäkelä & Tuunanen, 50). Transmission pipes can have different styles of insulations and assembly methods. Pipes are named with coding related to pipe properties. Properties are example cover type, insulation material, and other special properties like alarms or atmosphere installation. The most common pipe types used are Mpuk and 2Mpuk. They are polyethene covered polyurethane insulated pipes. 2Mpuk has separated covers for return and supply pipes and Mpuk has return and supply pipes located inside the same cover. 2Mpuk are used in pipe size with DN 20 up to DN 1200. Mpuk is used in pipe size DN 20 to DN 200. Mpuk has smaller heat losses compared to the same scale 2Mpuk pipes. Pipes are presented in Figure 3. (Koskelainen et al, 137-139).

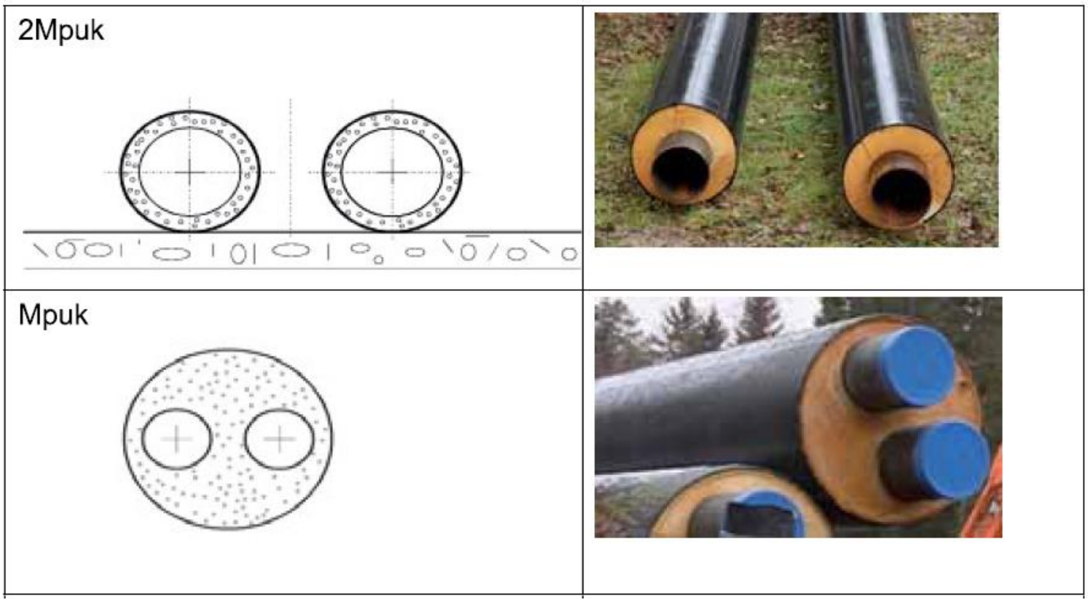

Figure 3 2Mpuk and Mpuk pipes (Mäkelä & Tuunanen, 50)

2.3 Reliability of heat production

District heat provider is obligated to deliver heat to customer related heat delivery contract. The delivery contract determines the quality and requirements for delivered heat. Deviation in heat delivery obligates heat providers to compensate losses on the customer.

Recommendations for heat delivery contract details in Finland are set by Finnish Energy. Heat delivery companies can adjust rules for their needs. (Energiateollisuus ry, 2017). DH production reliability is secured with proper maintenance and a variety of heat production units.

Each DH network has more than one heat production unit to increase the reliability of heat delivered to customers. More units are required because heat demand is varying and production units have planned or unplanned failures. Heat demand is varying seasonally which requires flexibility in heat production. Heat production units are separated into basic load, peak, and reserve units. The number of required units is depending on DH network size and special properties. Every network has at least one basic load unit and a reasonable amount of peak and reserve units. (Mäkelä & Tuunanen, 30) Optimal base load unit size is determined with annual peak-operating hours. In smaller DH networks annual peak-operating hours of 2500 h/a are used and 3200 h/a in larger networks for base load units. This dimension method leads to basic load production units covering 40 - 60 % of network peak demand and producing 80 – 90 % of annual heat energy demand. (Koskelainen et al. 322-324). If CHP unit is utilized electricity production can cover up to 70 % of city electricity demand. Peak and reserve units combined heating capacity is required to be at least the same as the largest basic load unit in the district heating system. Multiple heating units operating at the same time requires, that all units are producing the same supply temperature and only one unit is responsible for controlling heat demand changes. (Mäkelä & Tuunanen, 30-34). Peak and reserve units can be distributed along a different part of a network for increasing reliability in case of transmission line failures. (Koskelainen et al. 378)

2.4 Cost structure for heat provider

District heating cost structure is built from capital costs, variable costs, operation and maintenance costs. Capital costs consist of the main portion of heat provider costs. Capital costs are built mainly from district heat networks and production units' fixed assets investment costs. Operating in the industry requires constantly new investments which also increase fixed assets cost during operation. DH network costs are related to used transmission pipe type and network heat demand intensity. Network heat demand intensity describes how densely built area network is located. With densely built area investment cost is lower per delivered heat unit. Heat production unit capital costs are depending on the type of production unit and size of the unit. Main effect optimizing capital cost from heat production units selecting production capacities for basic load and peak load units. Operation and maintenance costs are built from labor, rents, maintenance, and other service costs. O&M costs in different scale heat production units and DH networks are presented in Figure 4 and Figure 5. There can be seen that cost varies related to the size of units. Variable costs consist of bought heat, fuel costs, fuel taxes, emission allowance costs, self-use electricity, and make-up water costs. (Koskelainen et al. 467 - 469)

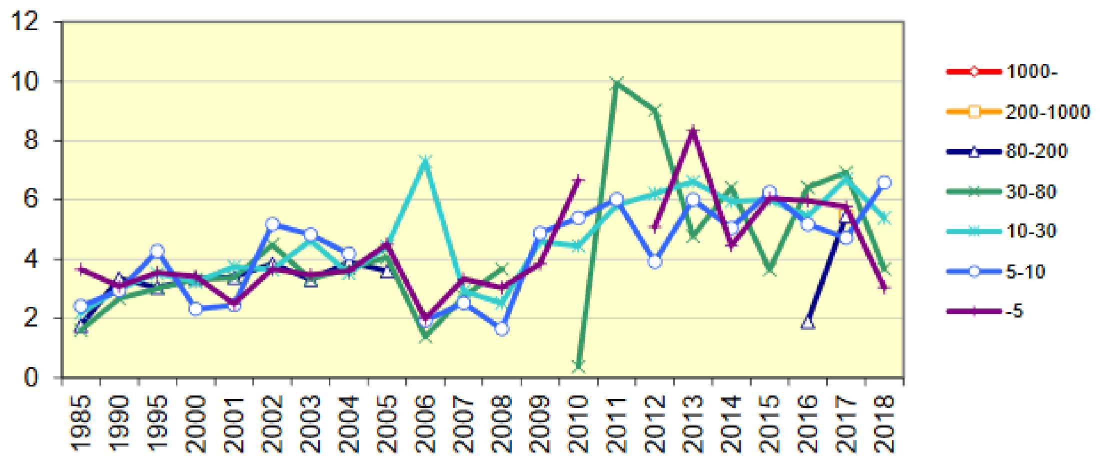

Figure 4 Operation and maintenance cost €/MWh in heat production units (Energiateollisuus ry, 2019)

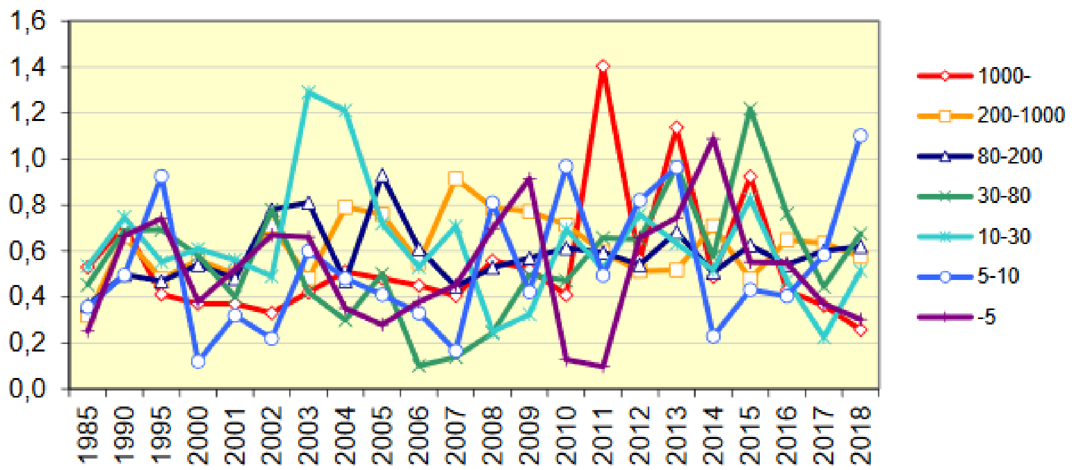

Figure 5 Operation and maintenance cost €/MWh of district heat network (Energiateollisuus ry, 2019)

2.5 Prospects of district heat

Finland has free markets in the heating sector which allows heat consumers to choose heating solutions freely (Pöyry Oy. 2018, 51). This requires DH companies to keep up attractiveness against alternative heating solutions. Accomplishing this DH industry requires constant evolving which includes conversion to renewable energy and adapting to a reduction in space heating demand in building stock reform, utilizing low-temperature distribution, adapting district cooling, two ways district heating, and adding intelligence in the system operation. These changes are defined as the concept of the 4th generation of district heat (4GDH). Earlier generations and changes in between are presented in Figure 6. There can be seen that the temperature level in district heating is decreasing and energy efficiency of the system is increasing, and new energy production and storage systems are applied. (Lund et all.)

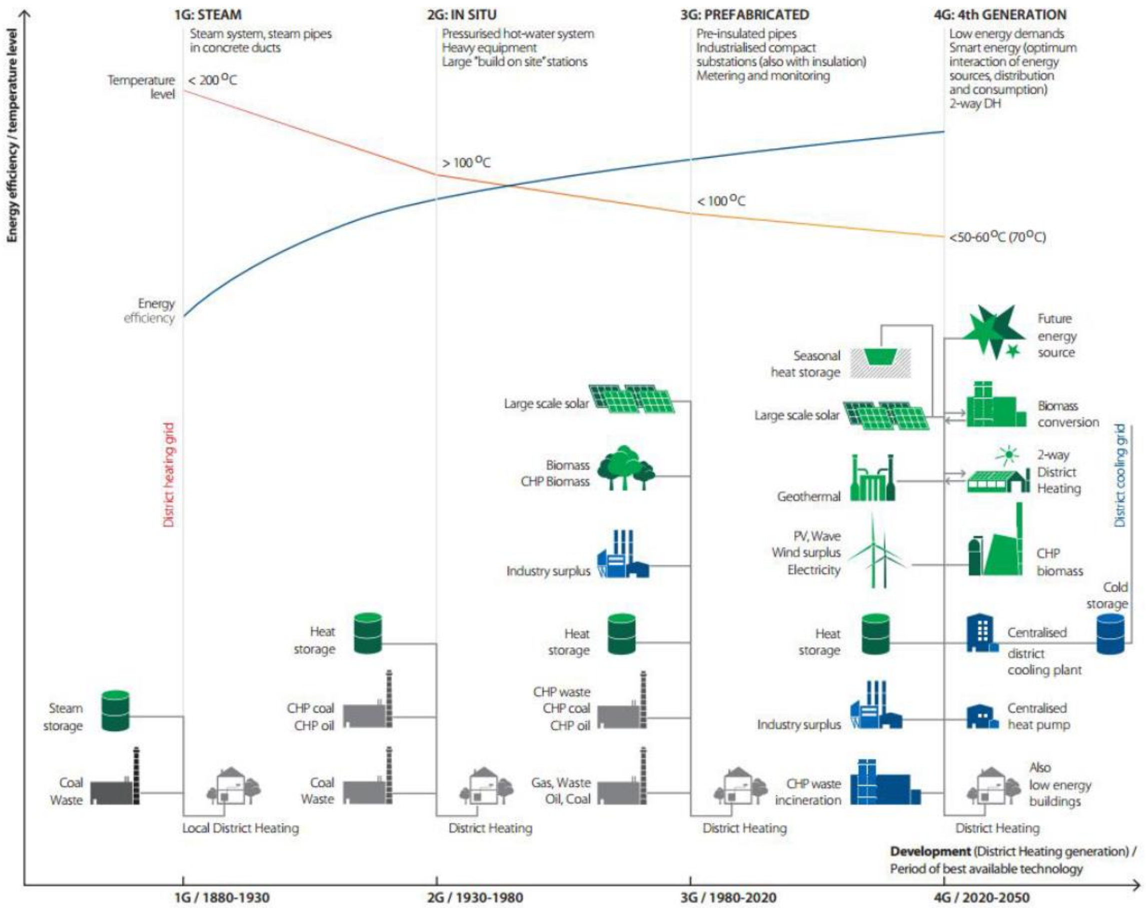

Figure 6 Illustration of the concept of 4th Generation District Heating (4GDH) (Lund et al. 2014, 9)

2.5.1 Intelligent district heating

Intelligent district heating means is a concept that describes a flexible way to produce heat for a customer. This involves control between centralized and decentralized heat production and the utilization of storage and production units to balance peak demands. This is done with data analysis on weather forecasts, historic data, and controlling production units in real-time. Costumers are attracted to intelligent systems with encouraging pricing for balancing peak demands. The main goal is to make the system more beneficial for everyone in the DH system. (Pesola et al. 17-18)

2.5.2 Synergy with electricity market

The synergy between district heat and electricity markets increases systems flexibility. For the electricity market, there is potential for control- and reserve markets. For DH there is potential to decrease carbon dioxide emissions. Increased renewable electricity generation may lead to a situation where some production requires to be disconnected to maintain grid stability. Preventing that excess renewable energy would be economically and environmentally friendly to be beneficial utilize in DH production. Suitable production methods for DH production could be electric boilers or heat pumps. In economical profitability calculations, all electricity price portions must be taken into count. (Pöyry Oy. 2018, 37-39)

2.5.3 Low-temperature distribution

The low-temperature distribution network is a concept where distribution supply temperature is below + 70 °C it is an essential part to make renewable energy sources more suitable for district heat production (Pöyry Oy. 2016, 9). Low temperature allows higher production efficiency from renewable energy sources. Also, distribution heat losses are lower compared to conventional temperatures-operated networks. Disadvantages are that customer district heat equipment requires changes and decreased heat transfer may cause more pumping for increased mass flow. This may require increased size for distribution pipes. (Pesola et al. 34) Low-temperature distribution is more viable for new distribution networks where customers have modern housing with low heat demand and low temperature in a household heating system. Modernization of old networks are required too many changes and achieved benefits remain lower than total costs. (Pöyry Oy. 2016. 19, Lund et all, 4)

2.5.4 District cooling

District cooling is a new concept in Finland. District cooling is used mostly in the office, commercial, and commercial buildings use in residential buildings is increasing. District cooling use distribution network like DH. The working principle is similar as in DH but energy is collected from the customer and send back to the district cooling provider. Energy recovered from cooling can be utilized in district heat production with a heat pump. (Pöyry Oy. 2018, 11) Finland district cooling energy delivery and connected load is shown in Figure 7. There can be seen cooling demand is increasing.

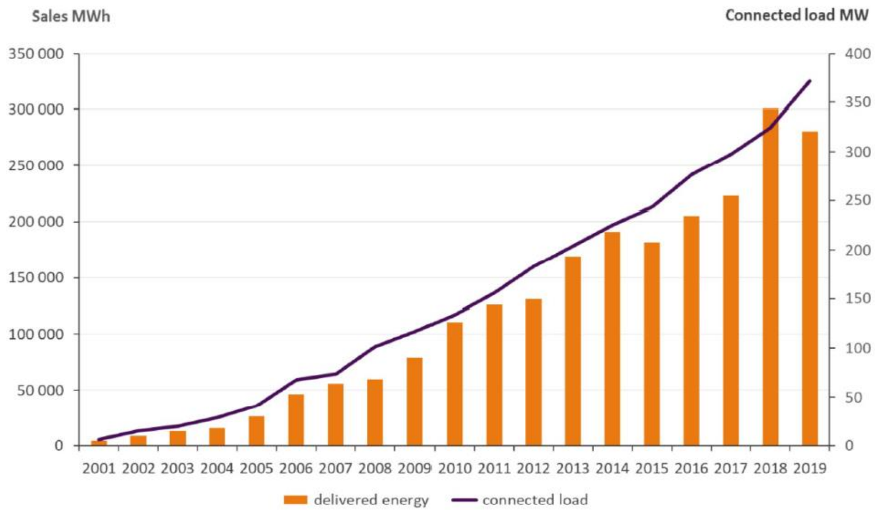

Figure 7 District cooling delivered energy and connected load in Finland (Energiateollisuus ry, 2020)

2.5.5 Two-ways district heating

Two-ways district heating is a concept where customers can produce and consume heat from the district heat network. Customers can be also only producers. Adapting two-way operation requires that the overall efficiency of the system increases, and negatively impact network operations are excluded. Positive impacts in system scale can be reduced use of reserve production units with fossil fuels during low heat demand seasons. The negative impact can be that individual heat production causes basic load powerplant or heat only boiler to require operate below minimum power. (Pöyry Oy. 2016, 5-8) Also, multiple heat supply points in the DH network can cause instability in pressure and temperature levels. The required temperature in level might be hard to achieve. Therefore, combined with low-temperature distribution improves economic viability. (Pesola et al. 35)

3 Combustion based carbon neutral heat production

Combustion is generating a major portion of Finland's carbon emissions. Depending on the fuel used in combustion effect on net addition in carbon dioxide in the atmosphere is different. Carbon dioxide is released in combustion when carbon in fuel reacts with oxygen producing carbon dioxide. Biomass combustion is considered to release an equal amount of carbon dioxide during burning as it has taken from the atmosphere during the growing period. If biomass is left to decompose in nature it releases carbon dioxide and stored energy slowly. By burning biomass store of energy is released quickly and stored energy can be utilized. (Saidur et all. 2011, 2266)

3.1 Combustion

Combustion is a thermochemical reaction where fuel is reacted with excess air producing hot gasses. Combustion is a complex phenomenon where series of chemical reactions take place which consists mainly of carbon oxidized to carbon dioxide and hydrogen oxidized to water. Also, other chemical reactions are involved. Characteristics of combustion are related to fuel elemental composition. Biomass fuel's elemental composition varies between each fuel type. (Saidur et all, 2275, Christoforou, E. & Fokaides P. 2019, 69)

Combustion can be separated into four different phases which are drying, pyrolysis, volatile gases combustion, and char combustion. During drying the moisture of fuel is evaporated. During pyrolysis wide range of combustible gases is released. These combustible gases are mostly hydrocarbons. Combustion of hydrocarbons is series of chemical reactions. In optimal combustion conditions, these reactions are reacting in the following order $CH_4 \rightarrow CH_3 \rightarrow CH_2O \rightarrow HCO \rightarrow CO \rightarrow CO_2$. The last phase of combustion is char combustion. Char combustion is defined to start after all volatile matter has been released. This left-over material is called fixed carbon. Fixed carbon is burned with surface reactions. In industrial boilers, char combustion and pyrolysis processes are overlapped. The heat released in combustion is related to reaction enthalpies in chemical reactions. Leftover solid material from combustion is called ash. (Vakkilainen, E. 2017, 33-34 & Raiko et all, 50, 60-61, 72-73)

3.2 Solid biomass fuels

Solid biomass fuels can be generated from various biomass feedstocks such as wood, energy crops, and residues from the forest industry, agriculture, or forestry. Organic components of industrial and municipal waste can be also utilized. Animal wastes and algae are also considerable. Wood and wood wastes are considered to the most potential feedstock for solid biomass biofuels. Solid biomass sources can be divided into four different categories. (Christoforou, E. & Fokaides P. 2019, 5)

- Woody biomass
- Herbaceous biomass
- Fruit biomass
- Aquatic biomass

Woody biomass included biomass resources mainly from forestry and fuel sources can be divided into the following sub-categories related to biofuel standard EN ISO 17225-1:2014. (Alakangas et all, 64)

1.1 Woody biomass from forest, plantation, or other virgin wood
1.2 By-products and residues from wood processing industry
1.3 Used wood

Classification of woody biomass fuels is presented in Figure 8. There can be seen that woody biomass is gathered from various sources and different type of fuels can be produced. Forest residues are the main sources of wood fuels from biomass from category 1.1. Forest residues contain logging residues which are consisted of treetops, stumps, branches, and small-diameter timber. These matters are pretreatment with chipper or crusher producing wood chips or hog fuel. By-products from the wood processing industry contain more variety in wood fuel classes which are grinding powder, cutter shavings, saw dust, and bark. These fuels can be also refined into pellets and briquettes. The last category is used wood which contains consumers recycled used wood which is separated into chemically and chemically not treated wood.

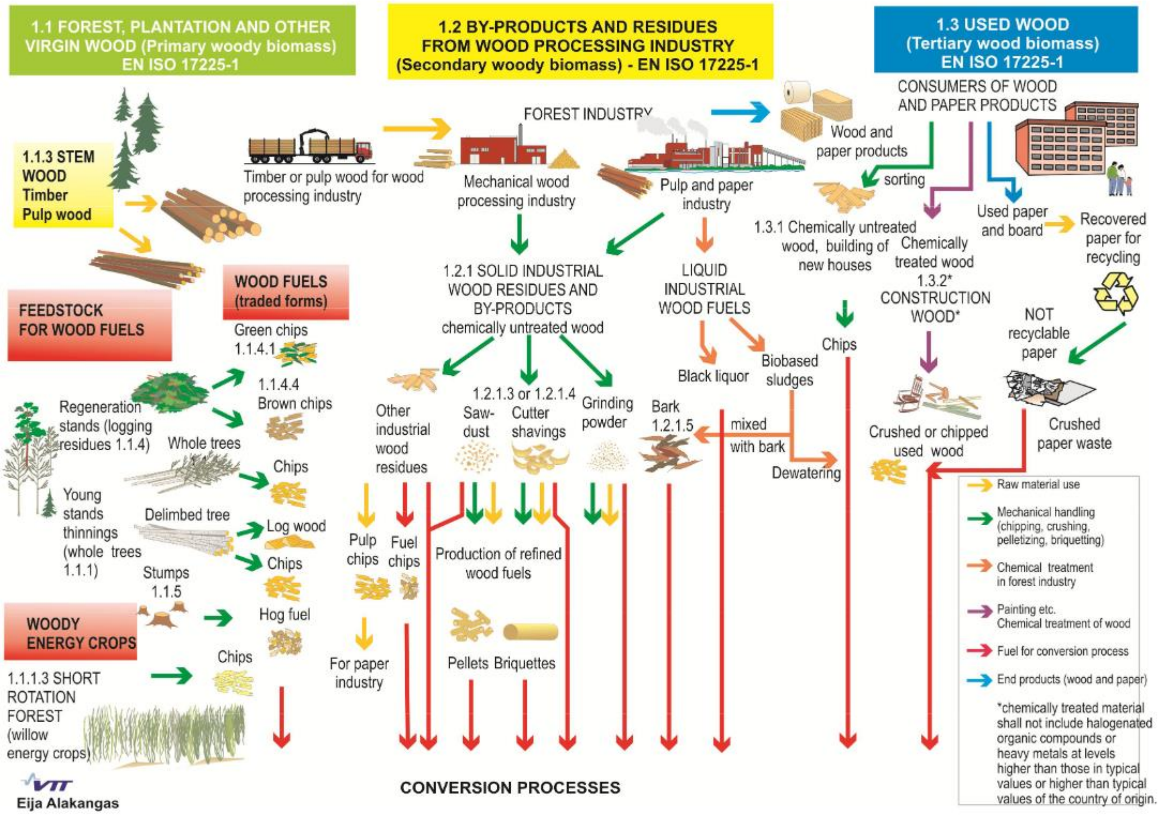

Figure 8 Classification of wood fuels (Alakangas et all, 64)

In 2020 Finland's forest is estimated to be grown 108 million cubic meters. The total harvested amount was 65,2 million cubic meters where 8,5 million cubic meters were used for energy. (Torvelainen, J. 2021) The distribution of different types of wood fuels in Finland is shown in Table 2. There can be seen that forest chips and industry by-products are the most used wood fuel sources.

