EFFICIENT DISTRICT HEATING IN LOW-ENERGY BUILDING AREAS

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PREFACE

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ABSTRACT

The purpose of this thesis was to investigate the possibilities to make district heating an efficient heat source in residential areas dominated by detached houses with heat demands significantly lower than the ones in traditional buildings.

The upcoming challenge for the concept of district heating has to do with the lower heat demands implying a higher relative loss of thermal energy. Low-energy buildings are in need of less heat on a yearly basis mostly because of their very low need of space heating from April to October. Still, the relatively high consumption during the winter months cannot be neglected, so the network should be dimensioned so that also the maximum heat loads during winter can be satisfied. This is the origin of the higher relative loss of thermal energy in networks distributing heat to low-energy buildings.

The possibilities to improve energy efficiency in this type of networks have been studied by simulating the heat distribution to the planned residential area Honkasuo, in northern Helsinki. It was found that lower temperature levels in the network improve energy efficiency significantly. A sufficient gap between supply- and return temperature is needed, but otherwise the temperature levels should be decreased as much as possible to increase the energy efficiency. By using pipes with thicker insulation layers, the heat losses can be further reduced.

How densely an area is settled also affects the loss of energy and makes it difficult to draw any general conclusions of how well suited district heating is for low-energy building areas. However, what can be said is that there are possibilities to make district heating more energy efficient and it should not be ruled out as the most suitable heat source only because a residential area is dominated by buildings with lower heat demands.

Key words: Energy efficiency, district heating, low-energy buildings

NOMENCLATURE

Symbols:

A	Area (m²)
c_p	Specific heat capacity $\left(\frac{\mathrm{kJ}}{\mathrm{kg \cdot °C}}\right)$
D	Diameter (m)
E	Distance between pipes (m)
H'	Height / Depth (m)
h	Heat transfer coefficient $\left(\frac{\mathrm{W}}{\mathrm{m^2 \cdot °C}}\right)$
K	Heat transfer coefficient $\left(\frac{\mathrm{W}}{\mathrm{m^2 \cdot °C}}\right)$
k	Pipe roughness (mm)
L	Length (m)
$\dot{m}$	Mass flow (kg/s)
n	Number of persons
P	Power (kW)
Δp	Pressure drop (kPa)
Q	Thermal energy (kWh)
$\dot{Q}$	Heat (kW)
q	Exchange factor $(\mathrm{h^{-1}})$
R	Thermal resistance $\left(\frac{\mathrm{m \cdot °C}}{\mathrm{W}}\right)$
Re	Reynolds number
r	Radius (m)
S	Number of degree days
T	Temperature (°C)
Δt	Time step (days)
U	Heat transmittance / U-value $\left(\frac{\mathrm{W}}{\mathrm{m^2 \cdot °C}}\right)$
v	Kinematic viscosity $\left(\frac{\mathrm{m^2}}{\mathrm{s}}\right)$
w	Flow Velocity (m/s)
β	Impact factor
ε	Average heat demand per maximum heat demand
ζ	Element resistance factor
η	Efficiency
λ	Thermal conductivity $\left(\frac{\mathrm{W}}{\mathrm{m \cdot °C}}\right)$
μ	Dynamic viscosity $\left(\frac{\mathrm{kg}}{\mathrm{m \cdot s}}\right)$
ξ	Pipe resistance factor
ρ	Density (kg/m³)
σ^2	Variance

Sub- and superscripts:

act	Actual
air	Air
avg	Average
circ	Circulation
comp	Complement
cond	Conduction
DHW	Domestic hot water
diff	Differential
dim	Dimensioning
g	Ground
gs	Ground surface
HR	Heat recovery
i	Insulation
in	Indoor
leak	Leakage
loss	Loss
mech	Mechanical
norm	Normative
out	Outdoor
pump	Pump
ret	Return
SH	Space heating
sup	Supply
term	Thermal
valve	Valve
vent	Ventilation
water	Water
wind	Wind

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1. INTRODUCTION

In today's society, an increased environmental awareness has led to new trends in building construction. Energy demand profiles for new-built houses can today be drawn lower than before and this affects the selection of suitable heat sources. District heating that traditionally has been seen as the most efficient method of heating in densely populated areas, will have to go through some changes in order to stay efficient also in areas dominated by buildings requiring significantly less thermal energy. What these changes are and whether their positive impact on the total energy efficiency is enough to make district heating competitive as a heat source also in low-energy building areas, has been studied in this thesis.

Since the use of district heating is very well-established in Finland already, most of the buildings that today still could consider a connection to a district heating network are not apartment complexes located in the city centers, but rather new-built, small detached houses in the outskirts of the cities. This entails even more challenges for heat suppliers since new buildings in this category not only need less heat, but also have a disadvantage when it comes to energy density. In a residential area where the energy demand is dense it is naturally easier to make district heating efficient.

Before tackling the problem of how to make district heating efficient in these new emerging residential areas, a closer look at district heating in general has been taken. The initial chapter about district heating is followed by a short review of low-energy buildings. Then the theory on how to design a district heating network is explained, also taking into consideration the changes low-energy constructions bring about. A case where an actual district heating network is being planned for a low-energy residential area, dominated by detached houses, is investigated later in the thesis. By determining representative heat demands for the area and by varying the selection of design parameters, networks have been modelled for the area in question. The possibilities to make district heating efficient in low-energy building areas have been studied by simulations of the modelled networks.

The term "efficiency", which is frequently mentioned, in most cases refers to the use of energy. A move towards a more efficient use of energy in district heating networks can, however, be seen from several perspectives. Not only are the global resources used in a smarter way and improving the environmental prospects of the future, but the providers of district heat can also keep their business profitable and maintain competitiveness on the market, which, in turn, will keep the price levels lower for the end consumer.

2. THE CONCEPT OF DISTRICT HEATING

The idea of district heating is to provide thermal energy from one common heat source, through a distribution system, to a residential area. The buildings in the residential area can be anything from detached houses and apartment complexes to business buildings and industrial constructions. The consumers in the area will simply be able to heat up their buildings and acquire domestic hot water with thermal energy generated somewhere else. District heating is the most efficient form of house heating in densely populated areas, and thus also an environmental friendly way of satisfying the heat demands [1]. District heating is in no way a new concept. It was developed more than hundred years back, but it is still being developed due to changes in both heat production and consumption, and building construction.

2.1. Historical perspective

The first commercial district heating system was constructed in Lockport in the United States in 1877 by Birdsill Holly. This system distributed steam for heating of buildings. Based on the good experiences in Lockport, several steam selling companies were founded in the US at the end of the 19^{th} century [2]. The earliest concept of what today we call district heating was thought of already in 1622 by the Dutchman Cornelius Drebbel, who proposed a distribution system of hot water. Whether the system ever was built or not is unclear, though [1].

Germany was the first European country to start a commercial district heating system. This happened in Hamburg in 1921 [2]. The first network was built already in 1893, though, in the same city [1]. Quickly the well-functioning concept of commercial district heating spread to other countries in Europe, for instance to Great Britain, the Netherlands and Denmark [2]. Also in Eastern Europe, district heating systems were early taken into use, but the development since then has not been as fast as in the rest of Europe and therefore the systems are less efficient [1]. The district heating distribution systems in Europe have afterwards become dominated by hot water networks, while steam networks are still more common in the US. However, steam systems have been proven less efficient than hot water systems. [1]

In Finland, the first district heating network was built in 1940 for the purpose of providing heat to the Olympic village, which at that time was under construction. The city of Helsinki began the actual district heating of the town in 1957 with a distribution network containing hot water heated with spare energy from a power plant [1]. The company Helsingin Energia today provides the city with district heat, and it covers over 90 % of the city's heat demand [3].

2.2. Operating principle

As earlier mentioned, the idea of district heating is to provide thermal energy from a common heat source to consumers in an urban area. The heat source is typically a power plant or a central heating plant, but also large heat pumps can be used. The primary distribution system is in practice a network of pipelines containing a heat carrying media, which ordinarily is water and in some cases steam. The hot media circulating in the pipelines can, after passing a heat exchanger, provide heat to the buildings.

2.2.1. Production

Power plants, boilers and heat pumps are used to generate the heat needed to district heating systems [1]. The types of power plants used for heat production are called combined heat and power plants (CHP). In a conventional power plant, where electricity is generated when high pressure steam passes a steam turbine, the spare energy in the expanded steam leaving the turbine can be used as the heat source for a district heating network. If a simultaneous heat production is required, the turbine must be constructed so that the steam does not condensate in the outlet of the turbine, but is kept pressurized. A plant operating in this way is called a backpressure plant. If there is no heat demand and the maximum energy content of the steam is extracted for electricity and the steam is condensed in the turbine outlet, the operation term used is condensing plant [4].

The level of efficiency is remarkably improved in combined heat and power plants, since both electricity and heat is produced from the fuel energy. The efficiency of the electricity production is, however, slightly lowered because of the unutilized energy in the steam leaving the turbine. In condensing plants, about 40 % of the fuel energy can be converted to electrical energy, while the rest of the energy is lost, mostly when cooling the condensate in a sea/river or cooling tower. A backpressure plant can, on the other hand, convert about 35 % of the fuel energy to electricity and 65 % to heat. This gives a total maximum efficiency level of about 90 % for backpressure plants [2]. The lost energy in this case is mostly tied to the hot flue gases leaving the plant. Small losses of mechanical energy also appear in the turbine and minor heat losses arise in the generator. It is possible for a combined heat and power plant to be operated as a condensing plant, but in this case the steam needed as heat source for the district heating network is tapped at an earlier stage in the cycle. This is not as energy efficient as a backpressure operating principle, but it gives a better ability to adjust the ratio between produced electricity and produced heat [1].

Gas turbines are also well suited for combined heat and power production. In a gas cycle process a gaseous fuel, together with compressed air, is fed through a turbine where the mixture is expanded and electricity is generated. The mixture leaving the turbine still contains a high amount of energy which can be recovered in a boiler or heat exchanger after the turbine and then used as a heat source for a district heating network. If the combustion principle is direct, which means that a fuel is burnt directly in the process, the fuel has to be in liquid or gas form. If the combustion principle instead is indirect, the fuel can be in solid form and fed into the process after being gasified. The total efficiency level of a gas turbine plant with heat recovery can reach 85 %. Of the total output typically about two thirds are heat. The gas turbine technology today is well developed and there are many benefits with a gas turbine plant. The turbines are inexpensive, their reliability is high and their need of service low. Additionally, they have a short start-up time, which also makes them suitable as back-up plants. [1]

In both steam and gas plants, there can be differences in burning techniques, flue gas cleaning etc. The above was only a basic explanation of their operating principle and their possibility to be utilized as heat sources for a district heating network. Large combined heat and power plants can consist of both steam cycles and gas cycles. The term used for constructions like this is combined cycle power plant. [1]

Also engine power plants can be used as heat sources for district heating. The operating principle of these power plants' is simply to feed fuel into a combustion engine connected to an electricity producing generator. The fuel used is normally heavy fuel oil, light fuel oil or natural gas. In these constructions, heat can be recovered from the exhaust gases by using a boiler or heat exchanger. As an example, a gas driven engine power plant produced by Wärtsilä

Finland Oy is reported to give an electrical efficiency of 45 % and a heat efficiency of 48 % . This means that the total efficiency level of engine power plants used for both electricity and heat production, can reach values over 90 %. [1]

Power plants are not the only heat sources for district heating networks. There are also central heating plants that only produce heat. Plants like these consist of a boiler where fuel is incinerated, which then releases thermal energy that can be transferred to the heat carrying media in a district heating network. The combustion techniques and fuel types vary. The use of biomass as fuel in incineration boilers has become more common, but also fossil fuels are used. About 90 % of the energy in the fuel in a heating plant can be transferred to the district heating network. [1]

Combined heat and power plants, as well as central heating plants, have strict emission regulations. Sulfur oxides, nitrogen oxides and carbon dioxide released into the atmosphere have a negative impact on the environment and for that reason they should be kept on allowed levels. The content of the fuel used, combined with the combustion technique, determines the amount of emissions released, which, in turn, is decisive when dimensioning the flue gas cleaning equipment. A larger amount of emissions leads to more expensive flue gas cleaning, which makes the use of fuels with low emissions beneficial. On the other hand, fuels suitable for the process have differences in both price and material wear. In other words, aspects regarding economics, environment and functionality all have to be taken into consideration when planning a central heating plant or a combined heat and power plant. [2]

Heat pumps extracting thermal energy from ground, sea water or waste water is another option of supplying a district heating system with heat. Such heat pumps work in the same way as heat pumps installed in many detached houses, but their size and output are many times larger. The operating principle is based on transferring low temperature heat from a source, for instance waste water, to the heat pump cycle containing a refrigerant. The refrigerant in the cycle is vaporized by heat exchange with the low-temperature heat source and is then led through an electrical compressor, where the pressure and the temperature of the refrigerant are increased. By leading the vaporized medium through another heat exchanger, the condenser, thermal energy can be transferred to another heat carrier at a higher temperature, such as a district heating network. In this heat exchanger, the refrigerant is condensed and later led through a throttle valve to receive low pressure and temperature before entering the evaporator again. The heat released from the heat pump is much larger than the electrical input to the compressor. The ratio between heat output and electrical input is called the coefficient of performance (COP), and this value is normally around 3. The COP value depends on the temperatures of the heat source and heat sink. It is, naturally, most beneficial to use heat pumps for producing heat to district heating networks when the electricity price is low. [2]

With a heat storage it is possible to even out variations in the running process of heating plants. If high peak demands occur in a district heating network, the stored heat can ensure that the heat demands are met. Storage of heat is possible in several stages of a district heating system. It is common to place the storages with large capacities close to a central heating plant. Storages are usually large insulated tanks that are able to keep hot water at high temperature for a certain time. The tanks can operate at atmospheric pressure or be pressurized. Most of the storages are short-time storages, which can store heat for no more than a few days. [2]

A district heating network can use many heat sources. In other words, several heat producing plants and heat pumps can be connected together with pipelines. In really large networks, it might be challenging for heat suppliers to decide which heat producing plant should supply which consumer in order to make the distribution as efficient as possible. Optimization methods that tackle such problems, and in other words find the optimal distribution based on the location of production plants, consumers and storages as well as on the capacity of the plants and the consumer demands, have been developed [5]. Variations in every customer's momentary heat demand make the optimization difficult, because in practice it means that the optimal solution for the distribution network can change from time to time.

2.2.2. Distribution

Distribution of district heat is done through pipelines in the ground. In branched supply pipes, hot water from the production plants is transferred to every consumer, where the thermal energy in the hot water is utilized in the customer's heat exchangers. The parallel return pipes then transfer the cooled water back to the production plant. Water is naturally the most common distribution media in the pipes, but also steam can be used. Other pipe structures are also possible, but in Finland, the mentioned method with one supply pipe and one return pipe is used. [1]

The supply- and return pipes are normally made of steel, but for temperatures under 90°C plastic pipes can be used [1]. The pipes are insulated to prevent large heat losses in the distribution. Polyurethane is typically used as insulation material and a plastic pipe of polythene works as outer casing of the pre-insulated pipe. In twin pipe structures both supply- and return pipe are placed in the same insulation pipe. Single pipe structure implies separate insulation pipes for supply- and return pipe. Twin pipe structures are more efficient than single pipe structures but not suitable for dimensions over DN200 [1]. Concrete can also be used as insulation for the pipes, but district heating networks are nowadays dominated by pre-insulated pipes, since their ability to reduce heat losses is better. The temperature level in supply pipes is from 70°C to 120°C and the water flow can be cooled down to about 40°C in the return pipes [1]. Heat losses in the distribution network are strongly affected by the temperature levels. Heat losses, and the factors affecting heat losses, are discussed later in the thesis.

It is possible to equip the pipelines with alarm wires, which makes it easy to control the pipelines at all time and rapidly recognize a leakage or a defect pipe. There are also special pipes for certain distribution situations. For example passing a traffic route or bridge sets higher requirements on the pipes. The ground laying work always has to be done appropriately, which implies that the ground’s interaction with the pipes has to be taken into consideration. The life length of district heating pipes is normally estimated to be at least 50 years. The pumps in the distribution network are electrically driven centrifugal pumps. [1]

The primary distribution networks are flexible in terms of the heat sources used. In other words, the network design does not depend on the heat production method or the fuel used in the production process.

2.2.3. Consumption

The total heat consumption of a customer can be divided into two separate heat loads; a heat load caused by space heating and another one caused by the providing of domestic hot water. The heat loads are met by exchanging heat from the primary distribution system. Every heat consuming building has its own heat exchanger unit, where heat is transferred to both the space heating distribution coil and the tap water system. There is though a possibility to directly connect the district heating network to the heat emitters in buildings and by that avoid the need of a heat exchanger, but indirect systems are more common nowadays. A reason is the high pressure requirements set on the primary circuit, and the consequences if the primary circuit is broken in a building. If the domestic hot water is provided with district heat, a heat exchanger is always required. [1]

Even if buildings nowadays in general are indirectly connected to the district heating network, there are still different possibilities on how to make the connection. Different connection possibilities also enable various temperature levels in the secondary heating coil [2]. Likewise the type of heat emitters in the buildings may require certain temperature levels. For instance radiators require higher temperature levels than underfloor heating. Lower temperatures in the secondary heating coil will at the same time allow lower temperatures in the primary district heating network, which reduces heat losses. [1]

Radiators or underfloor heating coils are, as earlier mentioned, suitable for emitting the heat to a building and by that satisfying the space heating demand. Also heating of the incoming ventilation air is common, and especially the use of a ventilation air heater combined with a radiator- or underfloor heating system has become more popular. [6]

The exchange of heat between the primary district heating network and the domestic hot water system varies with time more rapidly than the heat exchange for space heating. This is due to the fact that hot water taps occur spontaneously and for short time intervals. The peak demands of heat for domestic hot water can be reduced by connecting a storage tank of provided hot water after the heat exchanger [6]. Chapter 4 presents how to determine heat loads of both space heating and domestic hot water.

2.3. District heating in Finland

Considering the population in Finland, district heating is a well-developed concept in the country with a total network length of 13 600 kilometers and a total consumption of 34 000 GWh in 2012. 55 % of the heat delivered was consumed in dwelling houses. The total production of thermal energy for district heating during 2012 was 37 100 GWh. Thus, the average relative heat loss was only 8.4 %. The total amount of customers was 137 700 which included over 2.5 million inhabitants. The market share of district heating is 46 % according to statistical analysis (Figure 2-1) and the average selling price was 74 €/MWh. [7] [8]

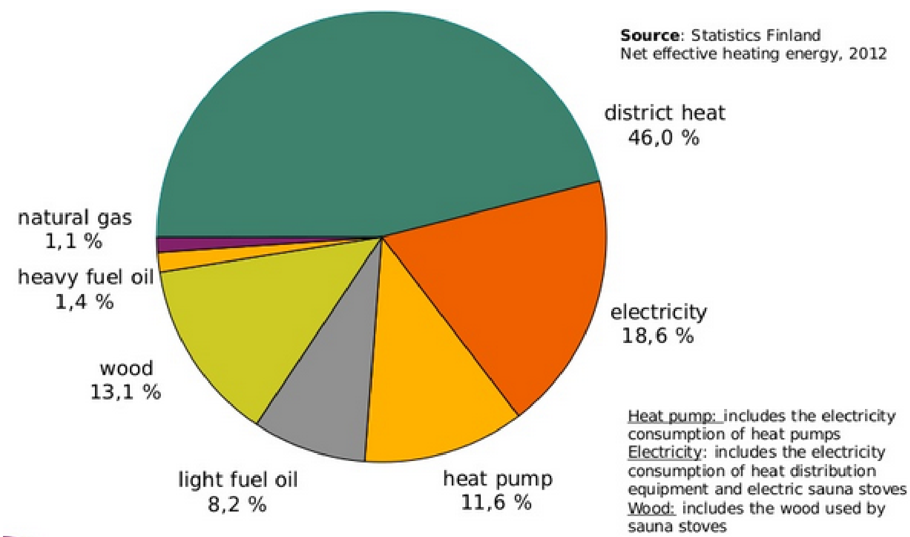

Figure 2-1. Market share of space heating in Finland [8]