Table 2 Solid wood fuel consumption in heating and power plants by year (Natural Resources Institute Finland, Statistic database)

	2016	2017	2018	2019
Forest chips [GWh]	14 805	14 427	14 844	15 111
Industry by-products [GWh]	19 997	21 251	20 842	21 184
Wood pellets and briquettes [GWh]	1 040	1355	1 287	1 363
Recycled wood [GWh]	1 545	1 423	1 654	1 866

Herbaceous biomass includes biomass from agricultural and horticultural sectors. Also, including by-products from the food and herbaceous processing industry. Herbaceous biomasses typically have high concentrations of elements that might cause issues with emissions, corrosion, and ash melting. (Christoforou, E. & Fokaides P. 2019, 6, 9) Related to

Alakangas et all most potential sources of herbaceous biomass in Finland are cereals with an estimated potential of 10,6 TWh.

Fruit biomass includes biomass obtained from bushes, trees, and herbs as fruit biomass material and vegetable residues from the fruit food processing industry. Examples of fruit biomass sources in Finland are turnip rape and oil seed rape. Leftovers in turnip rape seeds processing have an energy content of 4,43 MWh/m^3. (Christoforou, E. & Fokaides P. 2019, 10, Alakangas et all, 141)

Aquatic biomass includes biomass obtained from aquatic-based feedstocks like algae, water hyacinth, reeds, and seaweed. Reed canary grass and common reed are the most common aquatic biomass sources in Finland. Challenges using reed as fuel low density and ash smelting properties. Depending on harvesting time moisture and ash melting properties changes. Competence as a source of biofuel properties can be improved by producing pellets. As pellets density increases from 171 to 659 kg/m^3. Increasing density improves logistical and storage potential for fuel. (Christoforou, E. & Fokaides P. 2019, 10-11, Alakangas et all, 142-146)

3.3 Solid biomass combustion techniques

Combustion of solid biofuels is considered a low costs and high-reliability way to convert biofuels directly to heat. Properties of solid biofuel determine the most suitable conversion process. Moist important properties are related to the following properties: (Alakangas et all, 196, Christoforou, E. & Fokaides P. 2019, 11, 69)

– Moisture content
– Net calorific value
– Ash content
– Volatiles fraction and fixed carbon content
– C, H, N, S, O content
– Particle size

Industrial-scale combustion techniques units can be dived into the following categories: (Christoforou, E. & Fokaides P. 2019, 78)

- Grate combustion
- Fluidized bed combustion
- Pulverized combustion

3.3.1 Grate combustion

Grate combustion boiler can be classified by type of grate which can be stationary, moving, traveling, vibrating, and rotating. Stationary grates are used in smaller units and moving grates in larger units. Stationary grates are inclined to fuel to flow forward over the grate. Typically, 30 – 50 -degree inclination is used in boilers using biomass sources as fuel. Moving grates always have inclination but inclination less than on stationary grate around 15 degrees. Rotating grate boilers use conical grate sections which are rotating in opposite directions. Rotating grates allow well mixing for fuel and combustion air which makes systems suitable for combust high moisture fuels. Vibrating grates transport fuel with vibration they are used when fuel properties cause sintering or slagging. Grates are usually cast iron with small amounts of chrome to improve material properties and they are cooled with combustion air or water. (Christoforou, E. & Fokaides P. 2019, 78, Raiko et all, 466 - 475)

Combustion in grate boiler follows the same stages that occur in any other combustion application. Fuel is feed on the top part of the grate. Combustion in grate starts with drying at the top part of the grate where the moisture of fuel is evaporated. With biomass fuels moisture 30 – 60 % largest portion of grate total length is required for fuel drying. Drying can be optimized with fuel pretreatment and air preheating. After drying pyrolysis start and volatile gases are released and combusted. As biofuels have a high portion of volatile material which is around 70 % combustion air and volatile gases must mix well for efficient combustion. The last phase is char combustion which occurs in the last portion of grates. Combustion phases in grate boiler are shown in Figure 8 where number 1 presents fuel feed, 2 dryings, 3 devolatilizations, 4 char combustion, 5 ash, and 6 primary air. (Vakkilainen, E. 2017. 205-208 & Raiko et all, 466 - 475)

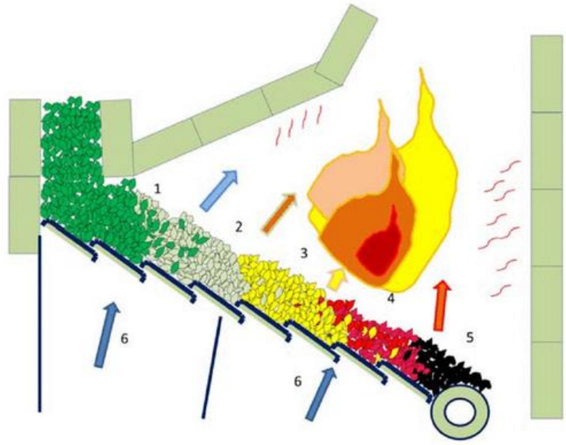

Figure 9 Combustion phases in grate boiler (Vakkilainen, E. 2017. 209)

For combustion air is distributed to primary air, secondary, and sometimes even to tertiary air. Primary air is blown to the furnace from below the grate. For combustion optimization, it is beneficial that primary air flow can be controlled separately to different parts of the grate related to phases of combustion. Even distribution of fuel is beneficial for even air mixing. (Vakkilainen, E. 2017. 205-208 & Raiko et all, 466 - 475) Grate combustion has certain problems related to combustion control, uneven distribution of fuel in the furnace which may lead to increased emissions. Benefits for grate firing that a variety of solid fuels can be cheaply fired. Finland grate combustion is used in applications below 5 MW and fluidized combustion is used in applications above that. (Huhtinen et all, 36 & Raiko et all, 466).

3.3.2 Fluidized bed combustion

Fluidized bed combustion has come popular in the 1970s. Fluidized bed combustion is a combustion method where fuel is combusted in the fluidized sand bed. The sand bed is in the bottom of the furnace, and it is fluidized with combustion air blown through it. Fluidized bed combustion suits well on high moisture and low-grade fuels. Also, a variety of fuel mixtures can be used, and changes in fuel quality have a low effect. Emission control for sulfur, NOx, CO emissions reduction adaption is technically feasible. Fluidized combustion can be categorized into two sections circulating fluidized bed (CFB) and bubbling fluidized bed (BFB). (Raiko et all, 490)

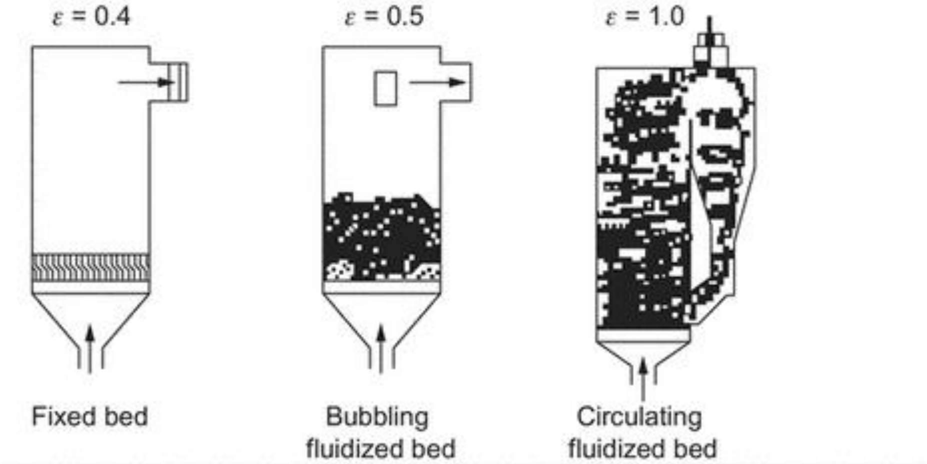

Figure 10 Different types of fluidization (E. Vakkilainen 2017)

Fluidized bed combustion has the following requirements. (Huhtinen et all, 37))

- Fluidizing air distribution is equal
- Fuel feed and quality is equal
- Bed temperature is in the range of 700 – 900
- Bed particle size is right
- Ash is removed as fly ash
- Bed height is right
- Air fuel rate is right

BFB boiler has 0,4 – 0,8 - meter height sand bed in furnace bottom which surface can be noticed. Sand results 6-12 kPa pressure drop over the bed. Sand particle size in BFB is around 1 mm. Fluidizing velocity is 1 – 3 m/s. Typically half of the total combustion air is feed from below the bed. Rest is blown in from furnace walls as secondary or tertiary air with air stagging NOx emission can be controlled. Fuel is fed to on top of the bed using one or more feed points. Small particles are combusted above the bed and heavier particles are dried and combusted in the bed. Bed sand is removed during operation to remove ash and rough sand from the bed. BFB is used in applications of unit size less than 100 MW but can units up to 300 MW are possible. (Huhtinen et all, 36-37, Vakkilainen E. 2017, 212, 218-220 & Raiko et all, 490)

CFB boiler has sand is flying among flue gasses. Typically, a cyclone separator is used to separate sand from flue gasses, sand redirected to the bottom of the furnace with a loop seal. Sand particle size in CFB is 0,5 mm. Fluidizing velocity is 8 – 10 m/s. The pressure of primary air is 15-20 kPa and typically 30 – 60 % of combustion air is primary air. Fuel feed can be similar arrangement as in BFB. In addition, fuel can be feed to the loop seal to be mixed with returning sand for uniform fuel distribution. CFB is used in applications above 100 MW. (Huhtinen et all, 36-37, Vakkilainen E. 2017, 212, 220-222 & Raiko et all, 490)

3.3.3 Pulverized combustion

Pulverized combustion has been utilized conventionally in coal and peat combustion. A similar application can be used for biomass. In pulverized combustion, solid fuels are ground to fine dust and combusted in the furnace. Dust is required to be so fine that complete combustion occurs rapidly in the furnace. High moisture fuels are dried before combustion for better ignition and combustion. Fuel is carried to burners with carrier air which is typically primary air. Secondary air is blown into burners for combustion. During operation fuel ignites from the heat inside of the furnace and during start-up fuel is required to ignite solid fuel. (Huhtinen et all, 93, Vakkilainen E. 2017, 204)

Fuel properties determine pulverized combustion type. The main properties are ash content and portion of volatiles matter of fuel. Combustion types are two smelt furnace combustion and dry furnace combustion. In smelt furnace combustion occur so high temperature that ash smelts. Smelt ash is then removed from the bottom of the furnace or specific chamber. Dry furnace combustion ash is removed from flue gases. Smelt combustion is suitable for high heating value fuels with low volatile matter content. High moisture or high ash content does not limit fuel capability for pulverized combustion if the heating value and portion of volatile matter are high enough to maintain stable combustion. Therefore, co-firing might be required if fuel quality is too low. Fuel moisture should be below 60 % and heating value higher than 7 MJ/kg. (Raiko et all, 455)

Burners in pulverized combustion can be separated into two types which are vortex and swirl burners. In Swirl burners, pulverized fuel ignition is based on hot flue gases inside the furnace. Vortex burners pulverized fuel ignition is based on vortices that bring already ignited fuel and hot flue gas back to the burner which ignites fresh fuel. NOx emissions are controlled by proper air stagging. (Raiko et all, 457-458)

3.4 Liquid biomass fuels

Liquid biomass fuels can be categorized into four different generations related to the basis of the feedstocks and technology utilized for their production. First-generation biofuels are produced from edible biomass sources. Second-generation biofuels are produced from a wide range of non-edible feedstocks from lignocellulosic feedstocks to municipal wastes. Third-generation biofuels are produced from algal biomass, also utilization of CO2 feedstocks. Production methods for producing biofuels are pyrolysis, fermentation, Fisher-Tropsch synthesis, methanol synthesis, and hydrolysis. (Soo-Young, N. 2019, 1-3)

Fast pyrolysis oil is estimated to be the most techno-economically profitable biofuel for replacing fossil heating oils in Finland. Fast pyrolysis oil is produced with heating biomass in less than two seconds to around 500 °C in a low oxygen environment. This causes biomass to convert to gases and aerosols which are liquified in the gas condenser. Fast pyrolysis oil production could be integrated into CHP units to increase production efficiency by generating heat and power and fuels simultaneously. Pyrolysis oil is properties and comparison between commercially used heating oils in Finland are shown in Figure 11. There can be seen that pyrolysis oils have higher moisture and lower net calorific value than conventionally used fossil mineral oils. Properties of pyrolysis oil are varied related to used raw material. (Alakangas et all, 174)

Conventional mineral oils using heat plants can be converted to using pyrolysis oil as fuel with relatively simple changes. Commercially few available burners for fast pyrolysis oil combustion are available. There have been challenges with maintaining a stable fire, ignition, and fuel atomization. Pyrolytic oil utilization challenges are acidity which can corrode materials and issues with long storage since pyrolytic oil properties change over time. (Alakangas et all, 174, Niskanen, T. & Karjalainen, T. 2014, 16 & Soo-Young, N. 2019, 202-203)

Property	Standard (see Appendix D)	Typical bio-oils	Heavy fuel oil 180/420	Light fuel oil
Solids, %	ASTM D 7579	< 0.5		
pH	ASTM E 70	2–3		
Water content, w-%	ASTM E 203	20–30	~ 0	~ 0
Viscosity (40 °C), mm²/s (cSt)	EN ISO 3104, ASTM D 445	15–35[1]	max 180/420 50 °C	2.0–4.5
Density (15 °C), kg/dm³	EN ISO 12185, ASTM D 4052	1.10–1.30[1]	max 0.99/0.995	max 0.845
Total acid number (TAN), mg KOH/g	ASTM D 664	70–100		
Net calorific value as received, MJ/kg	DIN 51900, ASTM D 240	13–18[1]	min 40.6	42.6
Ash, w-%	EN ISO 6245	0.01–0.1[2]	max 0.08	max 0.01
Carbon residue (MCR, CCR), w-%	ASTM D 4530, ASTM D 189	17–23		
C, w-%, dry	ASTM D 5291	50–60		
H, w-%, dry	ASTM D 5291	7–8		
N, w-%, dry	ASTM D 5291	< 0.4	0.4	0.02
S, w-%, dry	EN ISO 20846, ASTM D 5453	< 0.05	max 1.0	max 0.001
O, w-%, dry	calculation	35–40		
Na+K+Ca+Mg, w-%, dry	EN ISO 16476	< 0.06		
Cl, ppm	ISO 8754, ASTM D 4294	< 75		
Flash point, °C	EN ISO 2719, EN ISO 9038, ASTM D 93B	40–110[3]	min 65	min 60
Pour point, °C	EN ISO 3016, ASTM D 97	−36…−9	max 15	min −5

[1] Depends on the water content.
[2] Metals are oxidised on heating, which can lead to excessively high ash content (i.e. an ash content greater than the volume of solids).
[3] The flash point determination method is not suitable for pyrolysis oil. More information: Oasmaa et al. 2012.

Figure 11 Composition of typical fast pyrolysis oils and comparison to mineral oil (Alakangas et all, 176)

3.5 Liquid biomass combustion techniques

Liquid biofuels are supposed to replace heavy and light oils in boilers. Compared to fossil fuels liquid biomass fuel combustion is more complex. Because bio-oils are containing various compounds combustion occurs in two stages. In the first stage, moisture is evaporated and light compounds are combusted. In the second stage, heavier compounds are combusted. In industrial-scale applications, both stages must be combined in one flame to maintain stable combustion. This can be ensured with a proper burner design. (Lehto et all, 182)

Burner technologies used in heavy or light oil combustion can be applied with bio-oils. Burners' main task is to maintain stable and efficient combustion. For achieving this burner must atomize the liquid into small droplets, secure ignition, optimize air to fuel mixture, and control emissions. Atomization can be done with pressure swirl, air or steam-assisted atomizer, or with rotating cup atomization. Industrial-scale burners can be classified into two main types of mono-block burners and dual-block burners. Mono-block burners have integrated air blowers for atomization, and they are used in smaller applications up to 15 MW. Dual-block burners can have both pressure and auxiliary technologies for atomization. Auxiliary techniques involve compressed air or steam injection to improve atomization. Dual is used in applications above 10 MW. The third atomization method used in burners is a rotating cup which involves a rotor that mechanically improves atomization. This application can be utilized in 5 to 40 MW units. (Lehto et all, 183-184, Raiko et all, 441)

Bio-oils have a lower heating value compared to mineral oils which require higher flow rates for firing. Nevertheless, this difference is mostly neglected with lower air to fuel ratio with bio-oils since the oxygen content of a fuel is high. Air to fuel ratio in bio-oil firing is half from mineral oil firing. Also, the flame in bio-oil firing is physically larger. Therefore, if existing burners are converted for biofuels, they must be modified and the flame should be able to fit into the furnace. Also, all parts in contact with biofuels should be replaced with parts that are made from stainless steel or other acid-resistant material. (Lehto et all, 185)

3.6 Emission regulations

Heat production units that are based on combustion are controlled by regulations. Regulations set limits and requirements for the operation to be environmentally friendly. In Finland for combustion units with fuel power between 1 to 50 MW are controlled with the law Government Decree on Environmental Protection Requirements for Medium-sized Energy Production Units (1065/2017).

The law sets requirements for combustion unit emissions. Main regulated emissions are dust, NO_x, and SO_2. Required emission levels are depending on the fuel type and fuel power of the unit. All units medium-sized combustion units in Finland should be operated with new emission limits presented in Table 3. If the energy production unit started operation before the 20th of December in 2018 plants have time to adjust the process to meet these requirements. During this transition period emission limits are shown in Table 4. Before and after 2010 started units have different emission limits during the transition period. There can be seen that larger and older units have higher emission limits. For units above 5 MW, new mission limits are required to be meet on the 1st of January in 2025, and units in 1 to 5 MW new emission limits are required to be meet on the 1st of January in 2030. (1065/2017)

Table 3 Emission limits for medium size combustion units (1065/2017).

		Dust mg/m3n	NOx mg/m3n	SO2 mg/m3n	Unit size
Solid fuels	Solid biomass	50	450	200	1 < P > 5 MW
		50	450	200	5 < P > 20 MW
		30	560	200	P > 20 MW
Liquid fuels	Light fuel oil		200		1 < P > 5 MW
			200		P > 5 MW
		50	650	350	1 < P > 5 MW
	Other liquid fuels	30	650	350	P > 5 MW

Table 4 Emissions limits for medium size combustion units during transition period (1065/2017)

		Dust mg/m3n	NOx mg/m3n	SO2 mg/m3n	Unit size
Solid fuels	Solid biomass	300	450	200	1 < P > 5 MW
	Pre 2010	150	450	200	5 < P > 10 MW
		50	450	200	10 < P > 50 MW
	Solid biomass	200	375	200	1 < P > 5 MW
	After 2010	50	375	200	5 < P > 10 MW
		40	375	200	10 < P > 50 MW
Liquid fuels	Light fuel oil	140 (200)	900	350 (850)	1 < P > 15 MW
	Pre 2010	50 (140)	600	350 (850)	15 < P > 50 MW
	Light fuel oil	50	800	350	1 < P > 15 MW
	After 2010	50	500	350	15 < P > 50 MW

4 Non combustion-based carbon neutral heat production

District heat can be produced with non-combustion-based carbon-neutral production methods. Driving factors for district heating companies to utilize non-combustion-based production methods are tightening emission regulations, emission allowance costs, competition in the heating market, and goal for carbon dioxide-free production. Non-combustion production is done by utilizing various heat sources from the environment, industry, and other commercial or residential waste heat. Some heat sources have low-temperature levels. In these heat sources, heat pumps are used for increasing temperature for making it suitable for district heat. Heat pumps are considered a potential option cause electricity price has been low and excess production with wind power in certain hours might lead to even negatively priced electricity occasionally. Environmental heat contains sources from the sun, ground, ambient air, ambient waters, and geothermal heat. Industrial heat sources can be various waste heat streams, like flue gases or water treatment, or cooling waters. In commercial or residential sectors heat can be gathered from air conditioning, refrigerant systems, and sewage waters. Sewage waters can be utilized centralized at the municipal level in the wastewater treatment plant. (Valor Partners, 2016, 5, 13)

4.1 Solar heat

Solar heat is produced from converting radiation from the sun to heat. Potential heat from the sun can be determined with radiation intensity. Radiation intensity in Finland is estimated by the Finnish Meteorological Institute. In their estimations, Finland is divided into four weather zones which are presented in Figure 12. (Finnish Meteorological Institute. 2020)

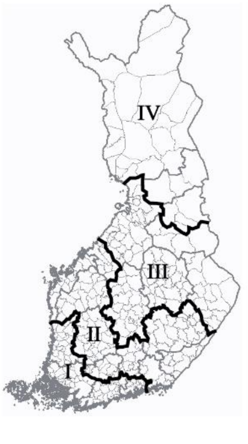

Figure 12 Weather zones in Finland ()

Radiation is varying seasonally, and this variation in weather zone III is presented in Figure 13. There can be seen that radiation is highest in April to August. During the winter months, radiation is low. Also, there can be seen that pointing the surface towards to sun increases potential radiation.

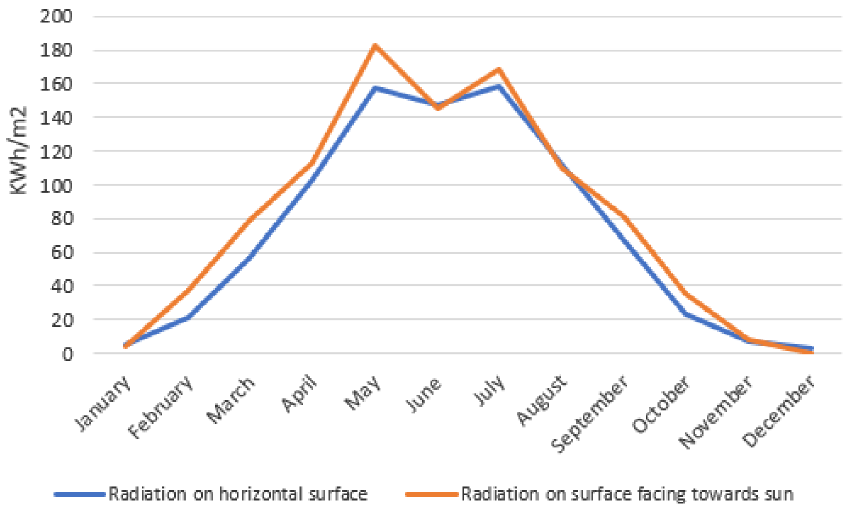

Figure 13 Monthly radiation in weather zone III (Finnish Meteorological Institute. 2020)

Radiation can be converted to heat with solar collectors. Various types of collectors are available. Collector type is selected related to the intended application. Output temperature is a key factor for selecting a suitable collector type. Different categories of solar collectors are shown in Figure 14. In high output temperature applications evacuated tube collectors or covered flat plate collectors are used. Non-covered collectors are used in low output temperature applications or used parallel with heat pumps. (Richter et all, 391)

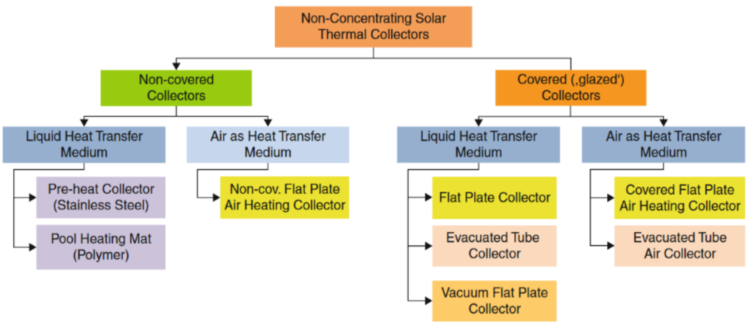

Figure 14 Different types of non-concentrating solar thermal collectors (Richter et all, 392)

Solar collector radiation to heat conversion efficiency is depending on three factors which are mean temperature in the heating system, ambient temperature, and irradiation. The lower mean temperature of the heating system increases efficiency therefore low inlet temperatures are beneficial. Low ambient temperature decreases collector's efficiency which lowers efficiency during wintertime together with lower irradiation. The efficiency of solar collector's reach can up to 85 % in optimal conditions. (Richter et all, 383, 392, 407)

Etelä Savon Energia has utilized solar collector's in Ristiina district heating network. Solar collectors are installed facing towards south inclined. The total area of solar collectors is 120 m^2. Annual production with solar panels has been 36.5 MWh in 2018. This present production capacity of around 300 kWh/m^2. Produced heat with solar collectors reduces fuel combustion in local heat plants. (Etelä-Savon-Energia. 2021)

4.2 Geothermal energy

In general, geothermal energy is heat stored and generated in the ground. Heat available in surface ground sources results from heat flux from the sun, geothermal heat flux through earth crust, and stored heat during seasonal environment temperature changes. In bed rock sources heat is generated from heat flux through earth crust and by heat released in radioactive material decay. Bed rock sources are not affected by seasonal changes in climate. Therefore, bedrock sources are considered stable sources for heat generation. (GTK. 2020, 8)

From bedrock, heat is collected with wells drilled to bedrock. Temperature gradient increases depending on the depth of the well. Depending on well depth they can be separated into three categories which are shallow-depth, medium-depth, and deep thermal energy. Shallow depth thermal energy is the most used geothermal source in Finland, and it is considered to utilizing heat from around 0 - 1000 m depth boreholes. These boreholes can generate flow with output temperature below 10 °C. Medium-depth thermal is in bedrock at 1 – 3 kilometers depth there can be generated output flows of 20 - 40 °C. Challenges with utilizing shallow and medium depth thermal energy in district heating production are low-temperature level which requires a heat pump. In Finland, there is currently a couple of medium-depth thermal boreholes under construction. Deep thermal energy is in 6 – 8 kilometers depth and there can be generated output flows of 100 °C. Therefore, deep thermal energy can be utilized in district production without a heat pump. (GTK. 2020, 9-10)

Heat is collected from boreholes using collector tubes. In shallow borehole applications U-pipe type collector tube where collector fluid is used for heat transfer. In the U-pipe cold collector, fluid is going down in another end and coming up heated up from the other end. The fluid used in collector tubes water-ethanol mixtures. Coaxal tubes are used in medium and deep thermal applications. In coaxal tubes, boreholes are tubed with different diameter tubes. Collector fluid is pumped to the borehole in the outer pipe and pumped up in the center pipe. Center pipe is used as a special type of insulated pipe to minimize heat flow from hot collector fluid to cold fluid. (Uski, M & Piipponen K. 2019, 8)

Utilizing geothermal energy sources in Finland requires permits. Permit procedure guarantees that geothermal energy utilization has a minimal negative impact on the environment. The main law’s that affecting permits are Land Use and Building Act (132/1999), Water Act (587/2011), and Environmental Protection Act (527/2014). Permits are issued by Municipal building control and Regional State Administrative Agency. For medium-deep and deep thermal energy evaluation towards seismic properties is also required. (GTK. 2020, 13-14)

The first medium-deep thermal application was started at Espoo. The application consists of one 1,3 kilometers deep well. Constant heating power from the well is estimated to be 250 to 300 kW with an annual energy production capacity of 1 GWh. Temperature levels generated from the well are not high enough to direct use and a heat pump is required. The first deep thermal energy application was placed in Espoo by St1 with two pipes with 6,4 kilometers depth holes. Temperature levels are high enough to be used directly to district heat. (Juuti P. 2020.)

4.3 Ambient air

Ambient air can be used as a renewable source of energy. The temperature level of ambient air is low, and it requires a heat pump for energy to be utilized. Ambient air temperature is changing during the day and seasonally. Therefore, as a heat source, ambient air is not stable, and the efficiency of a heat pump is hard to examine. Also, during wintertime heating demand is high and air temperature is at the lowest. Ambient air has been used conventionally in household applications in space heating or domestic hot water production.

In district heating production ambient air source heat pumps are not in common use. There is has been some applications in small district heating network. Suur-Savon Sähkö has installed ambient air and solar combined heat source heating pumps in their heating plant for reducing the combustion of fossil fuels. (Calefa Oy. 2019.)

4.4 Ambient waters

Ambient waters which can be considered as stable heat sources for heat pumps are large lakes and rivers also sea in coastal areas. The temperature of the heat source is relatively low, but heat is available throughout the year. (David et al. 2017, 578) In Figure 15 is presented surface temperature estimations for 2020 and 2021 for Nilakka lake. There can be seen that temperature can vary seasonally in inland lakes. During summer temperatures rise to around 20 °C and in winter temperature drops to 0 °C. Heat can be collected with an open-loop system or closed-loop system. In an open-loop system, ambient water is pumped from the ambient water reserve source to an intermediate heat exchanger and returned to the ambient water reserve. In a closed-loop system, heat exchangers are placed in ambient water reserve and collector fluid is circulated there. The closed-loop system is used in a colder climate. Advantages of the closed-loop system compared to open-loop systems are less fouling occurring, lower pumping power requirement, and the possibility to collect energy from a lower temperature level. (Kavanaugh, S., Raffery, K. 2014, 124-126)

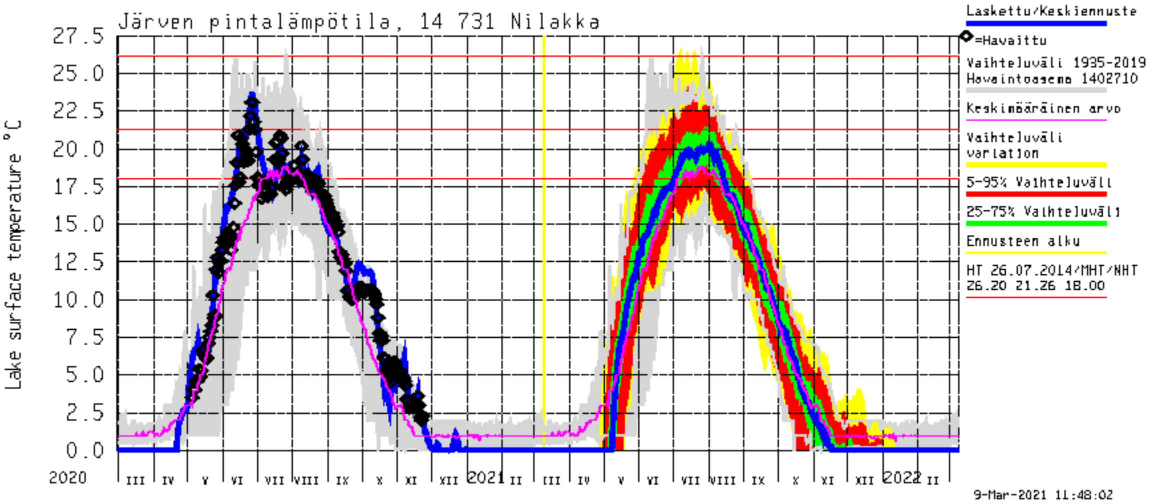

Figure 15 Surface temperature at lake Nilakka (Ympäristö.fi. 2021)

In Finland ambient water has been used conventionally in household heating applications but not industrial level. In recent years there has been an increase in industrial-scale heat pump applications. As an example, Helen has planned a heat pump application for district heating which uses a combination of cooling waters from powerplant and seawater for a heat source. The main source of heat is cooling waters, but seawater is used to increase annual operation time. (Helen 2019)

4.5 Heat pumps

Heat pump machines are used to transfer heat from lower temperatures source to higher temperature source. This procedure requires external power. Heat pump efficiency is defined with the coefficient of performance (COP). COP describes heat pump performance as a ratio of heat produced compared to mechanical work applied by a machine. Two main types of heat pumps are compression and absorption heat pumps. (Grassi, W. 2018, 4)

4.5.1 Compression heat pumps

Compression heat pumps use a compressor to apply external power to heat pump applications. The main components of compression heat pumps are compressor, expansion/laminal valve, condenser, evaporator. The basic scheme of a compression heat pump is shown in Figure 16. The compressor task is to keep proper pressure difference between evaporator and condenser for maintaining proper phase change temperatures. The expansion/lamination valve task is to release working fluid from the condenser to the evaporator. Evaporator task is to collect heat from a heat source and evaporate working fluid. Compression heat pumps can be electricity-driven (EHP) or gas-driven (GHP). (Grassi, W. 2018, 8)

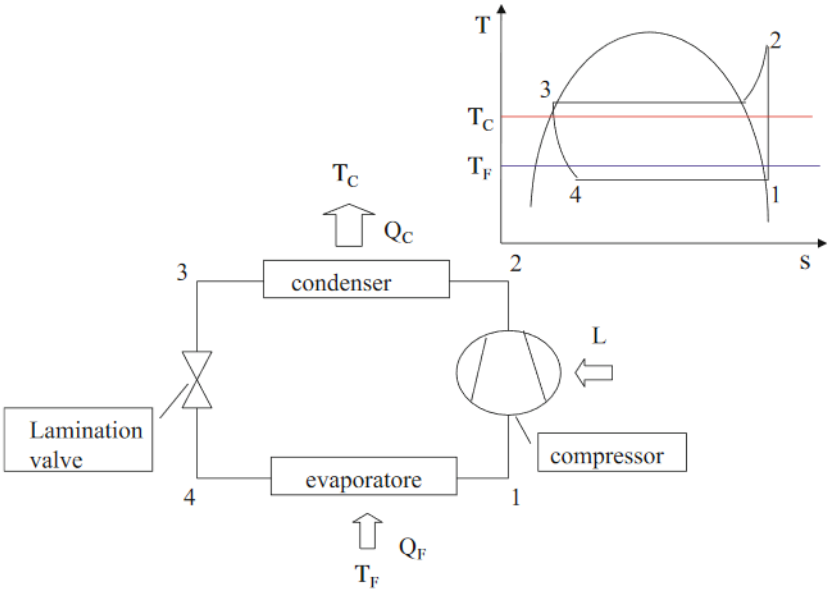

Figure 16 Basic scheme of compression heat pump and T,s chart (Grassi, W. 2018, 5)

4.5.2 Absorption heat pumps

Absorption heat pumps (AHP) uses a combination of two working fluids where the other fluid is a solute, and the other is solvent. Solute fluid has higher vapor pressure and solvent has lower. Combinations commonly used are ammonia-water and bromide-water. The basic scheme of an absorption heat pump is shown in Figure 17. There can be seen that the layout is almost the same as in the compressor heat pump except the compressor is replaced with a combination of components. This combination of components consists of a generator, heat exchanger, and absorber. The absorber task is to mix solute fluid vapor coming from the evaporator with a poor solution mixture coming from the generator. A fluid mixture is called a rich solution and it is pumped through a heat exchanger to the generator. The generator task is to separate solute from solvent fluid with distillation. Distillation occurs with the assist of heat and usually, a burner is used. Pure solute fluid vapor is then flowing to the condenser where it condenses and releases heat. Then expansion valve control flow rate to evaporator and rotation starts again. Therefore, in the condenser, expansion valve and evaporator fluid are pure solutes as an example in the ammonia-water system pure ammonia is flowing in these components. (Grassi, W. 2018, 73-74)

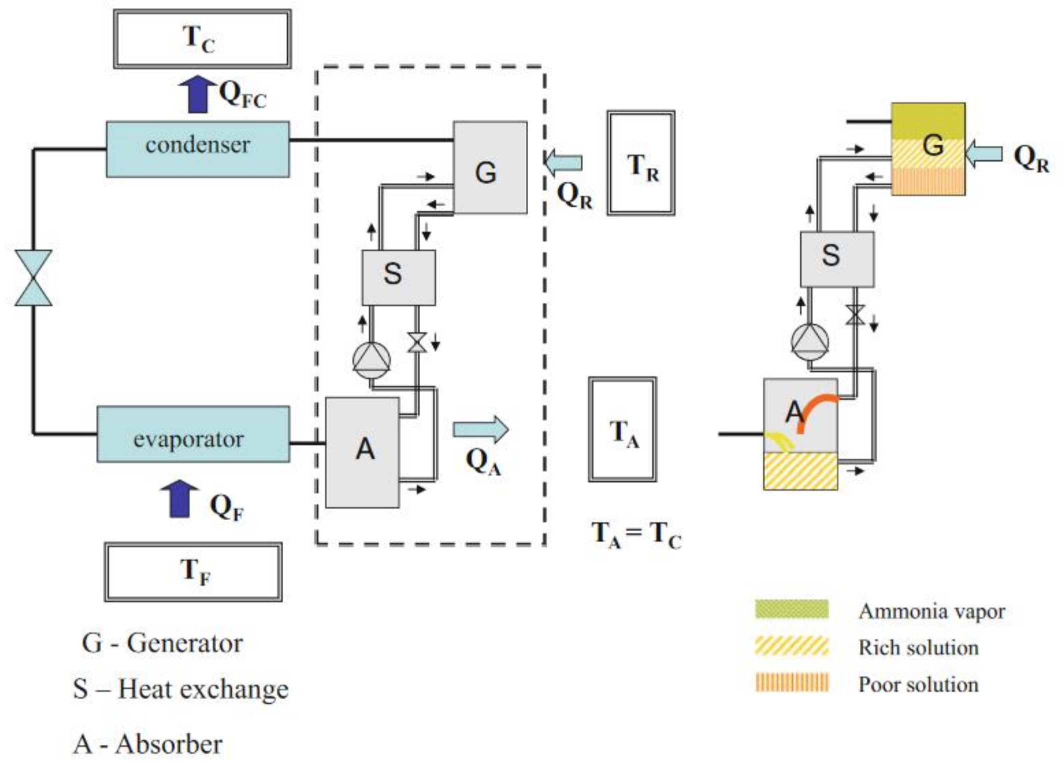

Figure 17 Basic scheme of absorption heat pump (Grassi W. 2018, 74)

4.5.3 Heat pump potential in district heat

Heat pumps are having multiple reasons as a potential way of producing district heat. These reasons are for example increased flexibility of district heating system, increased amount of renewable heat production, and potential for utilizing waste heat. Flexibility is considered to increase because heat pumps are easy to start up and shut down at a low cost. Also, utilization of electricity market volatility to select the optimal time to produce heat with heat pump and time to use alternative heat production like conventional combustion units. Benefiting from low electricity market prices usually requires a storage system. In some district heating networks, a basic load boiler might need to run below or at minimum load with low efficiency during summer. Heat pumps may be used during these times to delay start-up for higher heat demand times to increase system overall efficiency. (Valor Partners. 2016, 23)

Finland electricity grid company Fingrid has announced the possibility to electricity consumers and producers to apply for electricity control markets. This would be beneficial for district heat companies to utilize heat pumps among a variety of different heat production to participate in electricity control markets to obtain new sources of income. Heat pumps would be suitable for this because of fast start-ups and shutdowns. Constant start-ups and shutdowns might affect on technical life of heat pumps. Therefore, if heat producer desires to use heat pumps in the electrical control market heat pump unit suitability should be discussed with the manufacturer. (Valor partners. 2016, 28)

The Finnish government has presented that heat pumps producing heat to district heat are moved to electricity tax category II. Also, electricity tax is planned to be reduced towards the minimum rate allowed by the European Union. This improves heat pump competitiveness towards alternative heat production methods. (Government of Finland, 35)

4.5.4 Co-production with heat only boiler

Modern heat pumps can provide high temperatures + 80 °C conventional heat pumps have been limited to + 65 °C. District heat supply temperature level is increased from 90 to 120 °C during winter which decreases heat pump efficiency. Boilers can be used to prime the temperature to an optimum level. This is possible if the heat pump and boiler are located nearby. If the boiler is used only for priming district heat supply temperature it is not considered as an efficient way if the goal is to minimize fuel consumption. (Valor Partners. 2016, 25)

5 District heat in Keitele

Keitele is 2 200 resident municipality in North Savo. The District heating network operator is Savon Voima Oyj. Savon Voima Oyj purchases a major portion of heat from Keitele Energy Oy. Keitele Energy Oy is a company that is operating heat production in the Keitele Timber forest industry mill. Heat is produced by combusting by-products from timber. Timber mill is connected to district heating network with 5 MW heat exchanger. Amount of the heat available is related on timber mill operations. For heat production reliability Savon Voima Oyj has two light oil boilers as peak and reserve units. Peak oil boilers are LK-72 and LK-102. LK-72 has thermal capacity of 4,7 MW and LK-102 has thermal capacity of 5 MW. Peak and reserve units are used also during the timber mill annual revision and heat delivery problems from the timber mill. Annual revision of timber mill is lasting for 2-3 weeks and usually, revision is held in June. Length of revision is depending on mill annual maintenance demand.

Keitele district heating network is presented in Figure 18. There can be seen how heat production units are distributed along with the network. LK-102 and heat timber mill heat exchanger are on the same site. LK-72 is on a different site in other parts of the network. Transmission pipes are 2Mpuk and Mpuk pipes. The main portion of pipes used is 2Mpuk. The total length of the district heating network is 11,4 km. There is a total of 59 customers connected to the Keitele district heating network. Heat demands and portions of different types of customers are shown in Table 5.

Table 5 Keitele district heating network customers and contract powers (Energiateollisuus ry, 2019)

	Amount pcs	Power MW
Residential customers	30	1,1
Industrial customers	6	0,5
Other customers	23	1,4
Total	59	3

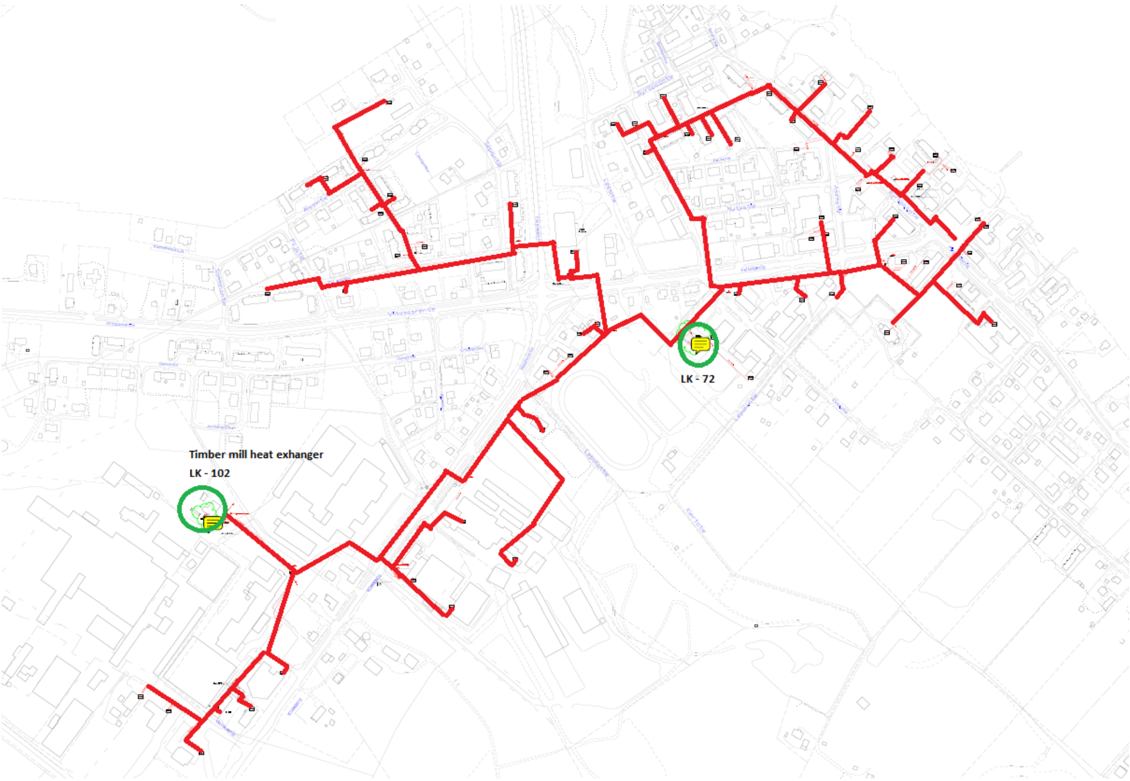

Figure 18 District heating network in Keitele

District production in Keitele in 2019 was based on purchased energy where total production was 10,6 GWh and purchased was 10,4 GWh. Purchased energy is produced by wood-based fuels in a timber mill. LK-102 boiler was used to produce 0,2 GWh of heat. Heat distribution loses was 2 GWh. For 2017 and 2018 heat production and consumption are presented in Table 6. There have been some annual differences in heat production.

Table 6 Heat production in numbers (Energiateollisuus ry, 2018, 2019, 2020)

	2017	2018	2019
Heat production Purchased [GWh]	11,6	10,4	10,4
Heat production Own [GWh]	0,1	0,1	0,2
Light oil consumption [GWh]	0,1	0,1	0,3
Heat demand [GWh]	11,7	10,5	10,6
Heat delivered to customers [GWh]	9,6	7,7	8,6
Network losses [GWh]	2,1	2,8	2

District heating network heat demand can be examined with heat production unit's hourly production. District heating hourly production data was given by Savon Voima from their database. The outside temperature was not saved in their database. Therefore, outside temperature date use was collected from the Finnish Meteorological Institute database. There was a metering station near Keitele at Vesanto. Hourly demand considers all heat production methods used in Keitele. In 2019 heat was produced with a timber mill heat exchanger and LK – 102 light oil boiler. Network hourly demand and outside temperature for 2020 are presented in Figure 19. There can be seen that heat demand is changing related to the season. During summertime, heat demand decreases and varies in the range of 0,3 to 0,6 MW. The highest peaks during winter are above 2 MW up to 2,5 MW.