Of the total heat produced in Finland in 2012, almost 70 % was generated in combined heat and power plants and the rest in separate boilers or heat pumps. The total amount of cogenerated electricity in the CHP-plants was 13 120 GWh [7]. Finland is the world's leading country when it comes to combined heat and power production. This concept improves the energy efficiency with about 30 % compared to separate production and corresponds to a decrease in carbon dioxide emissions with about 350 kilogram per produced megawatt hour. [1]

A reduced availability of fossil fuels and a move towards a more environmental friendly mindset has changed the use of fuels in both CHP plants and other heat producing units. While oil dominated 30 years ago, renewable fuels and natural gas are the most used fuels for production of district heat in Finland today. The use of coal has stayed relatively stable, and coal still stands for more than one fourth of the fuel energy used in the production of district heat. Figure 2-2 illustrates the fuel consumption in production of district heat in Finland in 2013. [8]

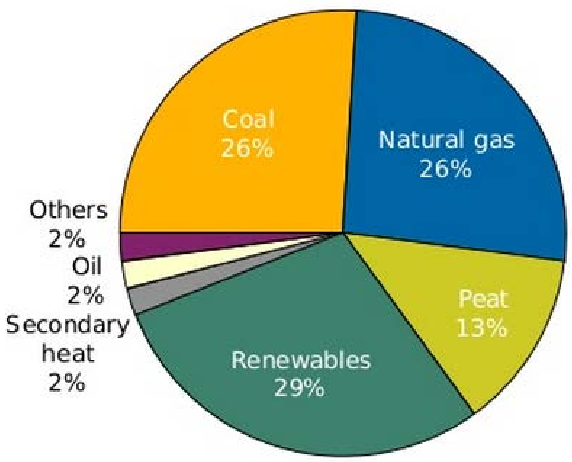

Figure 2-2. Fuel consumption in production of district heat and CHP 2013 [8]

The specific heat consumption is often used as a measurement on how efficiently buildings connected to a district heating network are heated. With better insulation, smarter distribution and effective heat recovery, the specific heat consumption in Finland has been reduced year after year. In 2012 the specific heat consumption was 38.3 kWh/m^3. Figure 2-3 illustrates the trend of the specific heat consumption since 1970. [7]

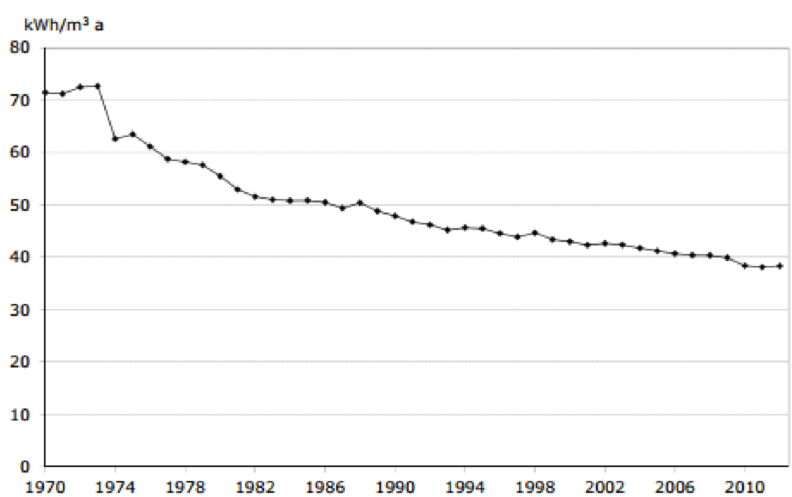

Figure 2-3. Specific heat consumption in district heated buildings in Finland [7]

3. LOW-ENERGY BUILDINGS

The decreasing trend in the specific heat consumption illustrated in the previous chapter makes it motivated to consider the construction changes that have led to it. This chapter will treat energy efficient buildings and their performance.

3.1. Building techniques and methods improving energy efficiency

The most important reason for the decreasing heat demand in new-built houses is more efficient heat recoveries and more insulation material in walls, floors and roofs. The insulation layers lower heat conduction from the building and also reduce leakage, so the thermal energy required for keeping a comfortable indoor climate is lower than in traditionally designed buildings. [9]

A construction element that is part of a building is characterized by a heat transmittance factor, by which the building's conductive heat loss can be defined. These elements are walls, floors, roofs, windows and doors. The effect of added insulation thickness is a decreased thermal transmittance, or U value, for walls from about 0.25 W/(m^{2}K) to, in the best cases, 0.1 W/(m^{2}K) [6]. Windows, and also doors, are the elements with the least efficient heat resistance in both traditional buildings and new low-energy buildings. Still, also these elements are made with a higher insulating capacity today. For instance, the thermal transmittance of windows has been reduced from 1.4 W/(m^{2}K) to about 0.8 W/(m^{2}K) [6]. The conductive heat loss depends on the temperature difference between inside and outside of the building. During the last decades, the winter climate has become warmer and this trend, which by many is seen as a clear impact of the greenhouse effect, also contributes to the fact that buildings are in need of less thermal energy on a yearly basis than before [9].

More insulation material placed in the walls, floors and roofs of low-energy buildings entails lower temperatures on the outside surfaces of the house. This affects the relative humidity in the construction elements negatively, placing higher demands on methods preventing moisture damages in the buildings [9]. Another potential problem in these types of buildings is overheating. This is also due to the high insulating ability, which during periods of high outdoor temperature makes it harder to maintain a comfortable indoor climate. Heat gains in low-energy buildings affect the indoor climate in a very similar way as in traditional buildings, and especially in low-energy buildings these heat gains must not be ignored in the design. [10]

Other methods that have become more common in order to decrease the need of heat in buildings are different types of heat recoveries. Heat recovery utilizing heat from outgoing ventilation air has been commonly used in buildings for longer periods, but is also gradually becoming more efficient. With an efficient ventilation heat recovery it is today possible to satisfy up to 80 % of the yearly heat demand for incoming ventilation air with recovered heat from ventilation air leaving the building. Heat recovery is also possible from domestic hot water passing to the drain. For instance, used shower water contains high amounts of heat which, if recovered, decreases the need of supplied heat. Heat exchangers that recover heat from shower drains are already manufactured, but this method of improving energy efficiency in buildings is still not common. However, it is a reasonable assumption that also this type of heat recovery will become more common in the future. [6]

3.2. Classification of low-energy buildings

"Low-energy buildings" is a generic term for buildings consuming a considerably lower amount of thermal energy than traditional buildings. Depending on how much the heat demand is lowered, low-energy buildings can be divided into specific classes.

If heat losses in a new-built house are 85 % or less compared to a traditional building, the house is classified as a low-energy building. In Southern Finland, this limit is 60 kWh/(m^{2}a), while it in Northern Finland corresponds to 90 kWh/(m^{2}a). [11]

Passive houses are a type of low-energy buildings. The criterion for passive houses is, according to international standards, a maximum yearly heat demand of 15 kWh/m^2, a maximum yearly demand of primary energy of 120 kWh/m^2 and a highest allowed air leakage factor of n_{50} = 0.6. The n_{50} air leakage factor indicates how much of the air in the building that would leak out during one hour at a pressure difference of 50 Pa between inside and outside. In Finland, the technical research center VTT has stretched the criteria slightly due to the cold climate. Since the weather conditions also differ considerably between regions in the country, different criteria have been set up for three geographical areas. Table 3-1 presents the criteria prevailing in Finland. [12]

Table 3-1. Criteria for passive houses in Finland

	South	Middle	North
Space heating demand (kWh/(m²a))	≤ 20	≤ 25	≤ 30
Primary energy demand (kWh/(m²a))	≤ 130	≤ 135	≤ 140
Air leakage factor, n_{50}	≤ 0.6		

A zero-energy building is a building where, on a yearly basis, as much renewable energy is captured as non-renewable energy used. This type of building is not common, and because of the cold climate in Finland passive houses are still considered more cost-effective. [11]

3.3. Future prospects

Figure 2-3 indicated that the consumption today is almost only half of what it was in 1970. Although progress has been made in low-energy construction, it is not reasonable to assume a similar decrease in the future. Even though the lowest level of the specific heat consumption has not been reached yet, it would be optimistic to assume that a similar decrease would be encountered in the future.

The criteria for passive houses are set very strictly and are therefore difficult to achieve cost-effectively with the construction technique available today [12]. Building areas dominated by passive houses thus still belong to the rarities.

The striving for environmental sustainability will change the use of heat sources in buildings and one may assume that a larger share of renewable energy will be used for heating. For instance, the concept of solar collectors as (complementing) source providing heat for domestic hot water is constantly under development.

Whether district heating, which today is the most common form of heating in Finland, is an efficient way of satisfying heat demands also in low-energy buildings has to be investigated in every residential area separately. As demonstrated later in the thesis, district heating networks can at least be designed so that the energy efficiency is improved, even though low-energy constructions entail some challenges for providers of district heat.

4. DESIGNING A DISTRICT HEATING NETWORK

When designing a district heating network, it is essential to determine the consumers' heat demand. The heat demand varies widely, mostly due to variations in weather but also because of the consumers' daily rhythm. The momentary heat demand is called the network's heat load. The dimensioning of a district heating network should also take into account heat losses in the pipe structure.

Pipe sizing and selection of valves and pumps are based on flow calculations, which, in turn, are determined by the heat loads. Pipes, pumps and valves should be dimensioned so they can be functional and sufficient throughout the year. An undersized network will lead to a lower indoor temperature than desired during the coldest winter days, while oversizing is both uneconomical and leads to problems regarding the water flow.