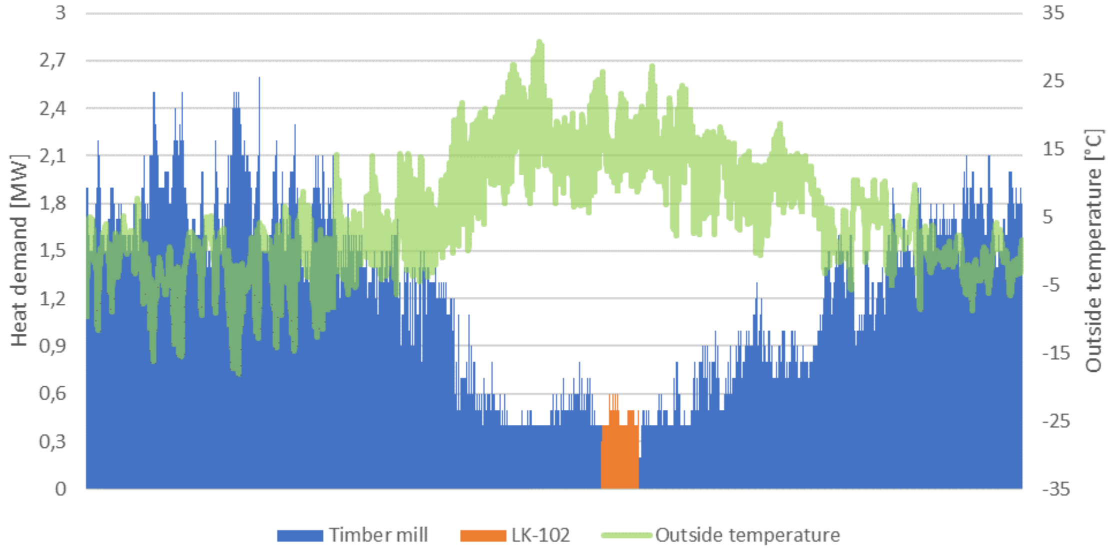

Figure 19 Keitele district heating hourly heat demand in 2020

The year 2020 was relatively warm and the coldest winter day was around -20 °C degrees which are not that low in the Keitele area. Therefore, for examining network heat peak demand relation with heating demand and the outside temperature was determined. This relation is illustrated in Figure 20. There can be seen heat demand is somehow linear related to the outside temperature. Keitele is in the area in Finland where the dimension outside temperature is – 32 °C. Thus, heat demand in this temperature is considered as peak demand. This same analysis was done for the year 2019 and peak demand was 3,5 MW for both years.

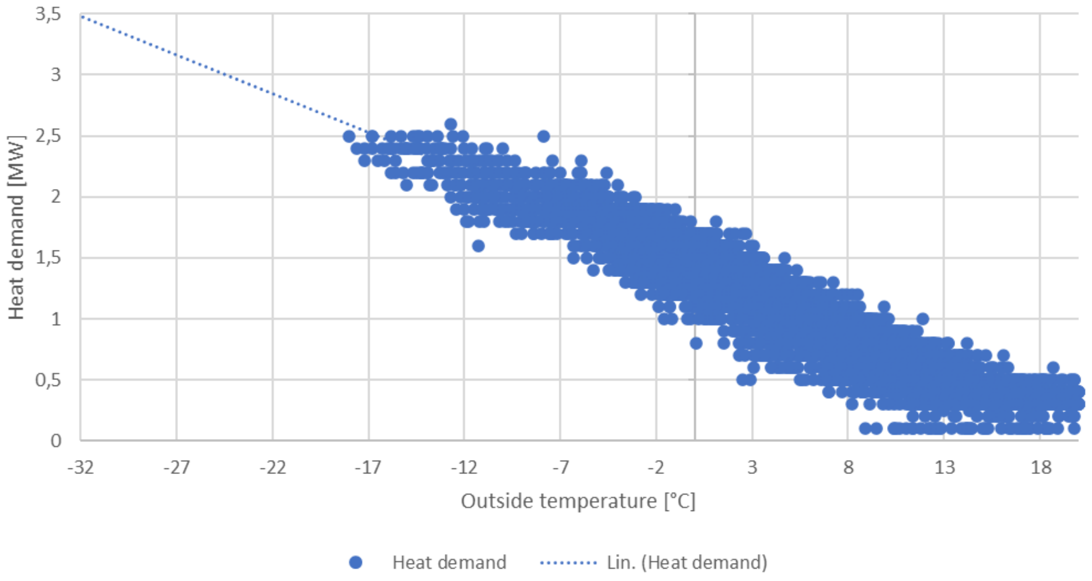

Figure 20 Heat demand related to outside temperature.

6 Potential heat production methods

For selecting potential heat production methods following assumptions and requirements were set.

- Heat production is carbon neutral
- Cost-effective
- Environmentally friendly
- Sustainable and predictable

Waste heat sources were not considered in this master's thesis, because there are no markable waste energy sources available in Keitele. Thus, the heat production methods considered were based on combustion and heat pumps utilizing ambient heat sources. For each proposed production method costs, environmental impact, role in heat production were evaluated.

6.1 Combustion-based methods.

Combustion-based carbon-neutral production methods considered are pellet and forest chip boilers. Two types of boilers are compared since depending on their role in heat production their cost-effectiveness is different. Major effecting properties are fuel price and investment cost and boiler efficiency. In this master's thesis, the exact location of heat plants is not determined there is assumed that the heating plant could be installed somewhere along with the district heating network.

Joroinen pellet boiler

Savon Voima Oyj has pellet boiler plant in Joroinen which can be moved to Keitele. Pellet boiler technical details are shown in Table 7. The Pellet boiler is a stroker type boiler that has two moving grate burners which allow the boiler to be operated with a wide range of load. The heat load can be varied from 5 % to 100 %. The boiler plant also contains a 2,3 MW light fuel oil boiler which can be used for peak or during downtimes of the pellet boiler. Estimation of cost for moving boiler plant to Keitele is 565 000 €. Completely new pellet boiler is estimated to cost 1,3 M€. Pellet boiler is currently in use at Joroinen district heating network and effects of boiler transportation to Keitele district heating network is not considered in this master's thesis.

Table 7 Pellet boiler technical details

	Value	Unit
Heating power	3	MW
Operating pressure	6	bar
Minimum load	0,6	MW
Efficiency 100% load	93,60	%
Efficiency 50% load	93,40	%
Efficiency 5% load	80,60	%

Peak heating demand in the Keitele district heating network was determined to 3,5 MW. Therefore, the pellet boiler covers around 85 % of peak power. For baseload unit peak load coverage is usually around 40 – 60 % which leads to 80 – 90 % annual energy coverage. This is usually done because during off-load situations boiler efficiency might be low, especially when the boiler is operated in low power. The Pellet boiler has good control and efficiency properties for load in 50 to 100 % range. Below 50 % load operation efficiency decrease. Therefore, the pellet boiler might be slightly oversized for the Keitele network. For a baseload boiler, a better-sized boiler with cheaper fuel would be more compatible. On the other hand, pellet boiler allows covering a high portion of production with carbon-neutral fuels. Pellet boiler could be considered as peak load boiler. Thus, heat pumps could be used as baseload units if they could produce baseload with lower energy unit price. Also, summertime low heat demands are challenging for pellet boiler. Since heat demand decreases to 0,5 MW which is below pellet boiler minimum load.

Forest chip boiler

Forest chips are cheapest option for biomass fuel. Therefore, basic load boiler using forest chips as fuel could be beneficial for minimizing variable costs. Forest chip boiler can be also dimensioned better for being more suitable compared to pellet boiler. Optimal sizing allows a boiler to be operated with high efficiency during the major portion of operation time. For investment cost for forest chip heating plant is used 1000 €/kW.

As a basic load unit with 40 – 60 % peak load coverage, there is a required peak load unit to produce heat during peak demands. Peak load could be produced with bought energy from the sawmill or be produced with bio-oil fueled peak load units. Challenges using sawmill as peak load coverage is the requirement to make a contract with sawmill and be depending on their production. Converting conventional mineral oil combustion peak units to combust bio-oils is expensive. An alternative option is using a pellet boiler as a peak load unit.

6.2 Heat sources for heat pump

Potential heat pump heat sources in Keitele are limited to low-temperature sources. Since higher temperature sources like waste heat are not available. Potential sources for a heat pump in this master’s thesis are geothermal, ambient air, and lake. For each heat source energy potential, environmental impact, investment costs, role in heat production, and risks are estimated.

Heat pump coefficient is determined with manufacturers given details. Two manufactures gave offers for their products regarding available heat sources. Properties of available heat sources are presented in Chapters 6.2.1 to 6.2.3. The main factors for determining heat pump efficiency are temperature level and available energy from a heat source and district heating supply and return temperature. Related to these characteristics request for quotation was asked from heat pump manufacturers. Two manufactures were contacted and there presented a couple of options. The heat pump from Oilon Oy was dimensioned for geo-energy heat sources. Calefa heat pump was able to utilize ambient air heat and various other heat sources.

Oilon Oy offered two heat pump systems which both had thermal capacity of 2 MW. The first system was dimensioned for shallow geothermal with a heat source temperature of - 1 / + 7 °C. The second system was dimensioned for medium-deep geothermal with a heat source temperature of + 20 / 40 °C. Heat pumps were capable to produce district heating supply temperature up to + 90 °C. Operated in nominal capacity with presented supply temperature range heat pumps system COP is 3,29 utilizing medium-deep geothermal sources and COP 2,31 utilizing shallow geothermal sources. For modeling purposes, these COP are used. Therefore, heat sources are considered to stay stable around the year. The potential of geo-thermal heat sources is presented in Chapter 6.2.1. (Oilon Oy. 2021)

Calefa Oy presented three systems that were able to generate district heat from multiple heat sources. The potential of utilizing ambient air for heat production was a key interest in their heat pump system. Also, the potential to switch heat source regarding which source is most economical to use in given time to improve cost-effectiveness. For ambient air heat pump systems, COP and thermal capacity determination are presented more precisely in Chapter 6.2.3. If a heat pump is used with heat sources like geothermal or ambient waters COP is determined regarding district heating supply temperature. This is presented in Figure 21. There can be seen that heat pump COP varies from 3 to 1,6 depending on district heat supply temperature. (Calefa Oy. 2021)

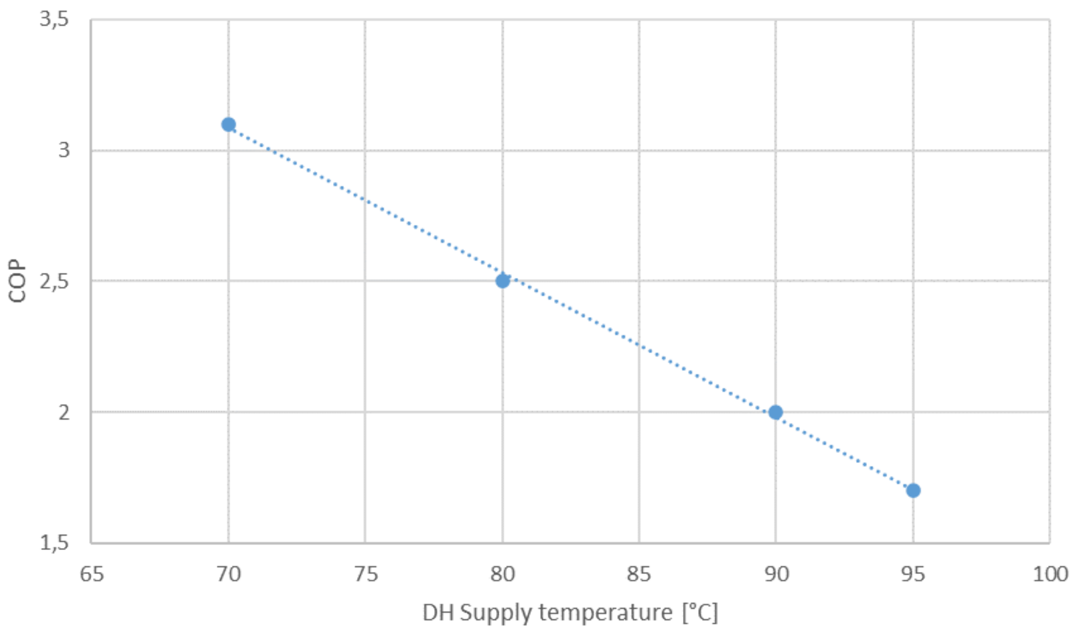

Figure 21 Heat pump coefficient as a function of supply temperature

6.2.1 Geothermal

Geothermal heat main limiting factors are groundwaters. Groundwater sources in Keitele are presented in Figure 22. There can be seen that there are no groundwater sources in the immediate presence of the Keitele district heating network. The closest groundwater source is in Maaherranniemi a couple of kilometers south of Keitele city center. Therefore, ground water is not considered as limiting factor for geothermal applications.

Geothermal utilization allows sustainable and predictable energy source. Temperature level stabilizes under 14-15 meters below ground and after that temperature increases with temperature gradient with 0,5 - 1 °C / 100 m. (FCG suunnittelu ja tekniikka Oy. 2017, 5)

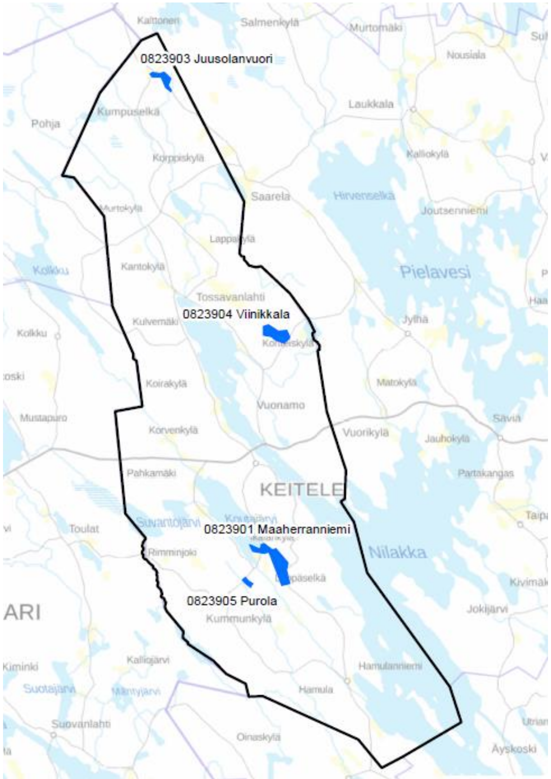

Figure 22 Keitele groundwaters (ELY Center. 2019)

Shallow geothermal in district heating scale requires large borehole field. A large borehole field is needed because one 300 m borehole can produce 30 - 50 MWh of heat annually. For a large borehole field, there should be enough space between each borehole otherwise boreholes are cooling too much each other. In calculations, 40 meters spacing between each borehole is used. Boreholes are expected to produce 100 kWh/m and 30 W/m. Also, heat energy density for hectare is estimated to below 240 MWh/ha/a to prevent boreholes freezing (Kallio et all, 86). As drilling cost for 300 m boreholes 40 €/m is used. With these assumptions required borehole field sizes for different heat, demands are presented in Table 8. Shallow geothermal boreholes are considered to generate collector fluid to heat up from – 1 °C to + 7 °C (FCG suunnittelu ja tekniikka Oy. 2017, 5).

Table 8 Shallow borehole requirements for different heat demands

Heat from ground [MWh]	Total depth [m]	Boreholes [pcs]	Borehole field size X (m)	Borehole field size Y (m)	Heat density [MWh/ha]	Investment €
1 000	10 000	40	120	360	231	400 000
2 000	20 000	70	240	360	231	800 000
3 000	30 000	100	360	360	231	1 200 000
4 000	40 000	140	520	360	214	1 600 000
5 000	50 000	170	640	360	217	2 000 000

For decreasing required borehole field space deeper boreholes can be used. Medium deep geothermal is considered an option. Challenges with medium-deep thermal are higher drilling costs. In deeper boreholes installations final borehole deep has been lower than expected. Also, energy potential is hard to examine. Medium deep geothermal energy potential is estimated by the Geological Survey of Finland. They have estimated that in the Uusimaa region geothermal potential from one 2 kilometers depth borehole is 860 – 1140 MWh for sustainable use for 50 years without freezing borehole. (GTK 2019, 31). Local geological properties affect on energy potential available. In the Northern part of Finland earth's crust is cooler and energy potential lower. Therefore, it is estimated that one medium-deep borehole can produce 860 MWh of heat, and maximum thermal power from one hole is assumed to be 300 kW. For drilling cost of 1,4 million euros per borehole is used. Collector fluid is heated form + 20 °C to + 40 °C. With these assumptions different sized systems investment costs are presented in Table 9.

Table 9 Medium-deep thermal boreholes requirement for different heat demands

Heat from ground [MWh]	Total depth [m]	Boreholes [pcs]	Investment €
860	2 000	1	1 400 000
1 720	4 000	2	2 800 000
2 580	6 000	3	4 200 000

Deep geothermal energy is not considered since it is expensive and unpredictable. Also, heat demand in the Keitele network is not suitable for geothermal applications since heat capacity would be oversized. For example, St1 deep geothermal plant have a heat production capacity of 40 MW with two 7-kilometers deep boreholes. The deep geothermal potential is there that heat could be used in district heating without a heat pump. Therefore, deep geothermal is more potential on district heat networks with higher heat demand.

High investment cost determines that geothermal energy is most suitable as a heat source for heat pumps covering the base load of district heat. Thermal capacity of boreholes limits peak heat demand from boreholes. Too high heat demand for borehole might cause boreholes to freeze. Because of the low-temperature level available heat pump is required.

Environmental impacts of geothermal application can be divided on drilling phase impacts and on operational impacts. During operations impacts can be considered to be neglected. In medium deep applications there is a small risk of induced seismic activity. During drilling there can be leakage of chemicals and mineral oils from drilling equipment. Drilling sludge is waste which must be treatment. Also, large borehole fields or deep boreholes require drilling around the clock which requires public announcement for momentary disturbance. (GTK. 2020, 19-20)

6.2.2 Ambient waters

Near Keitele is Nilakka lake which could be used as a heat source. District heating network transmission pipes are going near the lake. This reduces modifying requirements for connecting ambient water source heat production on the district heat system. Therefore, in the district heating network side Keitele is suitable for using ambient waters in heat production. For Nilakka properties as a heat source, there are certain challenges which are shallow water areas near Keitele. The depth of the lake is illustrated in Figure 23. There can be seen that there is a basin next coast with a dept of 5 to 10 meters. In other areas near Keitele depth varies in 0 – 3 meters. In this master's thesis, lake suability as a heat source is examined from an economic point of view. If the lake is selected as a heat source more study for lake energy balance, effect on the ecosystem is required. Before starting heat production permissions from the water system owner and ELY center are required.

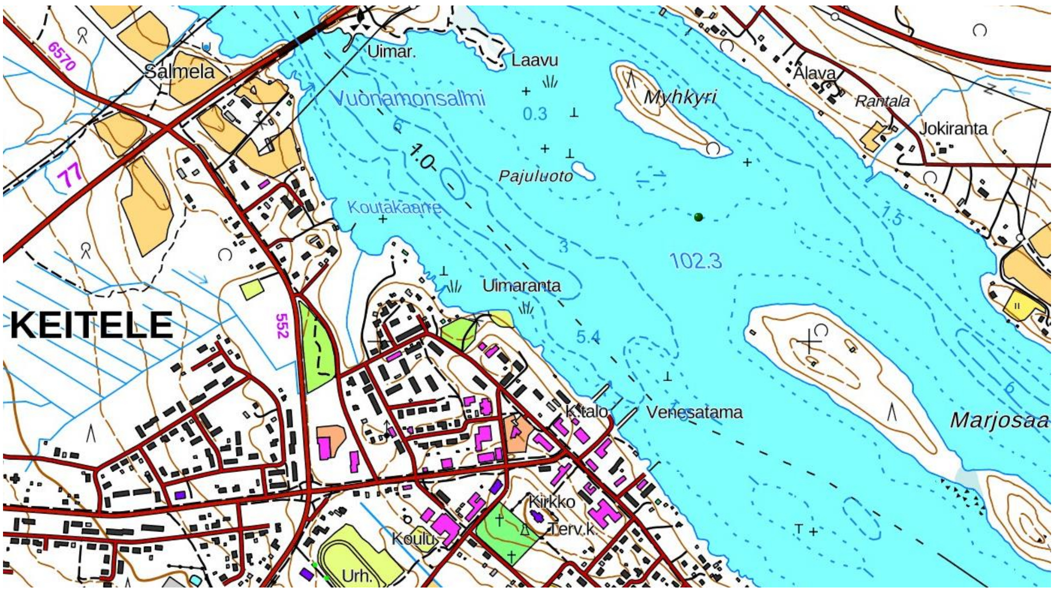

Figure 23 Nilakka depth near Keitele city (National Land Survey of Finland. 2021)

Lake as heat source faces seasonal variations. Therefore, the heat reservoir temperature level varies throughout the year. This causes challenges on especially during winter when the temperature of the water is around freezing point. Freezing is the main limiting factor for heat collection from ambient waters. Freezing of heat collector tubes or heat exchangers may cause break up. Freezing is a major problem in shallow waters where water is not building proper temperature layers. In-depth waters most dense + 4 °C degree water is set on the bottom of the lake where heat collector pipes could be installed. Therefore, heat could be collected during winter. During summer lake temperature is highest on the lake surface. Thus, in summertime heat collection would be beneficial to be collected from the surface.

Depending on heat production purpose as heat source different types of collect method can be used. Heat collector methods that can be used are open and closed-loop systems and sediment collectors. For summer only production open-loop and closed-loop system could be both possible. During winter closed-loop system and sediment collectors are more effective because of low-temperature level of the heat source. Open-loop systems would be facing more problems with freezing.

The actual heat potential of the lake should be estimated with measurements and research. Potential heat collected from the lake is depending on the heat balance of the lake. The heat balance of the lake is depending on solar irradiation, streams, heat flux from water to sediment and sediment to water, surface evaporation, and convection from the water surface to air. In this master’s thesis, the energy balance of water is not analyzed. Theoretical potential from an economic point of view is issued by assuming investment costs for different scale of heat collector systems with different annual heat demands. For closed-loop system and sediment collector system investment costs are presented in Table 10 and Table 11. Investment cost was determined with the following assumptions. Collector pipes are expected to collect 70 kWh/m. The specific cost for collector pipes was 25 €/m. Collector heat power was assumed to be 20 W/m for closed-loop collector pipes and 40 W/m for sediment-assembled collector pipes.