4.1. Heat loads

The total heat load of a consumer consists of both the heat needed for heating the building, also called space heating, and the heat needed to provide domestic hot water. These two heat requirements combined are called the net heat load. When heat losses from the production plants to the consumers are taken into consideration and added to the net heat load, the term used is gross heat load. Heat losses also appear in the production plant when heat is extracted from a fuel, but these losses do not affect the district heating network dimensioning. [2]

4.1.1. Space Heating

The intention of space heating in buildings is to maintain a comfortable inside climate independent of external circumstances. A comfortable inside climate is synonymous with a temperature just above 20°C and a sufficient exchange of air. The space heating demand occurs due to conduction through the building, ventilation and air leakage. [1]

Conduction through buildings appears through walls, roofs, floors, doors and windows. All these building elements have different thermal transmittances, or *U* values, which are given by the element provider, usually expressed in W/(m^2°C). By adding up the element areas multiplied by the elements' *U* value, a total value of how much heat is needed per a temperature difference of one degree centigrade (or Kelvin) between inside and outside is obtained. Even though two buildings are built of elements with identical thermal transmittance, the total thermal transmittance per housing area can vary because of differences in the buildings' shape and design. The heat required due to conduction can be calculated by [1]

$$\dot{Q}_{cond} = (T_{\mathrm{in}} - T_{\mathrm{out}}) \sum_i U_i A_i \tag{1}$$

where U_i is the *U* value of the *i*th building element (W/(m²°C))

A_i is the area of the *i*th building element (m²)

T_{in} is the required indoor temperature (°C)

T_{out} is the outdoor temperature (°C)

Ventilation is important for maintaining a comfortable inside climate, but it also causes heat losses in the buildings. To be able to calculate the heat demand arising from ventilation, the air exchange factor, which expresses how much of the air in the building is replaced in one hour, has to be known. The air exchange factor combined with the volume of the house give the volume flow of fresh outside air that has to be heated from outdoor temperature to the required indoor temperature. Nowadays, almost every ventilation system is equipped with heat recovery. This means that heat from the used indoor air is recovered when the air is leaving the building and used to heat up the fresh air entering the building. The value of the air exchange factor typically lies between 0.3 and 0.6 and the efficiency of the heat recovery system can reach values up to 80 % with today's technology. The heat required due to ventilation can be calculated by [1]

$$\dot{Q}_{\mathrm{vent}} = \rho_{\mathrm{air}}\, c_{p,\mathrm{air}}\, \dot{V}_{\mathrm{out}}\, (T_{\mathrm{in}} - T_{\mathrm{out}})(1 - \eta_{\mathrm{HR}}) \tag{2}$$

where ρ_{air} is the density of air (kg/m³)

$c_{p,\mathrm{air}}$ is the specific heat capacity of air (kJ/(kg°C))

$\dot{V}_{\mathrm{out}}$ is the volume flow rate of exhaust air (m³/s)

η_{HR} is the efficiency of the heat recovery system

Due to the differences in density, the volume flow of exhaust air is typically a little higher than the volume flow of supply air. Therefore, also a compensating air flow has to be heated and the heat required for that can be calculated by [1]

$$\dot{Q}_{\mathrm{vent,comp}} = \rho_{\mathrm{air}}\, c_{p,\mathrm{air}}\, (\dot{V}_{\mathrm{out}} - \dot{V}_{\mathrm{in}})(T_{\mathrm{in}} - T_{\mathrm{out}}) \tag{3}$$

where $\dot{V}_{\mathrm{in}}$ is the volume flow rate of supply air (m^3/s)

Air leakage is the last contributing term to the total space heating demand. A common way to express air leakage is to use the n_{50} value. This value expresses how many times per hour the volume of air in the house is exchanged at a 50 Pa pressure difference between the inside and outside. For passive houses the n_{50} value should be below 0.6 but for old, less well sealed buildings values above 5 are possible. Nowadays, another way to express air leakage is to use the q_{50} value which basically expresses the same thing, but here the air exchange per hour is multiplied by the volume of the house and divided by the housing area, so that the leakage factor becomes proportional to the housing area and no buildings automatically receive a higher leakage coefficient because of disadvantageous design and shape. The pressure difference of 50 Pa that is used in these expressions is much higher than typical pressure differences between inside and outside. The real pressure difference depends on factors such as outdoor temperature, wind velocity and ventilation settings, but as a rule of thumb the actual leakage is on average about 20 times smaller than the n_{50} and q_{50} values. The actual leakage factor, q, can be calculated more accurately by [13]

$$q = q_{50} \frac{(\Delta p_{\mathrm{term}} + \Delta p_{\mathrm{mech}} + \Delta p_{\mathrm{wind}})^{2/3}}{\Delta p_{50}{}^{2/3}} \tag{4}$$

where q_{50} is the q_{50} value ($m^3/(m^2h)$)

Δp_{term} is the pressure difference arising from thermal conditions (Pa)

Δp_{mech} is the pressure difference arising from mechanical conditions (Pa)

Δp_{wind} is the pressure difference arising from wind conditions (Pa)

Δp_{50} is the pressure used in the q_{50} measuring, i.e., 50 Pa

When the air leakage factor has been calculated or estimated, the volume flow of leaking air is known and the heat required to compensate for the leakage can be calculated by [1]

$$\dot{Q}_{\mathrm{leak}} = \rho_{\mathrm{air}}\, c_{p,\mathrm{air}}\, \dot{V}_{\mathrm{leak}}\, (T_{\mathrm{in}} - T_{\mathrm{out}}) \tag{5}$$

where $\dot{V}_{\mathrm{leak}}$ is the volume flow rate of leakage air (m³/s).

When heat losses through conduction, ventilation and leakage have been determined, the total space heating demand can be calculated as [1]

$$\dot{Q}_{\mathrm{SH}} = \dot{Q}_{\mathrm{cond}} + \dot{Q}_{\mathrm{vent}} + \dot{Q}_{\mathrm{vent,comp}} + \dot{Q}_{\mathrm{leak}} \tag{6}$$

As all the terms in the equation depend on the outdoor temperature, it is important to choose an outdoor temperature that is low enough in the dimensioning. The dimensioning outdoor temperature should correspond to the coldest temperature of the year, but because of the uncertainty in yearly weather variations, regulations of which temperature to use are made [14]. Even if the outdoor temperature would sink below the dimensioning temperature for a short time period, the indoor climate need not be affected due to the dynamics of the house and internal heat gains. Figure 4-1 illustrates the dimensioning outdoor temperature that should be used in Finland.

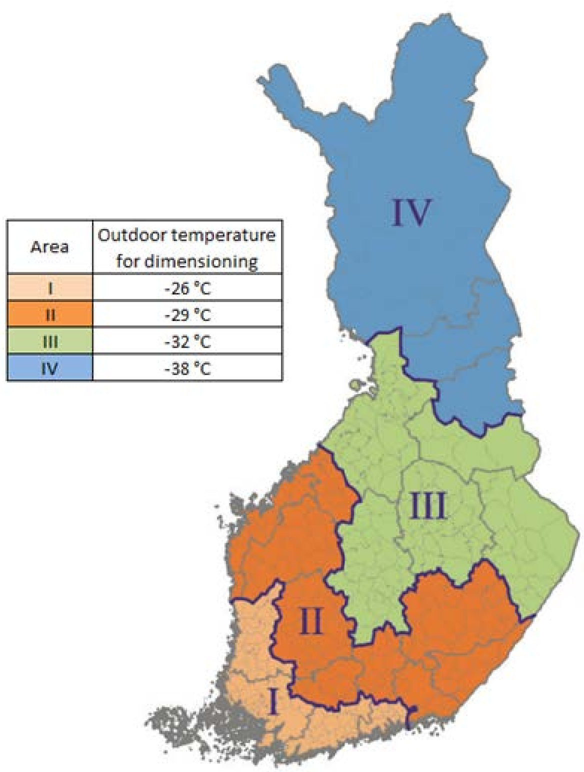

Figure 4-1. Dimensioning outdoor temperatures used in Finland [14]

If the space heating demand throughout a year is plotted, the area under the curve is equal to the thermal energy need during the year. In order to make it easier to estimate the yearly thermal energy needed, a concept called *number of degree days* has been developed. The number of degree days is simply a sum of the temperature differences between outdoor and indoor for a time period, which usually is a year or a month. The higher the number of degree days, the larger the space heating demand is. The temperature difference is, however, calculated with an indoor temperature of 17°C, which has been set as the so called effective indoor temperature. It is predicted that even though the heat transfer from the heat supply unit is stopped at an indoor temperature of 17°C, the temperature inside will reach the comfortable 21°C due to internal heat gains. The number of degree days, *S*, is calculated by [1]

$$S = \Delta t \sum_{u=1}^{n} (17 - T_{\mathrm{out},u}) \tag{7}$$

where $T_{\mathrm{out},u}$ is the average outdoor temperature during the *u*th time step (°C)

Δt is the length of the time step (days)

The number of degree days should still only include the days when the average outdoor temperature during a day falls below the *heating limit*, which from January to July means below 10°C and from July to December below 12°C [1]. The Finnish Meteorological Institute has calculated a yearly average number of degree days for the time span 1981-2010 for many locations in Finland. This long-term number of degree days per year can be used as a normative factor when thermal energy demands from different years are compared. The normative thermal energy demand during a year is determined by [1]

$$Q_{\mathrm{norm}} = \frac{S_{\mathrm{norm}}}{S_{\mathrm{act}}} \cdot Q_{\mathrm{SH,act}} + Q_{\mathrm{DHW}} \tag{8}$$

where S_{norm} is the normative number of degree days per year (°Cd)

S_{act} is the actual number of degree days per year at the location in question (°Cd)

$Q_{\mathrm{SH,act}}$ is the actual yearly thermal energy consumption for space heating (kWh)

Q_{DHW} is the yearly thermal energy consumption for domestic hot water (kWh)

Table 4-1 presents the number of degree days for every month during the year 2013, and also the long term, normative number of degree days, for some locations in Finland.

Table 4-1. Heating degree days in Finland [14]

Heating degree days 2013

	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Year
Maarianhamina	650	515	676	431	96	8	0	0	93	283	369	432	3553
Vantaa	711	554	733	429	57	0	0	0	103	317	406	488	3798
Helsinki	678	527	690	417	73	0	0	0	91	291	370	455	3592
Pori	663	529	707	423	71	0	0	0	98	331	399	477	3698
Turku	700	544	729	438	76	0	0	0	100	319	395	468	3769
Tampere	719	560	768	442	71	0	0	16	125	361	439	515	4016
Lahti	730	564	763	441	58	0	0	11	123	367	444	522	4023
Lappeenranta	756	581	770	433	64	0	0	0	96	350	440	541	4031
Jyväskylä	751	585	810	461	76	0	22	24	168	391	477	547	4312
Vaasa	681	564	739	443	108	0	0	0	101	340	439	507	3922
Kuopio	760	600	821	449	110	0	6	0	110	376	472	560	4264
Joensuu	785	604	830	458	111	7	7	16	128	391	478	585	4400
Kajaani	794	647	892	497	155	8	23	25	139	415	519	616	4730
Oulu	778	633	841	486	163	8	11	25	108	408	510	586	4557
Sodankylä	883	740	937	536	213	37	53	59	206	516	688	780	5648
Ivalo	834	727	925	545	235	52	63	49	201	518	673	754	5576

Heating degree days during the normal period 1981-2010

	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Year
Maarianhamina	592	567	551	406	216	34	3	17	135	308	432	542	3803
Vantaa	682	640	586	376	146	16	2	21	158	348	497	625	4097
Helsinki	647	612	566	383	153	11	1	12	125	316	464	588	3878
Pori	677	633	585	389	181	26	3	25	171	352	497	622	4161
Turku	663	625	575	377	161	19	2	18	149	338	486	608	4021
Tampere	724	675	612	400	176	28	5	34	192	382	529	667	4424
Lahti	726	677	610	395	159	20	4	31	191	383	528	668	4392
Lappeenranta	759	699	621	403	165	22	5	28	184	386	546	692	4510
Jyväskylä	785	721	646	440	206	40	10	56	227	414	569	718	4832
Vaasa	719	666	619	424	214	29	5	35	192	377	526	663	4469
Kuopio	812	741	653	445	198	31	7	38	194	400	571	735	4825
Joensuu	826	753	665	456	216	39	10	47	215	416	589	752	4984
Kajaani	864	777	695	479	251	57	17	75	245	441	618	785	5304
Oulu	824	742	677	465	249	47	9	55	224	423	593	749	5057
Sodankylä	946	838	760	548	345	106	49	136	316	523	722	891	6180
Ivalo	923	819	755	557	377	146	69	147	318	523	722	875	6231

4.1.2. Domestic hot water

In addition to space heating, the production of domestic hot water forms a relevant part of the heat load of the consumer. Since the consumers' hot water consumption vary considerably even on a daily basis, the heat needed to provide hot water fluctuates much more than the heat load caused by space heating. Also, in this case the variations are caused by social factors and human behavior rather than physical factors. Here one can speak of a social heat load in contrast to the physical heat load caused by space heating. Social factors and human behavior are in many cases more difficult to predict than physical factors, which means that dimensioning based on social heat loads may require some more consideration. [2]

The heat required for providing domestic hot water depends on the required hot water flow and the temperature difference between the incoming cold water and the provided hot water. The required heat can be expressed as [1]

$$\dot{Q}_{\mathrm{DHW}} = \rho_{\mathrm{water}}\, c_{p,\mathrm{water}}\, \dot{V}_{\mathrm{DHW}}\left(T_{\mathrm{DHW}} - T_{\mathrm{water,in}}\right) + \dot{Q}_{\mathrm{circ}} \qquad (9)$$

where ρ_{water} is the density of water (kg/m³)

$c_{p,\text{water}}$ is the specific heat capacity of water (kJ/(kg°C))

$\dot{V}_{\text{DHW}}$ is the volume flow of hot water (m³/s)

T_{DHW} is the temperature of hot water (°C)

$T_{\text{water,in}}$ is the temperature of the incoming water (°C)

$\dot{Q}_{\text{circ}}$ is the heat loss in the hot water circulation coil (kW)

In Finland, there are regulations about the domestic hot water temperature, which say that the temperature of the hot water must be at least 58°C. In case of installed hot water storage, the heat has to be switched on when the content in the boiler goes below 55°C. On the other hand, the temperature is not allowed to exceed 65°C. With temperatures in this interval a safe use of hot water is guaranteed and the risk of legionella bacteria is eliminated. The incoming cold water temperature depends on the outside temperature, but typically it lies between 5°C and 10°C. [15]

The problem when it comes to estimating the heat requirement for domestic hot water lies in determining the required volume flow. Usually, a value of 0.3 l/s can be used as an absolute maximum value for the volume flow rate per person. This value can, for example, be reached when a person is taking a hot shower and it corresponds to about 60 kW of heat transfer. However, two persons do not necessarily have a maximum hot water heating demand of 120 kW, and ten persons do certainly not need 600 kW to provide them with hot water. This is due to the very low probability that all the persons tap their maximum flow rate of hot water at the same time. The heat demand for hot water can, naturally, also be estimated from measurements of one person's daily use of hot water. From the measurements a maximum heat demand can be recognized and an average heat demand can be calculated. From the average demand also the variance and the standard deviation can be established. When the number of persons in a house increases the average heat demand and the variance can simply be multiplied by the number of persons. To estimate the maximum heat demand we may use [1]

$$\dot{Q}_{\text{DHW,max}} = n\dot{Q}_{\text{DHW,avg}} + 2\sqrt{n\sigma^2} \qquad (10)$$

where n is the number of persons

$\dot{Q}_{\mathrm{DHW,avg}}$ is the average hot water heat demand per person (kW)

σ^2 is the variance in one person's use of hot water (kW^2)

With this formula the estimated maximum heat demand for hot water will be exceeded with a probability of only a few percent. This can be seen in a plot of the cumulative distribution function. The true probability for the heat demand to exceed the estimated maximum depends on how the measurements are available in estimation. The shorter the sampling time in the measurements, the better the estimated maximum heat demand for hot water is [1].

There are other formulas that can be used when calculating the maximum heat demand of hot water for a building or area with many inhabitants. For instance, the Velander formula [1]

$$\dot{Q}_{DHW,max} = 63n\left[\varepsilon + \frac{1-\varepsilon}{\sqrt{n}}\right] \tag{11}$$

has been used, where ε is the estimated ratio $\dot{Q}_{\mathrm{DHW,avg}}/\dot{Q}_{\mathrm{DHW,max}}$

Another formula is the one framed by Energiateollisuus ry in Finland;

$$\dot{Q}_{\mathrm{DHW,max}} = 57 + 15.3[\ln(n^3 - n^2 + 1)]^{1,17} \tag{12}$$

According to Danish standards the formula [1]

$$\dot{Q}_{\mathrm{DHW,max}} = 1.19n + 18.8\sqrt{n} + 17.6 \tag{13}$$

can be used. The results from these formulas differ quite extensively. Later in the thesis, these formulas will be compared to actual measured values, which will give an indication of whether any of the formulas is appropriate for determining the maximum heat demand for domestic hot water in a building complex.

Although an increased number of persons consuming hot water reduces the variations in heating demand, some trends in the use can be recognized. Most clearly the daily trends can be seen in a consumption chart. Typically, peak loads take place during the morning before people go to work and during the evening hours. During the night the consumption is lowest. Even on a weekly basis trends can be spotted. In homes, the daily consumption during weekends is evened out, while the consumption at workplaces usually decreases, or even totally stops, depending on the type of workplace. On a yearly basis, the hot water consumption is typically a little lower during the summer months and the heating demand is even more reduced due to a higher temperature of the incoming cold water. [2]

In Sweden, a simulation program for the use of hot water has been developed. It is based on probability profiles of hot water tapping in different taps of a house. In case the consuming building is an apartment complex, it is assumed that every apartment has three taps: a shower, a washbasin and a kitchen faucet. In case the consuming building is a detached house, it is necessary to extend the number of taps with one more shower. In the simulation for every second and every tap it is randomly generated, based on a probability profile, whether there is a use of hot water or not. If there is a use of hot water in a second, also the flow of hot water and the time of the tap are randomly generated considering probability profiles. The probability profiles used in the simulation program were developed in the 1980's, so the total use of hot water might be slightly higher than it would be in reality, but the profiles are easy to recalibrate to lower absolute values. The probability profiles presented in [10] are illustrated in Figures 4-2 – 4-4.