Table 10 Bottom installed closed loop system requirement for different heat demands

Heat from lake [MWh]	Total length [m]	Pipes [pcs]	Investment €	Power [MW]
1000	12500	31	312 500	0,3
2000	25000	63	625 000	0,5
3000	37500	94	937 500	0,8
4000	50000	125	1 250 000	1,0
5000	62500	156	1 562 500	1,3

Table 11 Sediment collector pipes requirement for different heat demands

Heat from Sediment [MWh]	Total length [m]	Pipes [pcs]	Investment €	Power [MW]
1000	14 286	48	428 571	0,6
2000	28 571	95	857 143	1,1
3000	42 857	143	1 285 714	1,7
4000	57 143	190	1 714 286	2,3
5000	71 429	238	2 142 857	2,9

Summertime heat can be collected from the surface of the lake to make use of increased lake surface temperature. Nilakka surface temperature can be examined with measurements done by Finland environmental administration. Nilakka surface temperature is illustrated in Figure 24. There can be seen that the lake has ice cover from November to the start of May. From the start of May temperature starts to increase to around 20 °C after that temperate starts to decrease towards November. Potential time to use surface heat is considered a time when surface temperature above 10 °C. Therefore, surface temperature utilization is at an optimal level between mid-May to start of October.

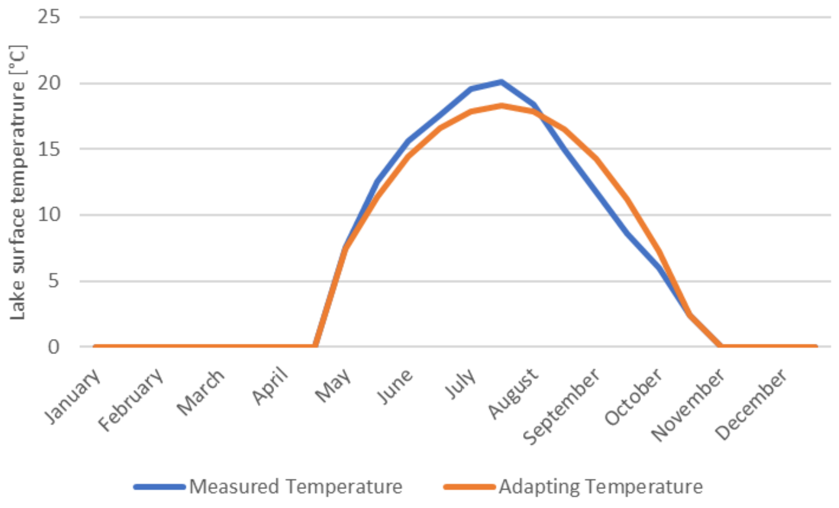

Figure 24 Nilakka surface temperature

Role in heat production is depending what type of applications heat collecting method is used. For example heat from lake sediment could be used during wintertime for balancing high peak heat demands. Nevertheless, investment cost is still markable so baseload coverage would be the most economically viable option. Same reasons bottom installed closed-loop system would be best for baseload. An open-loop system would be most suitable for producing heat during the summertime.

Environmental impacts should be taken into count if the lake would be used as a heat source. Depending on the amount of heat is collected from the lake effects are different. Therefore, the determination of actual heat potential from the lake is important. Heat collection effects on the local lake ecosystem. Effects can be distributed during install and operation time effects. During installation assembly of collector, pipes might lead nutrients released from the bottom of the lake to cause to increased risk of eutrophication. During operation heat collection have a decreasing effect on lake temperature which might affect fishes and aquatic plants. There is also a risk of leakage of collector fluid if collect pipes are broken. Biodegraded collector liquids could be used for preventing the consequences of leakage.

6.2.3 Ambient air

Ambient air as a heat source is a flexible option since it can be assembled almost anywhere. Also, the investment cost is moderate as a result of a simple solution for heat collectors. The downside of ambient air as a heat source is seasonal variation. During summer outside temperature is high and during winter temperature is low. Therefore, heat pump efficiency would be highest during summertime and worst in winter which is not ideal compared to district heating heat demand. Ambient air would be potentially an unlimited source of heat, but heat efficiency and heat pump technical properties limit heat production at certain outside temperatures. Therefore, an economically, and technically viable portion of potential energy is determined. Energy consumption of auxiliary devices like air blowers in evaporators and defrost energy should be considered.

Ambient air heat pumps have ambient air shutdown temperatures which prevent heat pumps from operating below certain ambient temperatures. Shutdown temperature is not universal, and it is depending on heat pump technical features. Manufacturers present their heat pumps with shutdown temperatures. Nevertheless, the incidence of low temperatures limiting ambient air heat pump operation is relatively low at the annual level. Annual ambient air temperature load curves are presented in Figure 25. There can be seen that temperatures below – 15 °C are rare. Only 4 % of annual hours are below – 15 °C and 33 % below 0 °C.

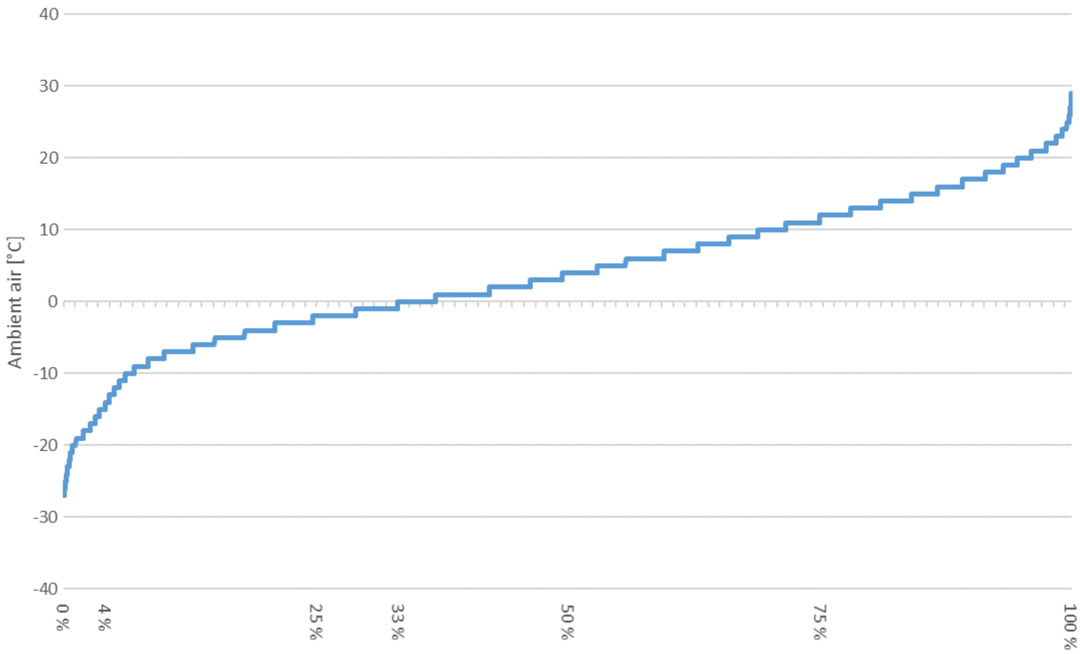

Figure 25 Outside temperature as a function of the proportion of annual hours in weather zone III (Finnish Meteorological Institute. 2020)

Ambient air as a heat source would be most suitable for covering the base load of heat production. Challenges having ambient air heat pump producing baseload is that during high heat demand hours ambient air heat pump might be required to be shutdown which requires more flexibility from other heat production units. Also, heat production capacity and maximum supply temperature decrease when ambient air temperature decreases. Therefore, alternative heat production methods are required as backup.

For determining technical features of ambient air heat pump offer was asked from the manufacturer. The manufacturer offered three different sizes of heat pump systems that can utilize ambient air as heat and other sources in meantime. Offered system is designed for district heat level temperatures. When HP is using ambient air as heat source supply temperature is limited to + 75 °C. The manufacturer delivered system COP as a function of ambient air temperature which is presented in Figure 26. There is considered that heat pump produces supply temperature is constant + 75 °C. All three systems are considered to have the same COP factor. There can be seen that heat pump efficiency decreases when the ambient air temperature is decreased. Also, heat pump thermal capacity as a function of ambient air temperature was delivered which is presented in Figure 27. There can be seen that the thermal capacity of the heat pump system is decreasing when the ambient air temperature is decreased, and the heat pump could be operated to an ambient temperature above – 20 °C. (Calefa 2021)

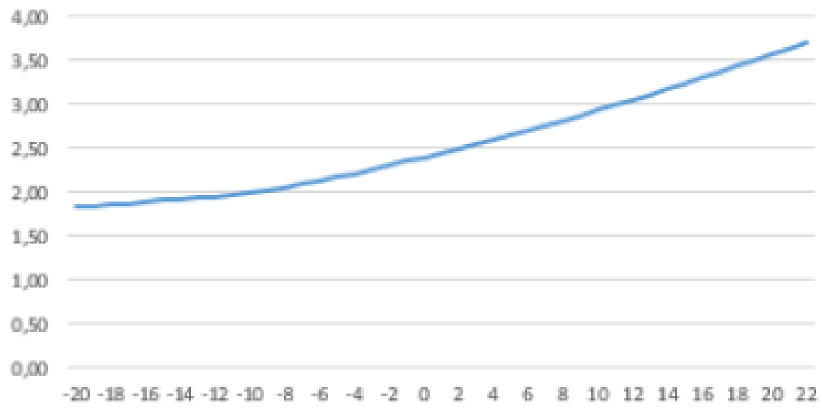

Figure 26 Ambient air heat pump COP as a function of ambient air temperature (Calefa 2021)

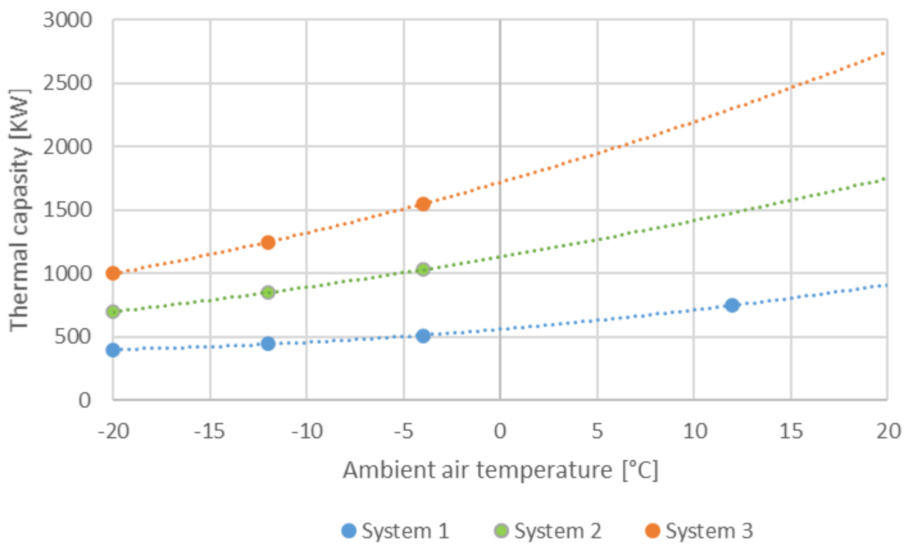

Figure 27 Heat pump thermal capacity as a function of ambient air temperature (Calefa 2021)

6.3 Solar energy

Solar energy potential is related to solar irradiation. Challenges using solar for energy are daily and seasonal variations. Solar energy potential is estimated with measurement data collected from Finnish Meteorological Institute measurement data. They have measured annual solar irradiation towards the horizontal surface from each measurement station. Nearest measurement station near Keitele is Kuopio Savilahti station. Measure data from there form 2020 is presented in Figure 28. Solar irradiation conversion to heat is done with solar collectors. Collectors' conversion efficiency depending on irradiation, technical features of collectors, ambient temperature, system temperature. Determining the actual efficiency of solar collector operational efficiency is a complicated process. In this master's thesis, the solar collector's efficiency is calculated with equation 1. For more accurate efficiency determination simulation is required since collector efficiency is affected by other reasons like mass flow in the system. (Richter et all, 391) Savo Solar flat plate collector's maximum efficiency 0,874 and linear loss factor 3.16 and quadratic loss factor 0,0098 are used. (Savo Solar. 2018) Solar energy collectors' price is estimated to be 350 €/m2

$$\eta = \eta_0 - a_1\left(\frac{T_m - T_a}{G}\right) - a_2 G\left(\frac{T_m - T_a}{G}\right)^2 \tag{1}$$

Where,

η	Efficiency
η_0	Maximum efficiency
a_1	Linear loss factor
a_2	Quadratic loss factor
T_m	System mean temperature
T_a	Ambient temperature
G	Solar irradiation

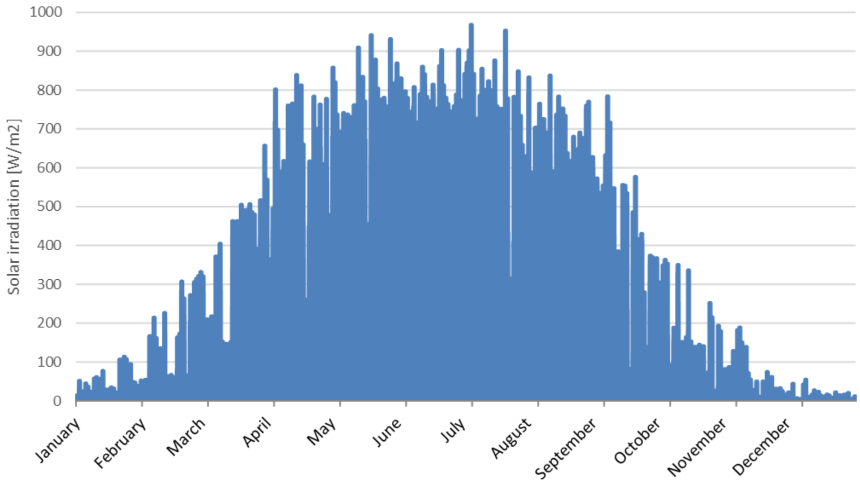

Figure 28 Solar irradiation towards horizontal surface in Kuopio Suvilahti (Finnish Meteorological Institute. 2020)

7 Heat production models

Heat production models for the district heating network in Keitele are built in Microsoft Excel. The model is built in hourly resolution. Heat demand data used in the model consist of hourly production data mixed from different year production data. This was done for more realistic heat demand. Heat demand data was selected from two years. The first part was selected from January to the end of March from the year 2021. The second part was selected from March to the end of December from the year 2020. These sections were selected for a model containing cold winter and mild winter operation situations. Model heat demand is shown in Figure 29. There can be seen that model consists of hours when outside temperature drops to – 30 °C which is typical for weather zone III where Keitele is located. The annual heat demand for the model is 10,2 GWh which is around the same level as heat demand in 2018 and 2019.

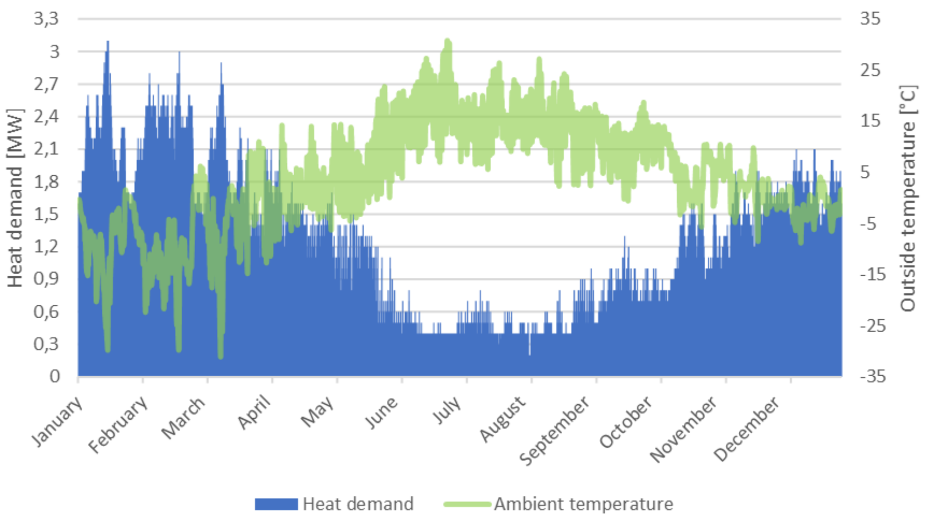

Figure 29 Heat demand and outside temperature used for heat production models

District heating supply and return temperatures used in heat models are shown in Figure 30. Supply temperature is increased when ambient temperature decreases. Higher supply temperature limits heat pump heat production. Thus, supply and return temperatures are considered in heat production models. Supply temperature is varying between + 70 – 80 °C from June to the end of August. During colder winter months supply temperature varies between + 80 – 110 °C. Return temperature is quite stable in the range of + 45 – 55 °C around the year.

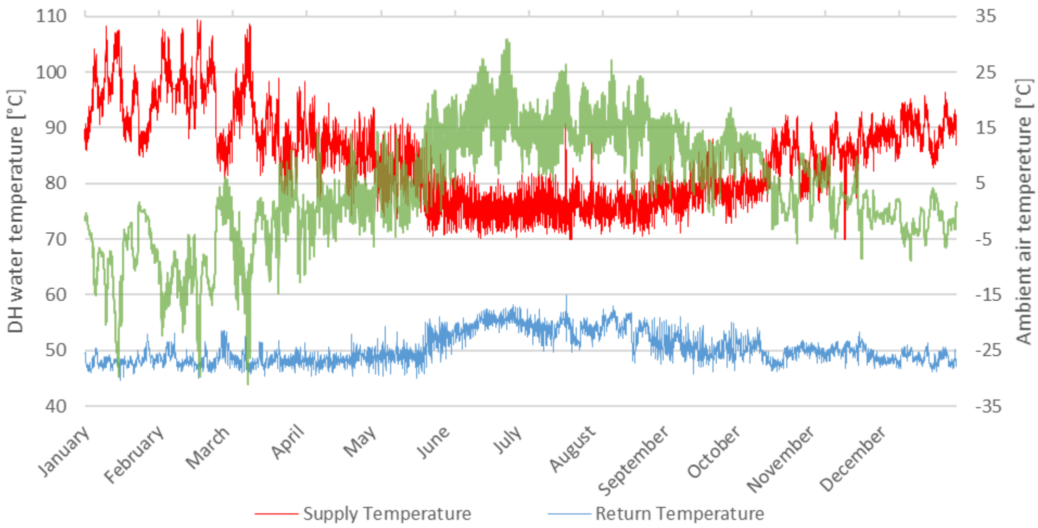

Figure 30 Supply and return temperatures used in heat production models

In models where heat pumps are included the cost of electricity is a major factor determining production costs. Therefore, electricity is specified at an hourly level. Electricity costs are built from transmission cost, energy cost, electricity tax. Electricity tax has two classes. At the moment heat pumps used in district heating production are in the electricity tax 1 category, but they are potentially moved to category 2 in near future. Therefore, calculations are done with both tax classes. For energy price, there are used historical market data from Nord Pool. Hourly data was selected from similar situations as heat demand data. Selected data is shown in Figure 31. There can be seen that energy price is fluctuating between 0 – 250 €/MWh. Transmission costs are related to the local electricity network company's price lists. Keitele is in Savon Voima Verkko Oy network area. Therefore, their price list is used. The transmission cost is varying seasonally from 20 €/MWh to 30 €/MWh. Energy prices are discussed more closely in Chapter 8.1. (Savon Voima Verkko Oy. 2021b)

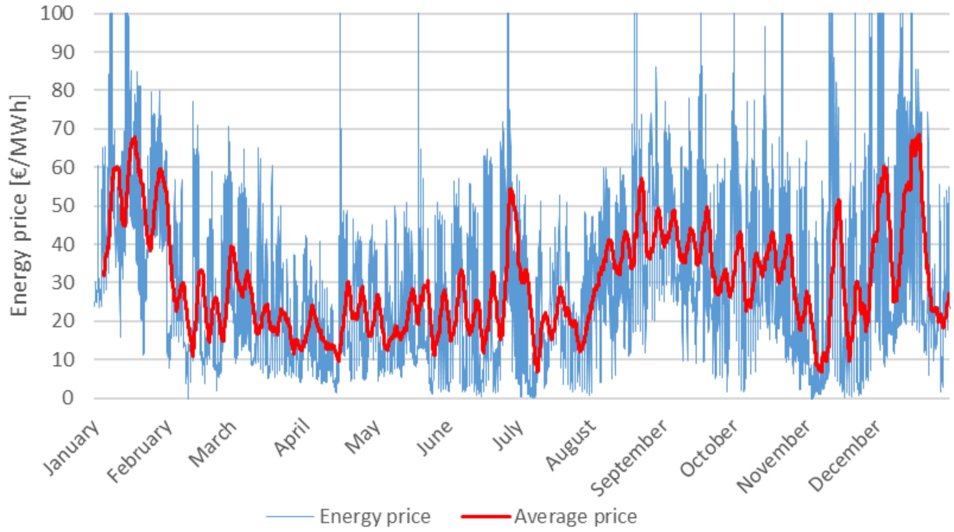

Figure 31 Electricity energy price used in production models (Nord Pool. 2021)

7.1 Combustion based heat production

For combustion-based production, two cases are considered. Two cases compared cases are pellet boiler-based heat production and forest chip boiler-based production. Heat production units in these models are one base unit and two peak load units. Peak load units in both cases are oil boilers LK-102 and LK-72. Peak load unit is also considered to be used during the annual revision of baseload unit. Revision time is three weeks in August. The overall system is a conventional small-scale district heating system where one baseload combustion unit is producing a major part of heat demand.

Fuel consumption of boilers is determined by boiler efficiency. Boiler efficiency is considered to change related to the operational load of the boiler. The operational load of the boiler is calculated with the hourly heat demand proportion of boiler thermal capacity. Boiler efficiency is decreasing linearly from when boiler operational load decreases. Peak load boiler efficiency is assumed to be constant at 70 %.

Forest chip boiler thermal capacity was selected so that peak load coverage is around 80 %. The selected thermal capacity was 2,5 MW. Thus, annual energy coverage is high, and the potential investment cost of the system is lower. This increases the cost-effectives of the system.

Heat production with different combustion-based production is shown in Figure 32 and Figure 33. There can be seen that forest chip boiler-based system requires more peak load boiler usage to cover heat demand. On the other hand, the pellet boiler system requires less amount of peak boiler usage during peak demands. Model energy production key numbers are shown in Table 12.