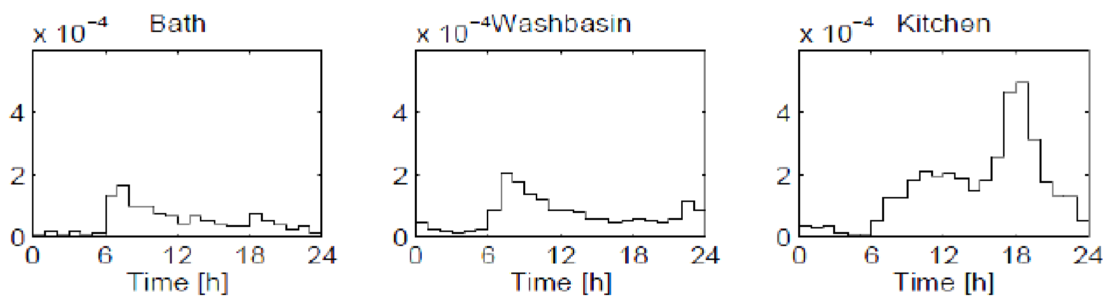

Figure 4-2. Probabilities of a hot water tap occurring at a given time [10]

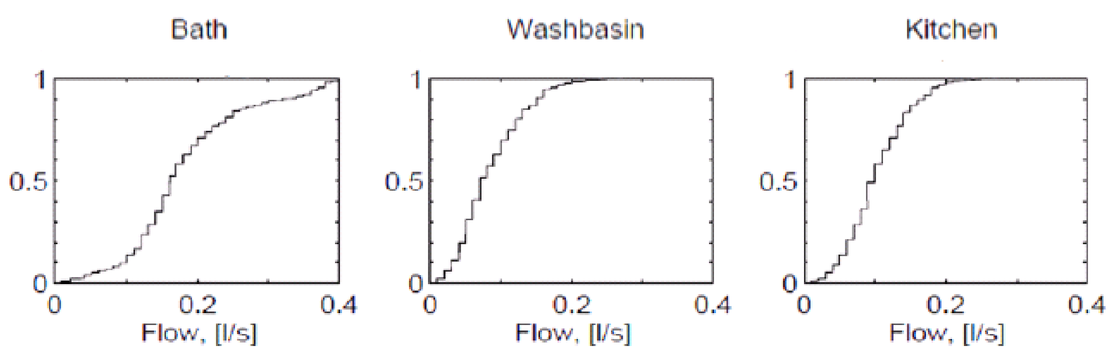

Figure 4-3. Probabilities of a specific volume flow of hot water [10]

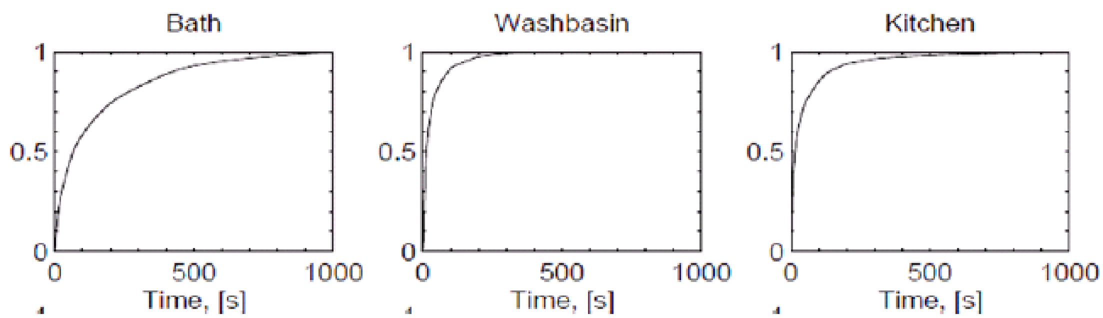

Figure 4-4. Probabilities of a specific length of the hot water tap [10]

In an apartment complex of 20 apartments in Malmö, the actual use of hot water was measured and compared to the results of the simulation. The comparison of measured values and simulated values is presented in Figure 4-5. [10]

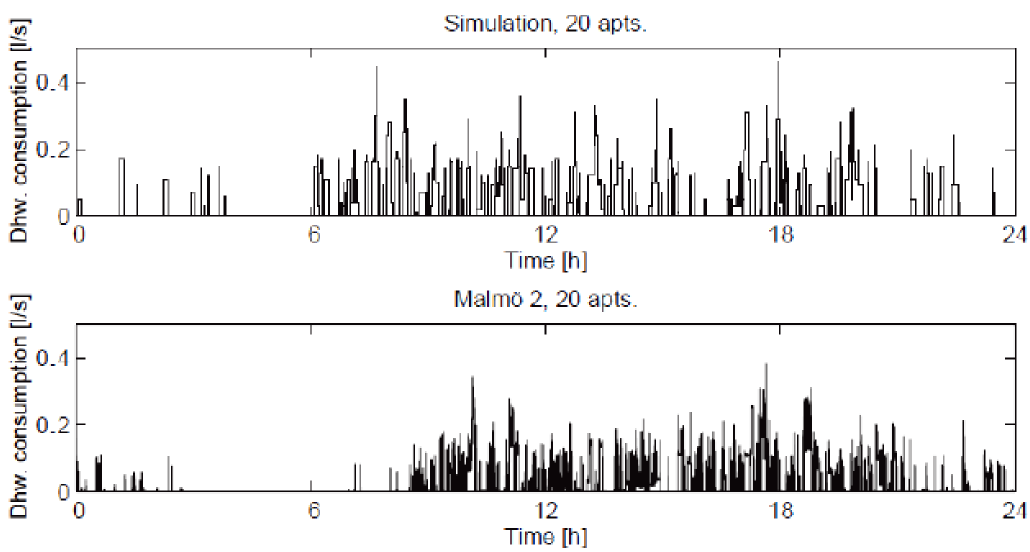

Figure 4-5. Comparison of simulated and measured hot water consumption values [10]

The amount of consumed thermal energy for providing domestic hot water is equal to the area under the heat demand plot. If the heat demand plot for space heating is added to the heat demand plot for domestic hot water, the total need of thermal energy is equal to the integral of the summed curve.

4.1.3. Heat gains

Heat gains occur for both internal and external reasons. Internal heat gains include heat from people, electricity used and from the providing and distribution of domestic hot water. The main external heat gain is caused by solar irradiation. Heat gains reduce the net heat loads of the buildings.

The heat emitted from the human body depends on the degree of activity. The average metabolic heat rate for a male adult lies between 80 W when sleeping, and 570 W when performing heavy work. The metabolic heat rate for an adult woman is about 85 % of the one for an adult male. Children's and older people's metabolic heat rate, in relation to an adult male's, is about 75 % respectively about 80 %. [16]

The heat gain from people consists of both sensible and latent heat. The sensible heat can be felt as a temperature increase while the latent heat implies to a change in state of the heated medium. The average heat emission from people can be scaled to a value of heat gain per living area. This value of course depends on the density of inhabitants and the share of time people actually are in their homes, but Swedish Fjärrsyn has determined 1.5 W/m² as the average heat gain value from people [10]. Energiateollisuus ry in Finland has listed average values for different types of houses. These values are between 0.9 W/m² for small detached houses and 1.9 W/m² for apartment complexes [1].

The heat gain in buildings that occur from electrical equipment is even larger than the one arising from people. Especially lights emit a lot of heat due to the low efficiency of traditional light bulbs and the high usage rate. Also equipment like freezers, fridges, TVs and computers contributes to the internal heat gain. All these pieces of equipment typically have a heat emission of 100-200 watts when they are running. Ovens have high heat emissions, up to 2 500 watts, but the degree of usage is relatively low. The traditional light bulbs, where over 95 % of the required power is emitted as heat, are gradually being replaced by more efficient halogen- or LED-lights, which means that the internal heat gain from lights is continuously reduced. [16]

The average heat gain from all electrical equipment has by Fjärrsyn in Sweden been established to 3.5 W/m² in homes [10]. Energiateollisuus ry has, on the other hand, listed average values from 5.7 W/m² for small detached houses to 9.1 W/m² for apartment complexes [1]. The conclusion that can be drawn from this is that the internal heat gain caused by electrical equipment varies a lot and is difficult to establish. Social factors, like human behavior, once again play a part, and these factors are challenging to model and determine. With certainty it can still be said that electrical equipment significantly contributes to reducing heat loads required from the external heating system.

The providing and distribution of domestic hot water usually implies a small internal heat gain because of heat losses from boilers and pipes. This heat gain is about 1.7 W/m² in homes. [1]

The external heat gain in buildings is mainly caused by solar irradiation. The solar irradiation in Finland is strongly varying throughout the year. The variations combined with window impacts based on size, direction, angle and transmittance makes it difficult to determine the solar heat gain. Also the environment of the house affects the heat gain due to shadow formations. [1]

Figure 4-6 describes the variation in solar insolation on a vertical surface facing directly south, in Helsinki, Finland [17].

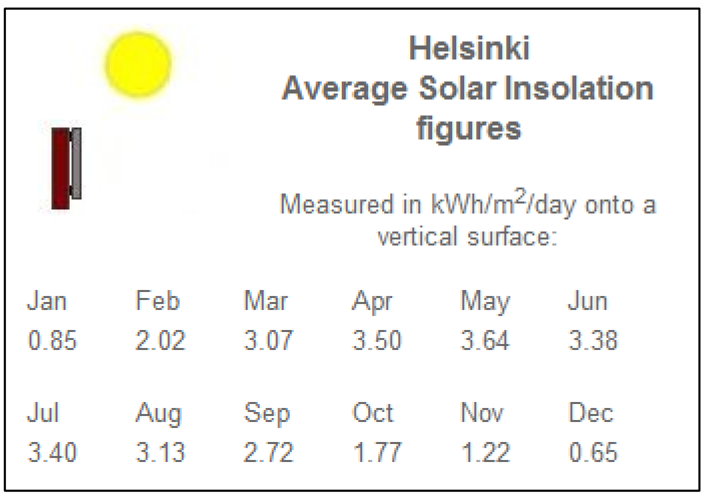

Figure 4-6. Monthly solar insolation on a vertical surface facing directly south [17]

It is noticeable that solar heat gain is significant especially during the time when the heat demand is low, in other words, during the summer months. This, in combination with the internal heat gains, can during the warmer half of the year lead to problems with overheating. The internal heat gains indeed reduce the heat demand, but since these heat gains, except maybe the one caused by people, are not costless, consumers should because of economic reasons not strive for an increased internal heat gain. [10]

4.1.4. Heat load changes caused by low-energy construction

Heat loads in low-energy buildings are naturally lower than in traditional buildings. The impacts of low-energy construction are largest on the heat loads caused by space heating. This is due to the lowered heat transmittance coefficients of the housing and the higher efficiency of the ventilation heat recovery. In traditional buildings the season when space heating demands occur is typically between eight and nine months annually, while investigations have shown that the space heating season in low-energy buildings can be reduced to less than five months per year. The annual demand of thermal energy for space heating can be reduced by more than 50 %. [6]

The heat load caused by the providing of domestic hot water is not reduced because of low-energy construction. To reduce this heat load the use of hot water should be decreased, which requires a change in the human behavior. Even though the low-energy construction does not directly affect the use of hot water, a trend where the hot water consumption decreases can still be recognized. The reason for this might be greater ambitions for energy efficiency and environmental awareness. Also manufacturers of showerheads and other faucets have gradually made their products more energy efficient. A concept where the heat demand for hot water significantly can be reduced is under development. In this concept waste heat from shower water is recovered. This type of heat recovery is not yet common but definitely upcoming in the future. The heat demand for hot water is estimated to be reduced by about half with efficient shower water heat recovery. [6]

In low-energy buildings, there is a greater risk for overheating than in traditional buildings and, therefore, the internal heat gains should be kept at a lower level, but it can be difficult to adjust them. Swedish Fjärrsyn claims that the average value for internal heat gains in low-energy buildings are close to 3 W/m^2 compared to 5 W/m^2 in traditional buildings. [10]

The share of the heat demand that is a result of space heating, has in traditional homes in Finland, been about 75 % of the total heat demand [1], but with more energy efficient buildings the space heating demand has in some cases even dropped below the level of heat demand for domestic hot water [10].

4.2. Heat losses

Heat losses appear in pipes, where a medium warmer than the surroundings is transported. Therefore, heat losses are heat loads only indirectly caused by the consumers. In small district heating networks typically 10-20 % of the thermal energy will be lost, while the corresponding share in larger networks is only 4-10 %. The reason why smaller networks have higher relative heat loss is that smaller pipes have a larger pipe area in relation to the pipes' flow capacity. The heat losses also increase linearly with the temperature of the transported media. By using pre-insulated pipes, the heat losses can be kept at a tolerable level in traditionally designed networks. [1]

The heat losses depend on many factors, which can be determined with a set of calculations. The heat loss of the supply- and the return pipes can be estimated by [1]

$$\dot{Q}_{\mathrm{loss,sup}} = K_{1,\mathrm{sup}}(T_{\mathrm{sup}} - T_{\mathrm{g}}) - K_{2,\mathrm{sup}}(T_{\mathrm{ret}} - T_{\mathrm{g}}) \tag{14}$$

$$\dot{Q}_{\mathrm{loss,ret}} = K_{1,\mathrm{ret}}(T_{\mathrm{ret}} - T_{\mathrm{g}}) - K_{2,\mathrm{ret}}(T_{\mathrm{sup}} - T_{\mathrm{g}}) \tag{15}$$

where T_{sup} is the temperature in the supply pipe (°C)

T_{ret} is the temperature in the return pipe (°C)

T_{g} is the temperature in the ground (°C)

$K_{1,\mathrm{sup}}, K_{1,\mathrm{ret}}, K_{2,\mathrm{sup}}, K_{2,\mathrm{ret}}$ are coefficients of heat transfer (W/(m°C))

In case of symmetrical supply- and return pipes, which in district heating networks usually are the case, the two equations can be simplified to one equation

$$\dot{Q}_{\mathrm{loss}} = 2(K_1 - K_2)\left[\frac{T_{\mathrm{sup}} + T_{\mathrm{ret}}}{2} - T_{\mathrm{g}}\right] \tag{16}$$

where $K_1 = K_{1,\mathrm{sup}} = K_{1,\mathrm{ret}}$

$K_2 = K_{2,\mathrm{sup}} = K_{2,\mathrm{ret}}$

The coefficients of heat transfer are determined by [1]

$$K_1 = \frac{R_{\mathrm{g}} + R_{\mathrm{i}}}{(R_{\mathrm{g}} + R_{\mathrm{i}})^2 - {R_{\mathrm{m}}}^2} \tag{17}$$

$$K_2 = \frac{R_\mathrm{m}}{(R_\mathrm{g} + R_\mathrm{i})^2 - {R_\mathrm{m}}^2} \tag{18}$$

where R_g is the ground's thermal resistance (m°C/W)

R_i is the insulation's thermal resistance (m°C/W)

R_m is the thermal resistance caused by the interaction between the pipes (m°C/W)

If these equations are combined, the following, more useful, relation is obtained;

$$K_1 - K_2 = \frac{1}{R_\mathrm{g} + R_\mathrm{i} + R_\mathrm{m}} \tag{19}$$

The thermal resistances varies a lot depending on type of pipe, but the following equations can be used when approximating the thermal resistances for pre-insulated single pipes [1]

$$R_\mathrm{g} = \frac{1}{2\pi\lambda_\mathrm{g}} \ln\left(\frac{4H}{D_i}\right) \tag{20}$$

$$R_\mathrm{i} = \frac{1}{2\pi\lambda_\mathrm{i}} \ln\left(\frac{D_i}{D_p}\right) \tag{21}$$

$$R_\mathrm{m} = \frac{1}{4\pi\lambda_\mathrm{g}} \ln\left(1 + \left(\frac{2H}{E}\right)^2\right) \tag{22}$$

$$H = H' + \frac{\lambda_\mathrm{g}}{h_\mathrm{gs}} \tag{23}$$

where λ_g is the ground's thermal conductivity (W/(m°C))

λ_i is the insulation's thermal conductivity (W/(m°C))

D_i is the outer diameter of the insulation (m)

D_p is the inner diameter of the insulation or the outer diameter of the pipe (m)

H' is the depth of the pipes (m)

h_gs is the heat transfer coefficient of the ground surface (W/(m^2°C)

E is the distance between the centerlines of the pipes (m)

Observe that these formulas are only reliable for pre-insulated pipes, but not for older concrete insulated pipes. These formulas are also framed for single pipes (2Mpuk). When using twin pipes (Mpuk) a bit more complicated formulas have to be used to determine the heat losses. This is due to the asymmetric cross sectional area of twin pipes. The heat loss in twin pipes can be estimated by [18]

$$\dot{Q}_{\mathrm{loss}} = \left(\frac{T_{\mathrm{sup}} + T_{\mathrm{ret}}}{2} - T_{\mathrm{g}}\right) 4\pi\lambda_{\mathrm{i}} h_{\mathrm{s}} \tag{24}$$

The factor h_{s} is the heat loss factor and it can be determined from [16]

$$h_s = \left(\frac{2\lambda_{\mathrm{i}}}{\lambda_{\mathrm{g}}} \ln\left(\frac{2H}{r_{\mathrm{i}}}\right) + \ln\left(\frac{{r_{\mathrm{i}}}^2}{2C_{\mathrm{H}} r_{\mathrm{p}}}\right) + \left(\frac{\lambda_{\mathrm{i}} - \lambda_{\mathrm{g}}}{\lambda_{\mathrm{i}} + \lambda_{\mathrm{g}}} \ln\left(\frac{{r_{\mathrm{i}}}^4}{{r_{\mathrm{i}}}^4 - {C_{\mathrm{H}}}^4}\right)\right) - \left(\frac{\left(\frac{r_{\mathrm{p}}}{2C_{\mathrm{H}}} - \left(\frac{\lambda_{\mathrm{i}} - \lambda_{\mathrm{g}}}{\lambda_{\mathrm{i}} + \lambda_{\mathrm{g}}}\left(\frac{2r_{\mathrm{p}}{C_{\mathrm{H}}}^3}{{\mathrm{r}_{\mathrm{i}}}^4 - {C_{\mathrm{H}}}^4}\right)\right)\right)^2}{1 + \left(\frac{r_{\mathrm{p}}}{2C_{\mathrm{H}}}\right)^2 + \left(\frac{\lambda_{\mathrm{i}} - \lambda_{\mathrm{g}}}{\lambda_{\mathrm{i}} + \lambda_{\mathrm{g}}}\left(\frac{2r_{\mathrm{p}}{r_{\mathrm{i}}}^2 C_{\mathrm{H}}}{{r_{\mathrm{i}}}^4 - {C_{\mathrm{H}}}^4}\right)^2\right)} \right) \right)^{-1} \tag{25}$$

where r_{i} is the radius of the insulation pipe (m)

r_{p} is the radius of the inner steel pipe (m)

C_H is half of the distance between the steel pipes (m)

The thermal conductivity of the ground varies depending on both type of soil and moisture content. Typically the value lies between 0.5 W/(m°C) and 3.5 W/(m°C). Polyurethane is usually used as insulation and it has a thermal conductivity of about 0.03 W/(m°C). The heat transfer coefficient of the ground surface varies between 12 W/(m²°C) and 15 W/(m²°C). The depth of pipe lines is typically about 0.8 m. [1]

4.3. Dimensioning

The dimensioning of components in the district heating network can be done based on the maximum heat demands. When the heat demands are known, or well estimated, and assuming design temperature levels to be given, the required flow of hot water to the heat exchanger can be calculated. The flows determine to a large extent how pipelines, pumps and valves should be designed. The required flow can then be solved from an energy balance equation [1]

$$\dot{Q} = \dot{m} \cdot c_p \cdot \Delta T \tag{26}$$

where $\dot{Q}$ is the transferred heat flow (kW)

$\dot{m}$ is the mass flow rate (kg/s)

c_p is the specific heat capacity for water (kJ/(kg°C))

ΔT is the temperature difference between supply- and return pipe (°C)

The mass flow rate is then easily converted to a volume flow by using the density of water. The design temperature levels in both traditional and new low-energy district heating networks will be discussed later.