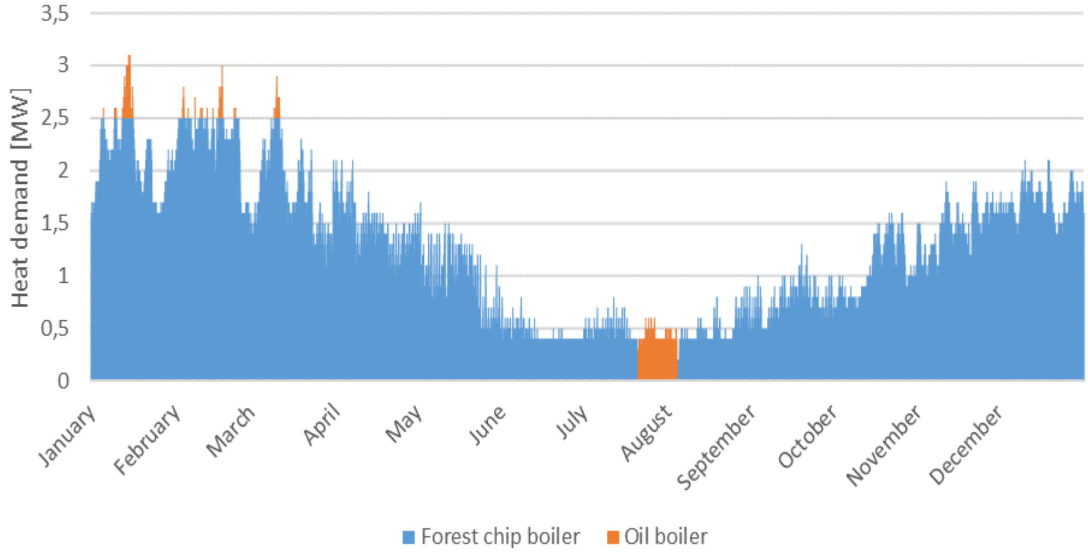

Figure 32 Forest chip boiler based system heat production model

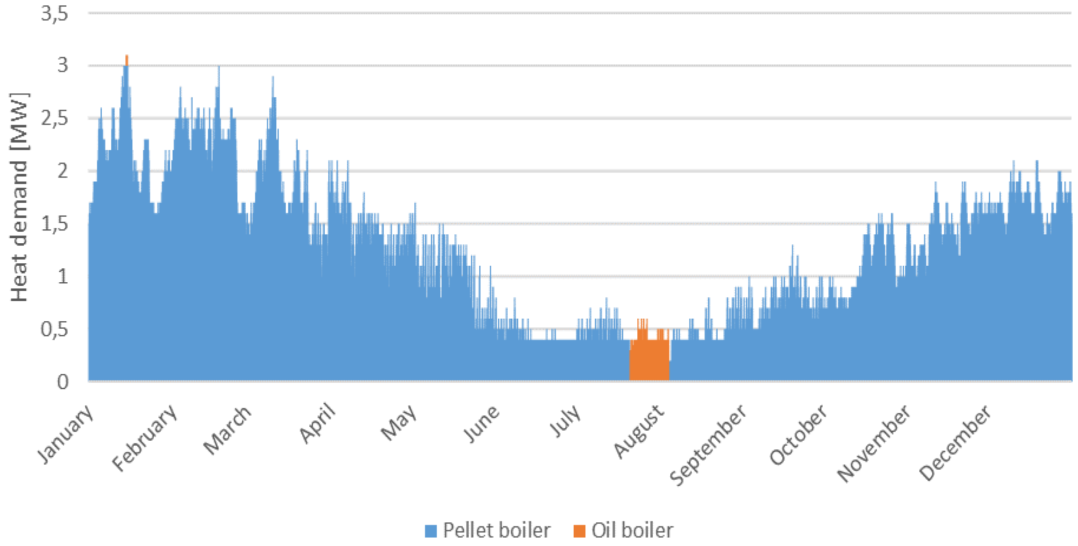

Figure 33 Pellet boiler based system heat production model

Table 12 Pellet and forest chip boiler annual production

	Pellet boiler	Forest chip boiler	Unit
Heat produced	10110	10076	MWh
Fuel used	11078	11359	MWh
Own use electricity	101	101	MWh
Annual energy coverage	98,8 %	98,5 %	
Boiler efficiency	91,3 %	88,7 %	
Thermal power	3	2,5	MW
Peak coverage	96,8 %	80,6 %	
Annual full load hours	3370	4030	h
Reserve unit heat demand	119	153	MWh
Reserve unit efficiency	70 %	70 %	
Oil consumption	170	219	MWh
Heat demand	10229	10229	MWh

7.2 Heat pump-based heat production

For heat pump-based heat production two cases with two different manufacturer heat pumps are used. Calefa heat pump system with smallest thermal capacity presented in Chapter 6.2.3 and Oilon heat pump presented in Chapter 6.2 is used as heat pumps. Two cases modeled consists of system where other utilize medium-deep geothermal and other utilize shallow geothermal source. Two systems are modeled because the variable costs of each system are different. Because of the heat pump COP is depending on heat source temperatures. The selected heat pump for geothermal source is Oilon heat pumps. For an ambient air heat source, Calefa heat pumps were used. Ambient air was used for heat sources for decreasing the number of required boreholes for increasing system cost efficiency.

Model using medium-deep geothermal boreholes as heat source contains four two kilometers deep boreholes. A required number of boreholes was selected regarding the heating power required for heat pump operation at the operating point. Properties of geothermal boreholes are presented in Chapter 6.2.1. Medium deep boreholes require less space therefore they would be more suitable as a heat source compared to shallow boreholes which require more space. Nevertheless, medium thermal holes are expensive to drill and therefore shallow geothermal boreholes are taken into comparison. Also, heat pump COP affects on amount of heat collected from the heat source. Therefore, shallow geothermal having lower COP allows less energy gathered from the heat source which decreases the required number of boreholes, and therefore investment cost of the system would be smaller.

Model using shallow deep geothermal boreholes as heat source requires 60 boreholes which are 300 meters depth. A shallow deep geothermal utilizing system faces problems with space. Therefore, the land is required to be rented or bought with 60 boreholes required land area with 40 meters spacing between each hole is around 7,2 hectares. Illustrating required space for borehole field normal size football field is around 0,7 hectares.

Heat pump COP and thermal capacity determination were introduced in Chapters 6.2 and 6.2.3. Heat production in this model is built so that heat production units are connected in series. In order where ambient air HP is first geothermal HP second and after that reserve unit. With this arrangement, ambient air hp is used to heat district heat return water to + 75 °C. If the DH network requires a higher temperature or thermal capacity of a heat pump is exceed the next production unit in the arrangement is used to cover heat demand. Geothermal HP is used to heat district heat return water to + 90 °C. The Reserve unit is used to cover the last portion of district heat demand. Reserve units are LK-72 and LK-102.

Heat production models are presented in Figure 34 and Figure 35. There can be seen that a heat pump-based system requires the usage of reserve units. Therefore, oil is consumed. If oil consumption is decreased more boreholes are required to drill, and a heat pump with a larger thermal capacity is required. The ambient air heat pump is used as a baseload unit. Ambient air is used as a heat source when the ambient temperature is above – 15 °C degrees. Geothermal is used as a heat source when the ambient temperature is below – 15 °C or district heating supply temperature is higher than + 75 °C.

Heat production units' annual details are shown in Table 13 and Table 14. There can be seen that both systems cover above 90 % of annual energy. Increasing energy coverage requires larger heat pumps and more boreholes. This would increase investment costs. Therefore, a heat pump is not suitable for covering a higher portion of heat demand. Increasing the HP portion in heat production requires HP to produce a higher supply temperature which leads to even lower efficiency. On the other hand usage of peak load unit is high. In this model peak load unit is the oil boiler. Therefore, oil consumption is high.

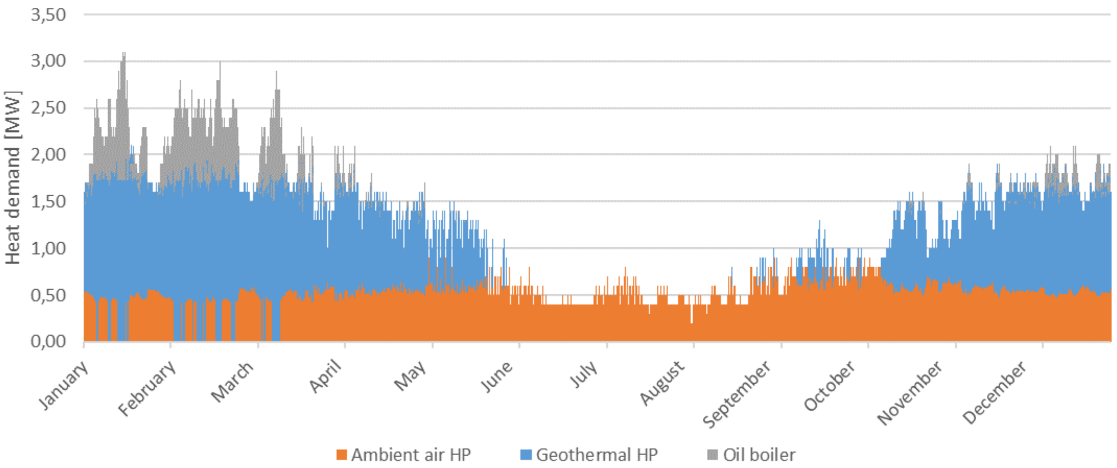

Figure 34 Heat pump-based heat production model with medium-deep geothermal

Table 13 Heat pump-based heat production with medium-deep geothermal

	Geothermal HP	Ambient air HP	Oil boilers	Combined	Unit
Heat produced	5198	4423	608	10229	MWh
Fuel consumption			869	869	MWh
Electricity consumption	1580	1900		3480	MWh
Heat from source	3618	2524		6141	MWh
Annual energy coverage	50,8 %	43,2 %			
Boiler efficiency			70 %		
SCOP	3,29	2,33			
Thermal power	1,72	0,74	1,38		MW

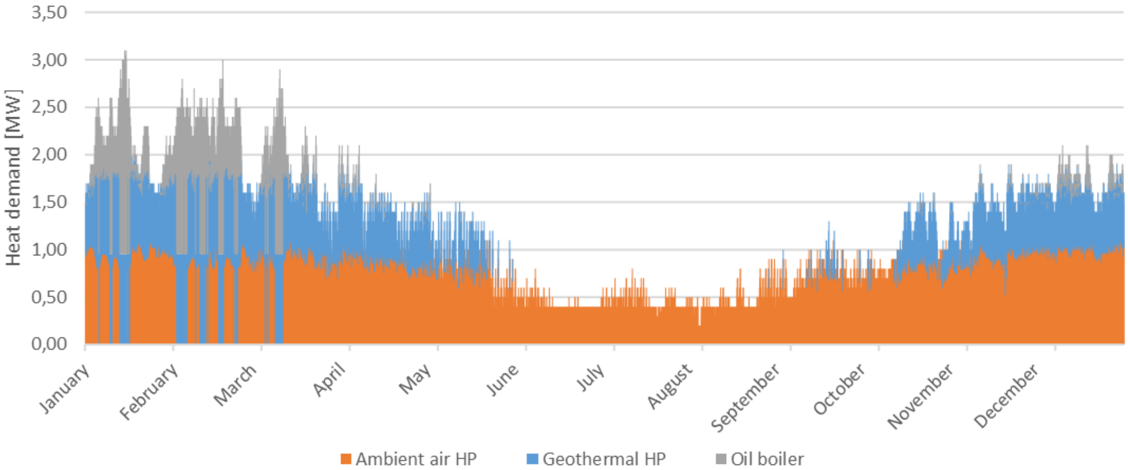

Figure 35 Heat pump-based heat production model with shallow geothermal

Table 14 Heat pump-based heat production model with shallow geothermal

	Geothermal HP	Ambient air HP	Oil boilers	Combined	Unit
Heat produced	2902	6403	924	10229	MWh
Fuel consumption			1320	1320	MWh
Electricity consumption	1256	2574		3830	MWh
Heat from source	1646	3829		5475	MWh
Annual energy coverage	28,4 %	62,6 %			
Boiler efficiency			70 %		
SCOP	2,31	2,49			
Thermal power	0,95	1,23	2,15		MW

7.3 Combustion and heat pump-based heat production

For combustion and heat pump-based production pellet boiler and HP using ambient air as a heat source were selected as heat production units. Pellet boiler was most suitable since it can be operated with a wide range of operational load and it has low investment cost. The heat pump selected for the system is the unit with the lowest thermal capacity introduced in Chapter 6.2.3. The system with the lowest thermal capacity is selected because it is capable to produce summer heat demand on its own. Also, ambient air is selected as a heat source as a cost-effective way to utilize ambient heat.

In this model heat production units are considered to operate in series where ambient air HP is used primarily to heat DH supply temperature to + 75 °C if the higher temperature or thermal capacity is required pellet boiler is used. Also, a production unit was selected related to heat production costs. If heat pump production cost exceeds pellet boiler production cost, pellet boiler is used. Production costs were calculated for the pellet boiler with fuel costs and efficiency of the boiler. For heat pump hourly electricity cost and efficiency was used. The heat pump is shutdown temperature set to – 15 °C.

Using pellet boiler as district heat supply temperature priming leads to decreased efficiency of pellet boiler. Thus, the effect should be taken into count if this production method is selected. Also, if a flue gas scrubber with heat recovery is installed on the boiler this effect would be neglected. Heat recovered from flue gas would be potentially used as a heat source of a heat pump. This would increase the overall efficiency of this type of heat production method.

The heat production model is presented in Figure 36 and Figure 37. There are presented the same model with different electricity tax categories. There can be seen that when heat pumps are in electricity tax category two this favors heat pump production over combustion more. The heat pump is cost-efficient almost around the year with tax category two and with tax category one operation is more limited on milder months. Annual production numbers are presented in Table 15 and Table 16. There can be seen that with electricity tax two category heat pump annual energy coverage is doubled compared to category one tax. Therefore, the price of electricity is playing an important role in achieving the true potential of heat pump potential capacity. Operation of peak load units is moderate because of the pellet boiler's high thermal capacity.

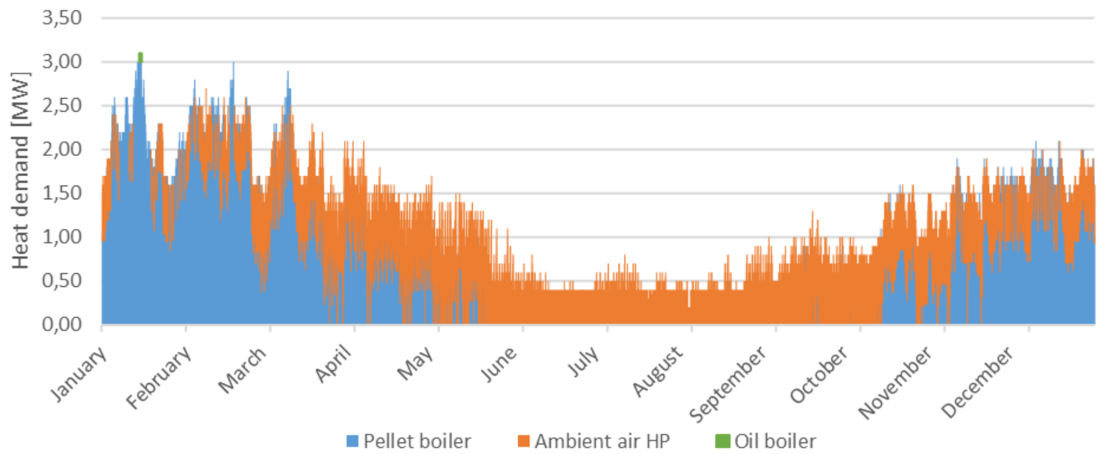

Figure 36 Pellet boiler and ambient air heat pump system with electricity tax 2

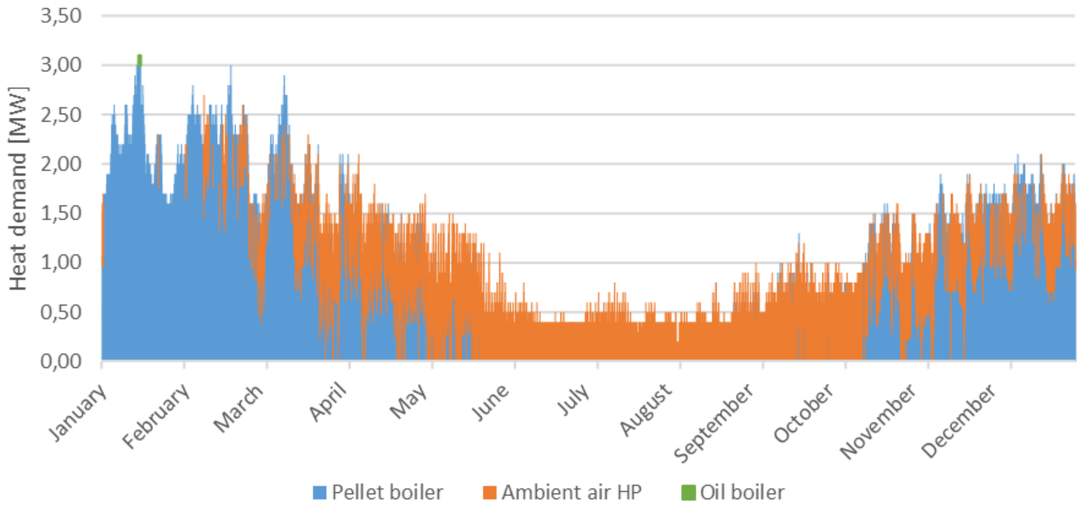

Figure 37 Pellet boiler and ambient air heat pump system with electricity tax 1

Table 15 Pellet boiler and ambient air heat pump system with electricity tax 2

	Pellet boiler	Ambient air HP	Oil boiler	Combined	Unit
Heat produced	6284	3945	0,30	10229	MWh
Fuel consumption	6938		0,43	6938	MWh
Electricity used	65	1658		1722	MWh
Annual energy coverage	61,4 %	38,6 %	0 %	100 %	
Boiler efficiency	90,6 %		70 %		
SCOP		2,38			
Thermal power (peak)	3	0,5			MW
Peak coverage	96,8 %	16,1 %			

Table 16 Pellet boiler and ambient air heat pump system with electricity tax 1

	Pellet boiler	Ambient air HP	Oil boiler	Combined	Unit
Heat produced	6896	3333	0,30	10229	MWh
Fuel consumption	7585		0,43	7585	MWh
Electricity used	71	1361		1432	MWh
Annual energy coverage	67,4 %	32,6 %	0 %	100 %	
Boiler efficiency	90,9 %		70 %		
SCOP		2,45			
Thermal power	3	0,5			MW
Peak coverage	96,8 %	16,1 %			

7.4 Sale and heat pump-based heat production

For sale and heat pump-based production two cases were considered. Another model has an ambient air heat pump. Other has ambient air and geothermal as a heat source for a heat pump. Heat pumps are considered to produce the baseload of heat demand. Purchased heat from sawmill is considered to be used for covering heat demand when heat pumps production capacity is exceeding.

For geothermal and ambient air system heat pump selected is the largest thermal capacity heat pump presented in Chapter 6.2.3. The heat pump is using ambient air and medium-deep geothermal as a heat source. Two medium-deep geothermal boreholes are selected for this system. Sawmill energy can be used as district heat supply temperature priming. Therefore, heat production units are connected in series. Selecting this production model requires the sawmill to agree that heat is used for district heating supply temperature priming. This arrangement increases return temperature from the heat exchanger back to the sawmill.

The heat production model is presented in Figure 38. There can be seen that heat production is covered from June to October with a heat pump using ambient air as a heat source. When heat demand increases geothermal heat is also utilized. Purchased heat is used when heat pumps are not capable to cover heat demand. From Table 17 can be seen annual energy production numbers. There can be seen that heat collected from geothermal source is in sustainable level if at least two medium-deep boreholes are drilled with the assumption of 840 MWh energy available per hole. Heat purchased from sawmill is less than ten percent from annual heat production. But heat is required when heat demand is high and required thermal capacity is high. Therefore, purchase heat demand would not be suitable for sawmill operations.

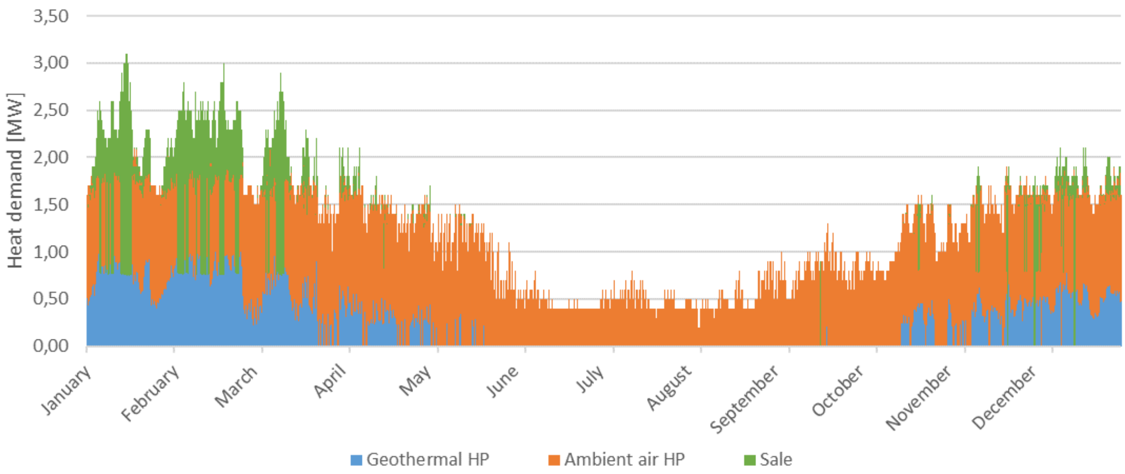

Figure 38 Sale and heat pump-based heat production

Table 17 Sale and heat pump-based heat production annual production numbers

	Geothermal HP	Ambient air HP	Sale	Oil boiler	Combined	Unit
Heat produced	2844	6328	1058	0	10229	MWh
Fuel consumption				0		MWh
Electricity used	1323	2540			3863	MWh
Heat from source	1521	3788			5309	MWh
Annual energy coverage	27,8 %	61,9 %	10,3 %		100 %	
Boiler efficiency				70 %		
SCOP	2,15	2,49				
Thermal power	1,09	1,23	2,35			MW
Peak coverage	35,3 %	39,7 %				

For the ambient air heat and sale-based model selected heat pump was medium size heat pump presented in Chapter 6.2.3. This heat pump was selected since it gives the highest annual energy coverage compared to three different ambient heat pump systems offered. Heat pump heat sink temperature is limited to + 75 °C. Heat capacity from the sawmill exchanger is depending on sawmill operation but a maximal thermal capacity of 2,7 MW is used. Therefore, oil is required to be burned when heating demand is high which can be seen from Figure 39. Ambient air heat source utilizing a heat pump minimum operating temperature is – 15 °C. Therefore, outside temperatures below that heat are produced with purchased heat and combusting oil in reserve units. Nevertheless, the ambient air heat pump is covering over 60 % of the annual heat demand. This can be seen in Table 18.

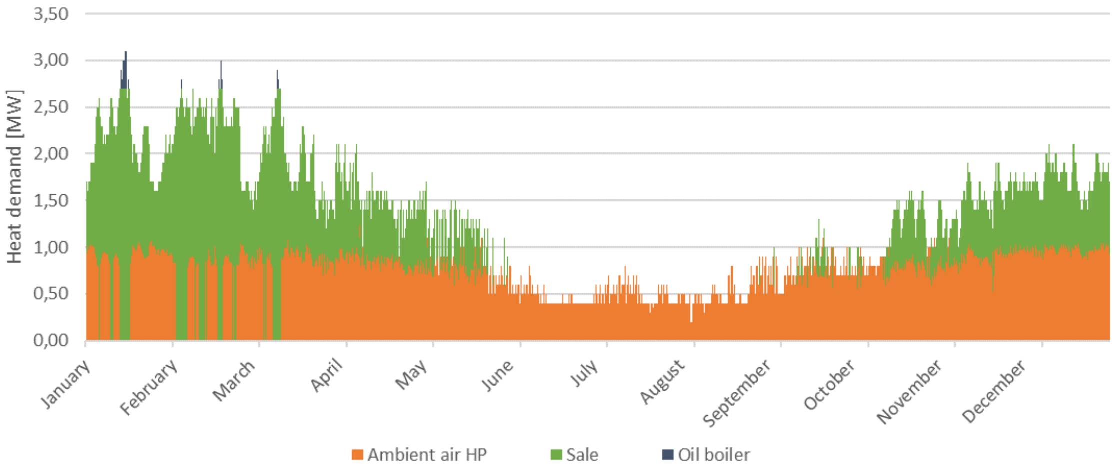

Figure 39 Purchased heat and ambient air HP based production

Table 18 Purchased heat and ambient air HP based production annual production numbers

	Ambient air HP	Sale	Oil boiler	Combined	Unit
Heat produced	6403	3816	11	10229	MWh
Fuel consumption			15,3	15	MWh
Electricity used	2574			2574	MWh
Heat from source	3829			3829	MWh
Annual energy coverage	62,6 %	37,3 %	0,1 %	100 %	
Boiler efficiency			70 %		
SCOP	2,49				
Thermal power	1,23	2,70			MW

7.5 Solar, combustion, and heat pump-based heat production

For solar, combustion, and heat pump-based production is selected the same mode as presented in Chapter 7.3 with the addition of solar collectors. In this model, it is expected that solar heat is producing heat in the highest priority and another production method after that. Heat production units are connected in series.

Solar heat collector’s energy production was modeled with solar irradiation measurement data and collector efficiency presented in Chapter 6.3. The number of solar panels was selected so that the hourly production of solar collectors does not exceed hourly heat demand.

Therefore, produced heat can be directly supplied to district heat. The selected collector surface area was 120 m^2.

The heat production model is presented in Figure 40. There can be seen that solar heat is available mostly during summer. Therefore, the heat produced with solar collectors is mainly reducing heat produced by the ambient air heat pump. From Table 19 can be seen solar collectors' annual heat production capacity. Heat production capacity in this model is theoretical and actual production capacity may be lower. Since dust and other impurities on the collector, surface decrease the production capacity of operating panels. Nevertheless, solar collectors cover a relatively small portion of annual energy production, less than one percent. the model was modeled with both electricity tax categories.

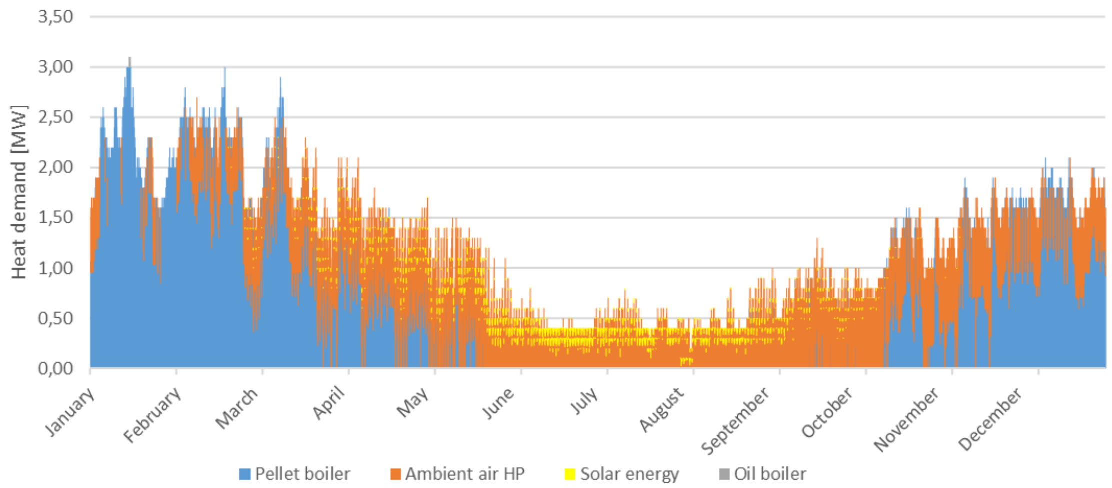

Figure 40 Solar, combustion, and heat pump-based heat production with electricity tax 2

Table 19 Solar, combustion, and heat pump-based heat production with electricity tax 2 annual production numbers

	Pellet boiler	Ambient air HP	Solar	Oil boiler	Combined	Unit
Heat produced	6265	3888	75,4	0,3	10229	MWh
Electricity consumed	64	1640			1705	MWh
Fuel consumed	6920			0,43	6921	MWh
Heat from source		2248			2248	MWh
Annual energy coverage	61,2 %	38,0 %	1 %	0 %	100 %	
Boiler efficiency	90,5 %			70 %		
SCOP		2,37				
Thermal power	3,00	0,74	0,10			MW

7.6 Solar, combustion, and sale based heat production

For solar, combustion, and sale-based heat production model, there was utilized forest chip boiler, solar collectors and purchased heat from the sawmill. Forest chip boiler was selected for the model as the cheapest option for producing the base load of district heat. Thermal capacity for forest chip boiler was selected so that annual energy coverage is 90 %. Purchased heat from sawmill is used to cover high peak demands and heat demand during the annual revision of the forest chip boiler. In this model forest chip boiler and sawmill heat exchanger would be assembled in series or parallel. Therefore, with parallel arrangement sawmill heat exchanger would have no changes in temperature levels compared to conventional use. Solar energy has a similar application as the model presented in Chapter 7.4.

The heat production model is shown in Figure 41. There can be seen that the forest chip boiler is covering a major portion of heat demand. During cold winter months purchased heat is used to cover peak demands and annual revision of forest chip boiler. Boiler revision time in this model has placed the end of July. Actual revision time is related to sawmill revision time. Solar heat is decreasing the demand for combustion during summer. Solar production requires the boiler to be operated with a moderate load which affects boiler efficiency. Annual production numbers are shown in Table 20. There can be seen that a major portion of annual heat production is produced by forest chip boiler.

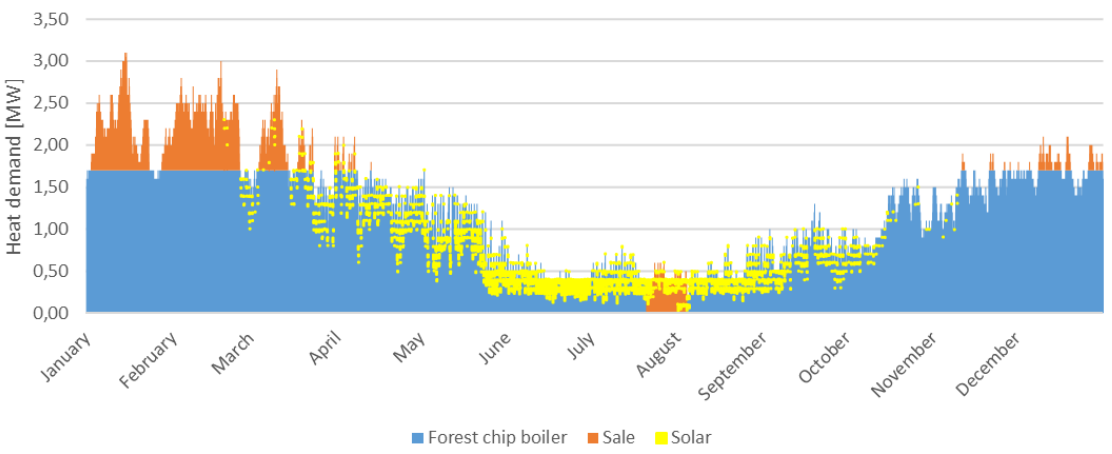

Figure 41 Solar, combustion, and sale based heat production

Table 20 Solar, combustion, and sale based heat production

	Forest chip boiler	Solar	Sale	Combination	Unit
Heat produced	9236	75	918	10229	MWh
Fuel consumption	10392			10392	MWh
Own use electricity	92			92	
Annual energy coverage	90,3 %	0,7 %	9,0 %		
Boiler efficiency	89 %				
Thermal power	1,7		1,4		MW
Peak coverage					

8 Comparison between heat production models

Heat production models are compared with economic and environmental impact points of view. In economical comparison levelized cost of heat production is calculated. In environmental comparison is done by comparing heat production carbon dioxide emissions. Emissions are estimated by using emission factors for specific fuels and the average electricity emission factor presented by the authors.

8.1 Economical comparison

Economical comparison of different heat production methods is done by comparing LCOH. The LCOH is calculated with the sum of heat production costs, including the cost of electricity, fuel costs, O&M costs, and investment costs. LCOH is calculated with equation 2. (Pieper et all, 2020)

$$LCOH = \frac{C_F + C_{El} + C_p + C_{inv,a} + C_{O\&M}}{Q} \tag{2}$$

Where,

LCOH	Levelized Cost of Heat
C_F	Annual fuel costs
C_{El}	Annual electricity costs
C_p	Annual purchased heat cost
$C_{inv,a}$	Annualized investment cost
$C_{O\&M}$	Annual operation and maintenance costs
Q	Annual heat production

Annual fuel costs are calculated with annual consumed fuel by boilers for each model. Fuel prices used in calculations are shown in Table 21.

Table 21 Fuel prices used in economical comparison calculations

	Value	Unit
Wood pellet	38	€/MWh
Forest chips	25	€/MWh
Light fuel oil	70	€/MWh
Purchased energy	XX	€/MWh

Electricity costs consist of electricity taxes, transmission costs, energy costs, and basic fees from the electricity network operator. Electricity costs are considered in calculations in two sections variable electricity costs and fixed electricity costs. Variable energy costs consist of electricity transmission, taxes, and energy costs. Fixed energy cost consists of basic fees and other service costs from the electricity network operator.

Electricity transmission and taxes used in calculations are shown in Table 22. A suitable electricity contract consists of seasonal variation in transmission cost. Transmission cost is different related to date. Price changes two times a year. For electricity energy price there is used Nord Pool historical market data. Selected data electricity data is a mix from ELSPOT-FI price from 2020 and 2021. (Nord Pool. 2021) Also, commission of XX €/MWh is used.

Table 22 Electricity tax and transmission costs (Savon Voima Verkko Oy, 2021a)

	Value	Unit
Electricity tax 1	22,53	€/MWh
Electricity tax 2	0,63	€/MWh
Transmission cost 1.11-31.3	30	€/MWh
Transmission cost 1.4 -31.10	20	€/MWh

Electrical connection costs affect variable costs of heat production units. These costs are determined related to local grid operator Savon Voima Verkko Oy's price list. Heat pumps require a low-voltage electricity connection. Low-voltage connection requires a capacity booking fee, upkeep fee, basic fee, and demand fee. Capacity booking fee includes electricity connection installation fees during heat pump installation at the start of operation. Prices used in cost calculations are shown in Table 23. For each heat pump system, the monthly demand fee was determined with the highest hourly electricity consumption for each month. Capacity booking fee was calculated with nominal electricity power required given by heat pump manufacturer.

Table 23 Prices uses for low-voltage electricity connection fees (Savon Voima Verkko Oy, 2021a, 2021b)

	Value	Unit
Capacity booking fee	112	€/kW
Upkeep fee	262	€/kk
Basic fee	146	€/kk
Demand fee	3,81	€/kW,kk

For determining annualized investment cost interest rate and the lifetime of the production unit are considered. The lifetime of a production unit is a major factor since the unit is re-placed after the end of the lifetime. A discount rate of five percent is used. For boiler plants, the technical lifetime is 15 years, and for heat pumps lifetime are 15 years. Geothermal heat source lifetime is considered 25 years. Solar collector's technical lifetime is also considered 15 years. The annualized investment cost is calculated with Equation 3. (Pieper et all, 2020)

$$C_{inv,a} = C_{inv} \frac{b}{(1+b)(1-(1+b)^{-T})} \tag{3}$$

Where,

$C_{inv,a}$	Annualized investment cost
C_{inv}	Investment cost
b	Discount rate
T	Lifetime of unit

Operation and maintenance costs used in models are related to the investment costs of systems. For boilers maintenance costs of two percent of the investment, costs are used. Maintenance work required in boiler plants consists of annual revision workload and component replacements. For heat pumps, one percent of maintenance costs are used. Heat pump maintenance costs consist of annual checks and maintenance work done by a service worker. Heat production units are operated in remote control. Therefore, operation costs of heat production units are not involved in calculations.

Calculated LCOH for each heat production model is shown in Appendix 1. There can be seen how cost structure of different systems are built. There can be seen that in combustion based systems cost structure is heavily based on investment cost and fuel costs. In heat pump-based systems investment cost and electricity costs represent major portion of system total annual costs. Directly comparing LCOH between heat production models most cost efficient heat production system is sale and heat pump-based production. Heat production systems are placed increasing LCOH order in Table 24. Systems including heat pumps have tax category one system and tax category two system. Heat production systems which include heat pumps are most cost-efficient with ambient air as heat source. Systems using geoenergy as heat pump heat source are most least cost-efficient. System having purchased heat in heat production allows most cost-efficient heat production.

Table 24 Heat production systems presented in increasing LCOH order

Heat production systems	Presented in Chapter
Sale and Ambient air HP Tax 2	7.4
Solar collectors + Forest chip boiler + Sale	7.6
Joroinen pellet boiler system	7.1
Joroinen Pellet boiler + Air HP Tax 2	7.3
Pellet boiler + Ambient air HP + Solar Tax 2	7.5
Sale and Ambient air HP Tax 1	7.4
Joroinen Pellet boiler + Air HP Tax 1	7.3
Forest chip boiler system	7.1
Pellet boiler + Ambient air HP + Solar Tax 1	7.5
Heat pump shallow system Tax 2	7.2
New Pellet boiler system	7.1
New pellet boiler + Ambient air HP Tax 2	7.3
New pellet boiler + Ambient air HP Tax 1	7.3
Sale and Geo + Ambient air system Tax 2	7.4
Heat pump shallow system Tax 1	7.2
Sale and Geo + Ambient air system Tax 1	7.4
Heat pump medium deep system Tax 2	7.2
Heat pump medium deep system Tax 1	7.2

Fuel and electricity prices are considered to increase during the coming years. Biofuel prices are considered to increase three percent annually and electricity prices are considered to increase two percent annually. Thus, variable costs of heat production are going to be increased and depending on fuel and electricity consumption price increase affect different. The effect of price increase on LCOH is presented in Appendix 2. There can be seen that systems LCOH is developing different in different heat production models. For comparison heat production models are presented in increasing order in Table 25. There can be noticed that systems with flexible heat sources are remaining most cost-efficient.

Table 25 Heat production methods presented in increasing LCOH order with developing variable costs

LCOH Year 5	LCOH Year 10	LCOH Year 15
Sale and Ambient air HP Tax 2	Sale and Ambient air HP Tax 2	Sale and Ambient air HP Tax 2
Solar collectors + Forest chip boiler + Sale	Solar collectors + Forest chip boiler + Sale	Solar collectors + Forest chip boiler + Sale
Joroinen Pellet boiler + Air HP Tax 2	Joroinen Pellet boiler + Air HP Tax 2	Joroinen Pellet boiler + Air HP Tax 2
Pellet boiler + Ambient air HP + Solar Tax 2	Pellet boiler + Ambient air HP + Solar Tax 2	Pellet boiler + Ambient air HP + Solar Tax 2
Joroinen pellet boiler system	Heat pump shallow system Tax 2	Heat pump shallow system Tax 2
Sale and Ambient air HP Tax 1	Sale and Ambient air HP Tax 1	Forest chip boiler system
Heat pump shallow system Tax 2	Forest chip boiler system	Sale and Ambient air HP Tax 1
Forest chip boiler system	Joroinen pellet boiler system	Joroinen pellet boiler system
Joroinen Pellet boiler + Air HP Tax 1	Joroinen Pellet boiler + Air HP Tax 1	Joroinen Pellet boiler + Air HP Tax 1
Pellet boiler + Ambient air HP + Solar Tax 1	Pellet boiler + Ambient air HP + Solar Tax 1	Pellet boiler + Ambient air HP + Solar Tax 1
New pellet boiler + Ambient air HP Tax 2	New pellet boiler + Ambient air HP Tax 2	Sale and Geo + Ambient air system Tax 2
New Pellet boiler system	Sale and Geo + Ambient air system Tax 2	New pellet boiler + Ambient air HP Tax 2
New pellet boiler + Ambient air HP Tax 1	New Pellet boiler system	New Pellet boiler system
Sale and Geo + Ambient air system Tax 2	New pellet boiler + Ambient air HP Tax 1	New pellet boiler + Ambient air HP Tax 1
Heat pump shallow system Tax 1	Heat pump shallow system Tax 1	Heat pump shallow system Tax 1
Sale and Geo + Ambient air system Tax 1	Sale and Geo + Ambient air system Tax 1	Sale and Geo + Ambient air system Tax 1
Heat pump medium deep system Tax 2	Heat pump medium deep system Tax 2	Heat pump medium deep system Tax 2
Heat pump medium deep system Tax 1	Heat pump medium deep system Tax 1	Heat pump medium deep system Tax 1

8.2 Environmental comparison

Environmental comparison of different heat production models is done by comparing heat production emissions. Major emissions released during heat production are carbon dioxide emissions. Carbon dioxide emissions are estimated with calculations for each heat production model. Emissions related to combustion like dust, NOx, and SOx are discussed in general. Alternative effects on the environment are noise and heat pump collector fluids leakage in nature.

Carbon emissions of different heat production models can be examined with consumed fuels and electricity. Different fuels have their specific carbon dioxide emissions. Heat pumps consumed electricity carbon dioxide emissions can be calculated with the average electricity emission factor. Purchased heat is produced with combusting wood fuels. The emission factor for electricity in Finland is 131 kg CO_2/MWh it is calculated by Statistic Finland by three years floating average. Statistic Finland has also presented fuel classification where different fuel emission factors can be found. Woody biomass fuels emission factor is 404 kg CO_2/MWh. For light fuel oil carbon emission factor is 255 kg CO_2/MWh. (Statistic Finland. 2021)

Calculated carbon dioxide emissions for each heat production model are presented in Appendix 3. There are calculated gross emissions and net emissions where biomass source fuel emissions are considered as zero. If wood fuels would be not considered anymore as carbon neutral heat production methods based on combustion would have major carbon dioxide emissions. With current regulations, wood fuels are carbon neutral. Therefore, systems based on combustion are as well producing the least amount of carbon emissions. Heat pump-based production emitting the highest amount of carbon dioxide. Regardless, every heat production method is generating less carbon dioxide emissions compared to completely fossil fuel-based systems. Carbon emissions for systems modeled in this master’s thesis vary between 1- 84 kg CO_2/MWh. In comparison fossil fuels like peat, coal has emission factors of 355 – 400 kg CO_2/MWh depending on their type. (Statistic Finland. 2021)

Heat pumps contain refrigerants that have global warming accelerating properties. Therefore, if the refrigerant is leaked it is released into the environment causing the global warming effect. Each type of refrigerant has its GWP value which indicates the amount of heat absorbed in the atmosphere compared to the same mass of carbon dioxide. Heat pumps used in this model contain refrigerants like R513A and R450. Refrigerant R513A has a GWP value of 631 and R450 has a GWP value of 547. The amount of refrigerant in systems used in these models has around 40 - 60 kg per heat pump. If one unit leaks all refrigerant to the environment it has a similar global warming effect as 20 – 38 t CO2 releasing to the environment.

Combustion-based methods are also producing emissions like dust, NOx, SOx. In Chapter 3.6 was described emissions limits for combustion units operated in Finland. It is considered that combustion units selected as heat production units meet these emissions limits. Dust emissions are controlled flue gas cleaning systems like electric precipitators or fabric filters. NOx emissions can be controlled with optimized combustion where combustion temperature is controlled with proper air staging. SOx emissions are related to fuel composition. Even to combustion units meet regulations today will be emission regulations straightening in the future. Therefore, combustion units might require technical modernization to meet the upcoming limits. This could increase the capital costs of combustion units.

8.3 Recommended heat production model

When the environmental and economical points of view are specified recommended heat production method is combustion and heat pump-based system. Selected heat production method presented in Chapter 7.3. Overall, this heat production method is cost-effective and competitive against the current heat production method. In economical comparison, this method is not the cheapest option but considering factors like peak load coverage, the flexibility of heat production, and moderate investment cost this production model is recommended. The issue with only combustion or heat pump-based production is the non-flexibility to adjust heat production related to variable costs. Also, for heat pump systems thermal capacity is a limiting factor in high peak demands. Covering high peak demands with heat pumps requires unnecessary high investment costs. Therefore, they always require a reserve unit in peak demand. Purchased heat systems are depending on the contract details with the sawmill.

The flexibility of heat production with recommended model allows utilization of electricity price fluctuation. Because pellet boiler is suitable for operating a wide range of load is heat pump suitable for the shutdown when the electricity price is high. On the other hand, heat pump could be used more when the electricity energy price is low. This allows cost-effective operation for heat production units. Also, the possibility of applying the electricity control market would increase system cost-effectiveness in the future. Control markets are controlled by Fingrid. Currently Fingrid requires customers to have at least 5 MW of control capacity to apply for control markets. Control capacity is sold in 1 MW blocks. Recommended system is not able to apply in control markets in current market state.

With this model, there is potential for an upgrade with medium-deep geothermal boreholes in the future if the cost for drilling is decreasing. Boreholes could be used as a heat source when the ambient air temperature drops below a certain level to optimize heat pump COP. This would allow heat pumps used in heat production around the year without ambient air limitations. The selected heat pump can easily adapt to alternative heat sources.

Pellet boiler and heat pump combination are also beneficial because essential district heat supply temperature priming required for ambient air heat pump could be done with the pellet boiler. Technically pellet boiler is suitable for a wide range of boiler loads with high efficiency. Utilizing boiler in supply temperature priming requires the boiler to be operated off-design situation which affects boiler efficiency. Which would increase fuel consumption.

The major risk for switching to this heat production method is fluctuation in fuel and electricity prices. This heat production method has some flexibility to optimize heat production related to variable costs. Heat production is depending on the combustion of pellets almost around the year. Only during the summer months heat pump is the capacity to take full control of heat production. Therefore, change in pellet fuel price affects more on systems cost-effectiveness. One reason for the pellet fuel price increase could be the EU LULUCF regulation proposed for 2021 - 2030. The regulation sets the reference for forest utilization for each EU-member country. EU-member countries have criticized calculation methods used for estimating sustainable forest felling amounts. If regulation goes through like it is presented it would effect on wood available on markets. Thus, the price of wood fuels would increase.

Electricity energy prices are depending on electricity markets. The increasing amount of renewable energy in energy production is causing more fluctuation in electricity markets. There are in total of 21 300 MW of planned wind power capacity in Finland. (Finnish Wind Power association. 2021) Also, electricity production starting in Olkiluoto 3 increases Finland's electricity production by 1600 MW. Olkiluoto 3 is considered to start producing electricity in February 2022 with the newest start-up schedule (TVO. 2021). In energy consumption wise energy-dense industries like steel production is moving towards environmental production methods that involve higher electricity consumption. Therefore, electricity demand is also increasing. In conclusion, electricity energy price is hard to examine, and it can vary a lot depending on new electricity production units and novel consumers coming into the market.

For electricity transmission costs Finnish government has set regulations for electricity network operators. This is done because transmission companies have a monopoly situation and natural market competition is not existing. Energy transmission companies are allowed for reasonable profits. Finnish Energy Authority is validation network operators profits and if profits are too high companies must compensate this to electricity network users. Therefore, electricity transmission price development can be considered as controlled. Annually electricity transmission charges can increase a maximum of 15 %. (Finland Energy Authority. 2021)

The Cost-effectiveness of this system is relating to the heat pump tax category. Heat pumps in district heat production have been discussed in Finnish government and tax category swift might occur in the coming years. In cost calculations, the effects of the tax category in recommended heat production method is roughly 3 - 4 €/MWh in LCOH analysis. Therefore, electricity tax cuts annual profits from 30 000 to 40 000 €. Also, tax category effects on heat pump and pellet boiler annual energy coverages if units are operated related to variable costs of heat production. Thus, tax category 1 increases the amount of heat generated with combustion, and tax category 2 increases the amount of heat from the heat pump. The effect of energy production this discussed in chapter 7.3.

9 Results analyze

Heat pump combustion-based production was selected as the most suitable way of generating heat in the Keitele district heating network. This production method was cost-effective, and it has the flexibility to optimize heat production with minimizing variable costs. Calculated results in the master’s thesis are related to data from different sources. For example, technical details of production units are given by manufacturers and literature. These details might vary in real operation. Data selected for modeling heat demand in Keitele network presents one type of heat demand profile in reality annual heat demand varies. All these factors cause errors between the calculated cost-effectiveness of heat production models in theory and reality.

In calculations, heat production units do not have downtime. Therefore, heat production units are operated ideally. In actual operation heat production units might have unwanted downtimes which would require heat production units to be operated non ideally. Thus, the use of reserve units would be higher in actual application. This affects cost efficiency at the system level.

Heat pump efficiency assumptions and power capacities used in calculations are a combination of manufacturers' given details and data analysis. In geothermal applications manufacturer, constant COP was used relating to collector fluid and district heating supply temperature. In operation heat, pump efficiency would change because of variation of temperatures in collector fluid and supply temperature. Also, heat pumps operated in part-load effects on efficiency. In ambient air heat pump applications heat pump thermal capacity and efficiency were estimated relating to the outside temperature. This method illustrates the theoretical capacity for an ambient air heat pump. Production capacity can be different in actual operation. Also, the amount of defrosting or self-use electricity is not calculated. Defrosting requires a heat pump to swift heat production to heat consumption for short period during defrosting evaporator. This effect requires either pellet boiler to follow defrosting cycles or utilization of moderate size heat storage. These factors should be considered if this production method is selected.

Solar collector’s theoretical potential was assumed with a combination of calculated theoretical conversion efficiency from irradiation to heat and solar irradiance towards the horizontal surface. This method resulted in a production capacity for solar collectors of 628 kWh/m^2. As a reference scenario, there were measurement details available from solar collectors used in Etelä-Savon Energia Oy district heating network in Ristiina. Compared to reference modeled production capacity for solar energy was optimistic.

Systems which involve purchased heat form the sawmill have assumption that purchased heat price is bought with current price and heat can be used heat demand exceeds own production capacity. In reality, obtaining a contract with these details might be challenging. Depending on which type of contract it is possible to get purchased heat production methods cost-effectiveness varies.

In variable cost of heat production systems, there was used for electricity energy price Elspot-FI from years 2020 and 2021. Elspot price was used to illustrate actual electricity variable costs. Therefore, the fluctuating price was used over the constant energy price. Selected price data was selected for similar hours as heat demand details. Nevertheless, electricity price in markets is relating to many other factors compared to heat demand which is mostly depending on outside temperature and domestic hot water consumption. In the selected range of data, the annual average price for electricity is 30 €/MWh. Thus, selected data for electricity price is optimistic. Electricity price is impossible to assumed correctly, and the price used in this masters’ thesis might illustrate future price bracket or not.

Investment costs of heat production systems used are a combination of manufacturers' offers from the request of proposals and typical prices used in reference scenarios or literature. The price given by manufacturers is realistic. Prices used for heat pump heat sources are taken from literature and reference scenarios. In this way price bracket for different heat sources was determined. For forest chip boiler investment cost was estimated with specific investment cost. Investment costs of all systems are estimated to be in a reasonable price bracket.

Maintenance costs for each system were assumed with the percentage of investment costs. Actual maintenance costs can vary annually. Maintenance costs for combustion units are considered to cover annual revision which involves two workers' workload for two weeks. Also, small component replacement costs. For heat pumps, annual checks for refrigerant leakages and system fully functional checks are done.

Heat production systems' overall cost efficiency was approximated by calculating LCOH. LCOH allows easy comparison between different heat production methods. It takes to count major cost factors in different heat production methods. Thus, calculation accuracy is depending on all factors used. Because results accuracy is depending on many factors and calculations involve assumptions errors are possible.

All in all, the results of this master’s thesis can be considered as accurate that they can be used in the selection of the cost-efficient way of generating heat in the Keitele district heating network. Calculation and models have some simplifications which do not take into count real-world variations. Therefore, heat production actual costs can vary compared to calculated costs.

10 Summary

In this master’s thesis aim was to review and estimate production costs of different heat production methods in the Keitele district heating network. Different heat production methods involved solar, combustion, and heat pump-based heat production methods. Heat production review was carried through with building heat production models which had a different type of heat production methods. Heat production methods are presented below.

- Combustion based production
- Combustion and heat pump-based production
- Combustion, heat pump, and solar-based production
- Heat pump-based heat production
- Purchased and heat pump-based heat production
- Purchased, combustion and solar-based heat production

Heat production models were modeled in hourly resolution. Hourly level modeling was done in Microsoft Excel, where properties of the Keitele district heating network were built in. The district heat network model involved heat demand, district heat supply, and return temperature, and outside temperature. Modeling was done at an hourly resolution for achieving accurate properties of heat production methods suitability for heat production. Details of heat production units were applied to Excel to determine the electricity and fuel consumption of different heat production methods. Also, fuel and electricity prices were applied in Excel to optimize heat production to minimize variable costs. In total there was modeled nine different heat production methods.

The cost-efficiency of heat production was compared with calculating LCOH for each heat production method. In LCOH comparison most cost-efficient heat production method was a system where heat is produced with purchased heat and ambient air heat pump. For the overall comparison of systems, environmental impacts and prospects of the energy market and policy development were discussed. Observing those factors recommended system was introduced as including a pellet boiler from Joroinen and an ambient air heat pump.

Major details impacting on heat production methods cost-effectiveness were investment costs, variable costs development, energy tax category, and properties of heat pump heat sources. Also, technical requirements set limits for heat production systems. For example, heat pumps are not able to produce sufficient supply temperature at a certain point which requires temperature priming with an alternative heat production unit.

Heat sources for the heat pump were selected ambient air and geothermal sources. Ambient waters were not used in heat production models because heat available from the lake is hard to be assumed. Also, utilization of temperature priming with pellet boiler when ambient waters are challenging to utilize since heat pump and pellet boiler must be located nearby each other. Therefore, geothermal sources and ambient air were most suitable for the Keitele network. Ambient air was most suitable as a low investment cost and non-location-based installation. Ambient air as a heat source is most suitable during summer when the outside temperature is high. Geothermal sources were considered as the second option as a stable and predictable heat source. The geothermal source's downside is high investment costs. On other hand, it can be also installed almost anywhere. Medium deep geothermal can achieve major potential if the cost of drilling is decreased in the future.

Variable cost development and heat pumps change to electricity tax category II are major factors for determining heat production methods cost-efficiency. Therefore, heat production models which can adjust heat production structure related to minimizing variable costs of heat production are more resistant to variation of electricity and fuel costs.

Further study is recommended for the development of the recommended system. Own usage electricity for ambient air collectors and defrost energy usage should be determined. Also, the potential for utilizing flue gasses from the pellet boiler as a heat source for the heat pump. During cold winter days, this would improve heat pump efficiency or even keep the heat pump operating. This would improve heat production's overall efficiency and decrease fuel combustion.

REFERENCES

1065/2017. Government Decree on Environmental Protection Requirements for Medium-sized Energy Production Units. Finnish parliament.

Alakangas E, Hurskainen M, Laatikainen-Luntama J & Korhonen J. 2016. Properties of indigenous fuels in Finland. VTT, Espoo. [Internet publication]. [Referenced 24.2.2021]. Available: https://www.vttresearch.com/sites/default/files/pdf/technology/2016/T272.pdf

Calefa Oy. 2021. Antti Porkka. Email and phone conversation. 6.4.2021.

Calefa Oy. 2019. Suomen aurinkoisin kunta Puumala lämpiää tulevaisuudessa auringolla ja lämpöpumpuilla. [Referenced 9.3.2021] Available: https://www.sttinfo.fi/tiedote/suomen-aurinkoisin-kunta-puumala-lampiaa-tulevaisuudessa-auringolla-ja-lampopumpuilla?publisherId=68350554&releaseId=69861332

Christoforou, E. & Fokaides P. 2019. Advances in Solid Biofuels. https://doi.org/10.1007/978-3-030-00862-8

David, A, Mathiesen, B., Averfalk, H., Werner, S. & Lund, H. 2017. Heat Roadmap Europe: Large-Scale Electric Heat Pumps in District Heating Systems. Energies 10 578.

ELY Center. 2019. Pohjavesialueiden kuvaukset, luokat ja rajaukset – pääsijaintikunta Keitele [Referenced at 20.3.2021] Available at: https://www.ymparisto.fi/fi-FI/Vesi/Vesiensuojelu/Pohjaveden_suojelu/Pohjavesialueet/Pohjavesialueet__PohjoisSavo(35978)

Energiateollisuus ry, 2021. Energiavuosi 2020 kaukolämpö. [Internet publication]. [Referenced 8.2.2021]. Available: https://energia.fi/files/4517/Energy_Year_2019_DistrictHeating_MEDIA.pdf

Energiateollisuus ry, 2020. Kaukolämpötilasto 2019. [Internet publication]. [Referenced 8.2.2021]. Available: https://energia.fi/files/5384/Kaukolampotilasto_2019.pdf

Energiateollisuus ry, 2019. Kaukolämmön käyttötaloudelliset tunnusluvut 2018. [Internet publificiation]. [Referenced 13.2.2021] Available: https://energia.fi/files/4158/Kayttotaloudelliset_tunnusluvut_2018.pdf

Energiateollisuus ry, 2017. Kaukolämmön yleiset sopimusehdot [Internet publication]. [Referenced 13.2.2021]. Available: https://energia.fi/files/1796/Suositus_T1_2017_Kaukolammon_yleiset_sopimusehdot.pdf

Energy authority of Finland. Sähkön toimitusvarmuus vuonna 2020 [Internet publification] [Referenced 15.2.2021] Available: https://energiavirasto.fi/documents/11120570/13026619/S%C3%A4hk%C3%B6n+toimitusvarmuus+vuonna+2020.pdf/74cfa703-eca8-2ab9-9094-50e5a3d04e30/S%C3%A4hk%C3%B6n+toimitusvarmuus+vuonna+2020.pdf?t=1606993678420

Etelä Savon Energia. 2021. Email conversation with Roni Koskelinen and Arto Nieminen.

FCG suunnittelu ja tekniikka Oy. 2017. Pohjois-Savon kohdennettu geoenergiapotentiaali-selvitys. [Referenced 23.3.2021] Available: https://www.pohjois-savo.fi/media/liitetiedos-tot/aluesuunnittelu/maakuntakaava-2040/kaavaselvitykset/pohjois-savon_geoenergiapoten-tiaaliselvitys_raportti_fcg_2017.pdf

Finnish Meteorological Institute. 2020. Energialaskennan testivuodet 2020. [Referenced 4.3.2021] Available:
https://www.ilmatieteenlaitos.fi/energialaskenta-try2020

Finnish Wind Power association. 2021. Projects under planning. [Referenced 14.5.2021] Available at: https://tuulivoimayhdistys.fi/en/wind-power-in-finland/projects-under-plan-ning

Finland Energy Authority. 2021. Regulatory methods 2016–2023. [Referenced 14.5.2021] Available at: https://energiavirasto.fi/en/pricing-regulation

Grassi, W. 2018. Heat Pumps Fundamentals and Applications. Cham : Springer Interna-tional Publishing

Government of Finland. Programme of Prime Minister Antti Rinne’s Government 6 June 2019. [Referenced 15.2.2021] Available: https://julkaisut.valtioneuvosto.fi/bitstream/han-dle/10024/161664/Inclusive%20and%20competent%20Finland_2019_WEB.pdf?se-quence=7&isAllowed=y

GTK. 2020. Uudenmaan geoenergiaselvitys. Uudenmaan liitto. Helsinki. [Referenced 8.3.2021] Alailable: https://www.uudenmaanliitto.fi/files/25236/Uudenmaan_geoener-giaselvitys.pdf

GTK. 2019. Helsingin geo-energiapotentiaali. [Referenced 23.4.2021] Available: https://www.hel.fi/static/liitteet/kaupunkiymparisto/julkaisut/julkaisut/julkaisu-25-19.pdf

Helen Oy. 2019. Vuosaareen uusi, ainutlaatuinen meriveden lämpöä hyödyntävä lämpö-pumppu. [Internet article] [Referenced 10.3.2021] Available: https://www.helen.fi/uu-tiset/2019/merivesilampopumppu

Juuti P. 2020. Suomen ensimmäinen geolämpölaitos käynnistyi – se saattaa korvata kivi-hiilen ja mullistaa lämmöntuotannon: "Olen suorastaan voitonriemuinen". [Referenced 9.3.2021] Available: https://yle.fi/uutiset/3-11158359

Lehto, J., Oasmaa, A., Solantausta, Y. Kytö, M. Chiaramonti, D. 2014. Review of fuel oil quality and combustion of fast pyrolysis bio-oils from lignocellulosic biomass. Kidlington: Elsevier Ltd.

Lund, H., Werner, S., Wiltshire, R., Svendsen, S., Thorsen, J., Hvelplund, F. & Mathiesen, B. 2014. 4Th Generation District Heating (4GDH) Integrating smart thermal grid into future sustainable energy systems.

Kallio, J., Korhonen, K., Wennerström, M., Sallasmaa, O. & Witick, I. 2019. Helsingin geoenergiapotentiaali. Helsingin kaupunki / kaupunkiympäristön toimiala

Kavanaugh, S., Raffery, K. 2014. Geothermal heating and cooling : design of ground-source heat pump systems. ISBN : 1-936504-85-5

Koreneff G., Lehtilä A., Hurskainen M., Pursiheimo E, Tsupari E., Koljonen T., Kärki T. 2016. Yhdistetyn sähkön- ja lämmöntuotannon hiilidioksidiveron puolituksen poiston vaikutukset. VTT-Tutkimusraportti. VTT-R-01173-16

Koskelainen L., Saarela R. & Sipilä K. 2006. Kaukolämmön käsikirja. Energiateollisuus ry. Helsinki

Mäkelä V & Tuunanen J. 2015. Suomalainen kaukolämmitys. Mikkelin ammattikorkeakoulu. Mikkeli

National Land Survey of Finland. 2021. View and download maps. [Referenced 19.5.2021] Available at: https://www.maanmittauslaitos.fi/en/maps-and-spatial-data/maps/view-and-download-maps

Natural Resources Institute Finland, Statistic database. Solid wood fuel consumption in heating and power plants by Year, Region, Unit and Wood fuel. [Referenced 24.2.2021] http://statdb.luke.fi/PXWeb/pxweb/en/LUKE/LUKE__04%20Metsa__04%20Talous__10%20Puun%20energiakaytto/01a_Laitos_ekaytto_maak.px/table/tableViewLayout1/?rxid=001bc7da-70f4-47c4-a6c2-c9100d8b50db

Niskanen, T. & Karjalainen, T. 2014. Biopolttoaineiden tuotantomahdollisuudet kainuussa. Oulun yliopisto.

Nord Pool. 2021. Historical Market Data [Referenced 14.4.2021] Available at: https://www.nordpoolgroup.com/historical-market-data/

Oilon Oy. 2021. Email conversation and heat pump offer.

Pesola, A., Bröckl, M. & Vahanen J. 2011. Älykäs kaukolämpöjärjestelmä ja sen mahdollisuudet. Loppuraportti Gaia Consulting Oy. [Internet publication] [Referenced 17.2.2021] Available: https://docplayer.fi/2848107-Alykas-kaukolampojarjestelma-ja-sen-mahdollisuudet.html

Pieper, H., Ommen, T., Buhler F. Torben J. Elmegaard, B & Markussen, W. 2020. Comparison of COP estimation methods for large-scale heat pumps used in energy planning. Energy (Oxford), 2020-08-15, Vol.205, p.117994

Pöyry Oy. 2020. Finnish Energy –Low carbon roadmap [Referenced 19.5.2021] Available at: https://energia.fi/files/5064/Taustaraportti_-_Finnish_Energy_Low_carbon_roadmap.pdf

Pöyry Oy. 2018. Älykäs kaupunkienergia. [Internet publication] [Referenced 17.2.2021] Available: https://energia.fi/files/2862/Alykas_kaupunkienergia_LOPPU-RAPORTTI_20180614.pdf

Pöyry Oy. 2016. Kaksisuuntaisen kaukolämmön liiketoimintamallit. [Internet publication][Referenced 18.2.2021] Available: https://media.sitra.fi/2017/02/27175247/Kaksisuuntaisen_kaukolammon_liiketoimintamallit-2.pdf

Raiko, R., Saastamoinen, J., Hupa, M., Kurki-Suonio, I. 2005. Poltto ja palaminen. International Flame Research Foundation – Suomen kansallinen osasto

Richter, C., Lincot, D., Gueymard, C. 2013. Solar Energy. New York, NY : Springer New Yor

Rämä, M. 2020. District heating with low carbon heat sources and low distribution temperatures.

Saidur, R., Abdelaziz, E., Demirbas, A., Hossain, M. & Mekhilef, S. 2010. A Reviev on biomass as fuel for boilers. [Referenced 18.2.2021] Available: https://doi.org/10.1016/j.rser.2011.02.015

Savo Solar. 2021. Savo 15 SG technical datasheet. [Referenced 15.4.2021] Available: https://savosolar.com/wp-content/uploads/Savo-15-SG-technical-datasheet-2018-09-21-EN.pdf

Savon Voima Verkko Oy. 2021a. Sähköverkon liittymismaksut 1.3.2021 alkaen. Referenced [21.4.2021] Available: https://savonvoima.fi/wp-content/uploads/2021/03/Sahkoverkon_liittymismaksut_01032021.pdf

Savon Voima Verkko Oy. 2021b. Sähkön verkkopalveluhinnat 1.1.2021 alkaen. Referenced [13.4.2021] Available: https://savonvoima.fi/wp-content/uploads/2020/12/Sahkon_verkkopalveluhinnat_01012021.pdf

Statistic Finland. 2021. Fuel classification. [Referenced 4.5.2021] Available at: https://www.stat.fi/tup/khkinv/khkaasut_polttoaineluokitus.html

Soo-Young, N. 2019. Application of Liquid Biofuels to Internal Combustion Engines. Singapore : Springer Singapore : Imprint: Springer

Torvelainen, J. 2021. Hakkuukertymä ja puuston poistuma [Internet publication] [Referenced 24.2.2021] Available: https://stat.luke.fi/hakkuukertyma-ja-puuston-poistuma

TVO. 2021. OL3. [Referenced at 14.5.2021] Available at: https://www.tvo.fi/tuotanto/laitosyksikot/ol3.html

Uski, M & Piipponen K. 2019. Selvitys geotermisen energian syväreikäporaamisesta, siihen liittyvistä ympästönäkohdista sekä riskienhallinasta.

Vakkilainen, E. 2017. Steam generation from biomass: construction and design of large boilers. Amsterdam : Butterworth-Heinemann

Valor Partners, 2016. Suuret lämpöpumput kaukolämpöjärjestelmässä. [Internet publication] [Referenced 15.2.2021] Available: https://energia.fi/files/993/Suuret_lampopumput_kaukolampojarjestelmassa_Loppuraportti_290816_paivitetty.pdf

Ympäristö.fi. 2021. Vesistöennusteet: Kymijoen vesistöalue – Nilakka. [Referenced 9.3.2021] Available: https://wwwi2.ymparisto.fi/i2/14/l147311001y/wqfi.html

APPENDICES

Appendices of this master's thesis includes detailed information of costs of heat production for each heat production system. This information was considered to keep within the company. Therefore, following appendices are not included in this public version.

Appendix 1: Summary of calculated LCOH for different heat production models

Appendix 2: Effect of fuel and electricity price increase on LCOH

Appendix 3: Carbon dioxide emissions for each heat production model

	Electricity	Wood	Oil	Carbon dioxide emissions (gross)		Carbon dioxide emissions (net)	
Combustion based production	**[MWh]**	**[MWh]**	**[MWh]**	**[tCO2/a]**	**[kg CO2/MWh]**	**[tCO2/a]**	**[kg CO2/MWh]**
Joroinen pellet boiler system	101	11 078	170	4 532	**443**	57	**6**
New pellet boiler system	101	11 078	170	4 532	**443**	57	**6**
Forest chip boiler system	101	11 359	219	4 658	**455**	69	**7**
Heat pump-based production							
Heat pump shallow system Tax 1	3 830		1 320	838	**82**	838	**82**
Heat pump shallow system Tax 2	3 830		1 320	838	**82**	838	**82**
Heat pump medium deep system Tax 1	3 497		787	659	**64**	659	**64**
Heat pump medium deep system Tax 2	3 497		787	659	**64**	659	**64**
Combustion and HP based system							
Pellet boiler + Ambient air HP Tax 1	1 432	7 585	0,43	3 252	**318**	188	**18**
Pellet boiler + Ambient air HP Tax 2	1 722	6 938	0,43	3 029	**296**	226	**22**
New pellet boiler + Ambient air HP Tax 1	1 432	7 585	0,43	3 252	**318**	188	**18**
New pellet boiler + Ambient air HP Tax 2	1 722	6 938	0,43	3 029	**296**	226	**22**
Sale and HP based system							
Sale and Geo + Ambient air system Tax 1	3 863	1 058		933	**91**	506	**49**
Sale and Geo + Ambient air system Tax 2	3 863	1 058		933	**91**	506	**49**
Sale and Ambient air HP Tax 1	2 574	3 816	15	1 883	**184**	341	**33**
Sale and Ambient air HP Tax 2	2 574	3 816	15	1 883	**184**	341	**33**
Solar + Combustion + HP system							
Pellet boiler + Ambient air HP + Solar Tax 1	1 427	7 535	0,43	3 231	**316**	187	**18**
Pellet boiler + Ambient air HP + Solar Tax 2	1 705	6 921	0,43	3 019	**295**	223	**22**
Solar + Combustion + Sale based system							
Solar collectors + Forest chip boiler + Sale	92	11 310	0	4 581	**448**	12	**1**