4.3.1. Pipelines

The volume flows determine the pipe standards that should be selected in the network. If the pipe diameters are too small, it results in too high velocities which, in turn, lead to large pressure drops. Too large diameters will, on the other hand, lead to increased heat losses and additional costs. Table 4-2 presents the highest recommended volume flow rates and flow velocities for welded steel pipes on the primary side of a customer's heat exchanger. These values require the consumer's technical equipment area to be correctly sized. The technical equipment area is the place where the consumer's heat exchanger is placed. Energiateollisuus ry in Finland has set up rules on how the technical equipment area should be sized and depending on the volume of the building, the area should be between 2 m² and 5 m². [19]

Table 4-2. Maximum flow rate and maximum flow velocity for different pipe diameters [19]

DN-Standard	Max flow [l/s]	Max flow [m³/h]	Max velocity [m/s]
20	0,3	1,1	0,74
25	0,6	2,2	0,92
32	1,2	4,3	1,10
40	1,7	6,1	1,16
50	3,2	11,5	1,37
65	6,4	23,0	1,65
80	10,0	36,0	1,87
100	19,0	68,0	2,10
125	35,0	126,0	2,54
150	60,0	216,0	2,97

The flow velocity can be calculated from the volume flow and the pipe diameter from

$$w = \frac{4\dot{V}}{\pi {d_\mathrm{i}}^2} \tag{27}$$

where d_i is the inner diameter of the pipe (m)

Often the regulations on maximum flow velocity to the consumers' heat exchangers determine the pipe diameters, but if these at very high heat demands could be allowed to be exceeded temporarily by a factor of 1.5, say, smaller pipe diameters can be selected. This could result in an energy efficient and profitable decrease in lost thermal energy without increasing the pumping costs excessively. Pipe material still sets limitations on how high flow velocities that can be allowed. The fact that low-energy building areas have lower heat demands than traditional buildings already allows for using smaller pipe diameters, but also such buildings have to be guaranteed a sufficient heat supply at peak demand conditions: This is when a temporarily higher allowed maximum flow velocity would give an opportunity to use smaller pipes. An analysis of such concepts will be presented in chapter 5.

The type of pipes that should be selected in a district heating network depends on heat loss factors and price. The target is often to minimize heat losses to an affordable price and without increasing the need of power for pumping. Twin pipe constructions, which mean that both the supply and the return pipe are inside the same insulation pipe, have the smallest heat loss factors and it is also economically more beneficial to lay them in the ground. When the pipe diameters are large, single pipes, with their own layer of polyurethane insulation, become more common. There are other types of district heating pipes, but welded steel pipes insulated with polyurethane and laid in single or twin pipe constructions are the most commonly used concepts in district heating networks in Finland. In traditional networks, pipes with a design pressure of 16 bar are used. [20]

Traditionally the supply temperature in district heating networks in Finland have been set to 70°C when the outside temperature is above 8°C and otherwise given by the relation [1]

$$T_{\mathrm{sup}} = 115°\mathrm{C} + (T_{\mathrm{dim}} - T_{\mathrm{out}})\frac{45°\mathrm{C}}{8°\mathrm{C} - T_{\mathrm{dim}}} \tag{28}$$

where T_{dim} is the dimensioning outdoor temperature (°C)

T_{out} is the actual outdoor temperature in (°C)

In really cold winter conditions this formula implies supply temperatures up to 120°C. With the traditional determination of the supply temperature the yearly average typically lies between 80°C and 90°C and the return temperature is commonly 40°C lower. In chapter 5 the impact from lower temperature levels will be analyzed in terms of energy efficiency.

The insulation class of district heating pipes affects the thermal energy lost in the distribution. The higher the insulation class, the thicker the polyurethane layer around the pipe and the smaller the heat loss. Naturally better insulated pipes are more expensive, but an investment in well-insulated pipes may pay off due to lower heat loss, better energy efficiency and lower operational costs. In a comparison between single pipes and twin pipes, it has been established that the use of twin pipes gives rise to less heat loss than single pipes. In Finland, there are four standardized insulation classes for single pipes and likewise for classes for twin pipes. A comparison of heat losses between different types of pipes is given in Appendix B.

4.3.2. Pumps

The pressure drop in the pipelines is decisive when sizing pumps in a district heating network. Furthermore, all consumers must be guaranteed an available differential pressure of 60 kPa at all times [1]. This means that at maximum flow rate, which creates the largest pressure loss in the pipelines, the consumer that is located furthest from the pump should have a differential pressure of 60 kPa available, and the pump should be able to cope with the total differential pressure. The static pressure, which is the pressure caused by height differences in the network and the steam pressure of the hot water, can be set aside when sizing a pump, but it is important to investigate the risk of exceeding or falling below the absolute pressure limits at any point in the network. [2]

The pressure drop in a pipeline can be determined by

$$\Delta p = \left(\xi \frac{L}{d_{\mathrm{i}}} + \sum \zeta \right) \frac{\rho w^2}{2} \tag{29}$$

where ξ is the pipe friction resistance factor

L is the length of the pipe (m)

ζ is the pipe element resistance factor

As can be seen, the pressure drop in pipes is directly proportional to the square of the flow velocity. This means that a doubled velocity increases the pressure drop by a factor of four. It can also be seen that the total pressure drop can be divided into two terms. One of them is caused by friction inside the pipe and the other occurs because of pipe elements such as elbows, valves and t-pieces. The pipe element resistance factors typically vary between 0 and 5, depending on the type of element. The resistance factor caused by friction in the pipe, on the other hand, depends on both Reynold’s number and pipe roughness. Diagrams where the friction factor can be read as a function of Reynold’s number and the ratio between pipe roughness and pipe diameter, have been constructed to simplify the determination of the friction factor.

The following equation also gives a good estimate of the friction factor but it requires that the flow is turbulent (Re > 2300) [21]

$$\xi = 0.01 \cdot \left(\frac{10^6}{\mathrm{Re}} + 18.7\left(\frac{1000k}{d_\mathrm{i}}\right)^{1.094}\right)^{0.25} \tag{30}$$

where Re is Reynold's number

k is the pipe roughness (mm)

The pipe roughness depends on type and age of the pipe. Typical pipe roughness values are 0.01 mm to 0.2 mm [21]. For district heating pipes the interval can be narrowed down to 0.04 - 0.1 mm [1]. Reynold's number is determined by

$$Re = \frac{wd_\mathrm{i}}{v} = \frac{4\dot{V}}{\pi d_\mathrm{i} v} = \frac{4\dot{V}\rho}{\pi\mu d_\mathrm{i}} = \frac{4\dot{m}}{\pi\mu d_\mathrm{i}} \tag{31}$$

where v is the kinematic viscosity of the pumped media (m^2/s)

μ is the dynamic viscosity of the pumped media (kg/(m·s))

The pressure drop, as a function of the volume flow, shows the characteristics of the pipeline. The pump that creates the required pressure increase should have matching characteristics and be able to work at a high efficiency for the volume flow rate in question. The large flow variations that can appear in district heating pipelines often make it most beneficial to have more than one pump in the system. If two parallel, but different sized pumps, are available, it is possible to cover a wide range of volume flow rates at high efficiency. By connecting pumps in series, a higher pressure level can be reached. The procedure is illustrated in Figures 4-7 and 4-8.

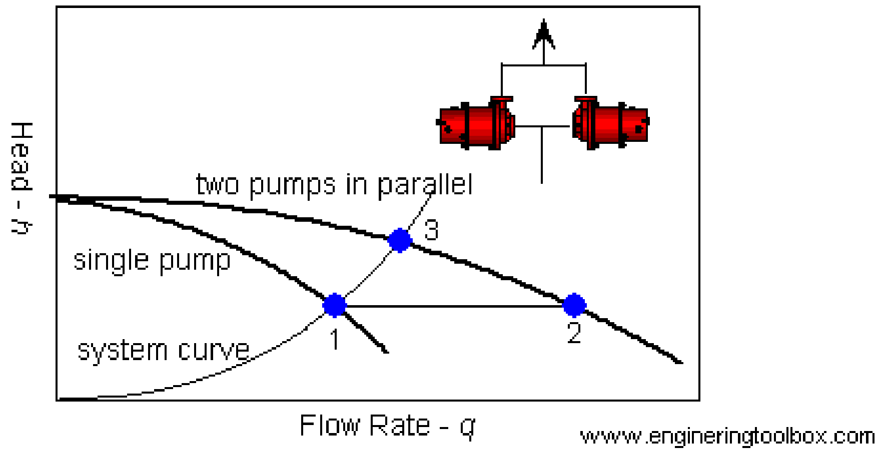

Figure 4-7. Characteristics for a single pump and two pumps in parallel [22]

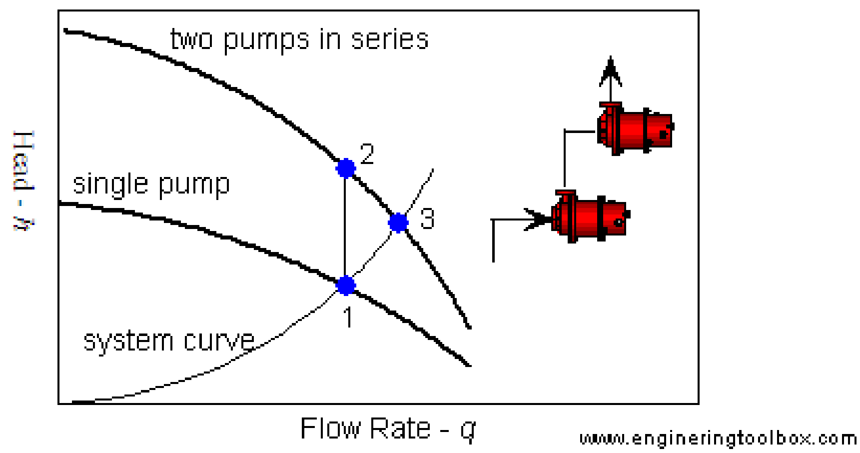

Figure 4-8. Characteristics for a single pump and two pumps in series [22]

In these illustrations, the head *h*, is equal to the pressure increase *Δp*, and the flow rate *q*, equals the volume flow $\dot{V}$. The coordinate where the characteristics of the pipe line, also called the system curve, meets the characteristics of the pump, is called the operational point of the pump. It is important to use pumps with high efficiencies at the operational point to minimize pumping costs. This is achieved by selecting a pump designed for a volume flow rate close to the operation point of the system. Typically, the pump efficiency varies with the volume flow, as indicated in Figure 4-9 [21].

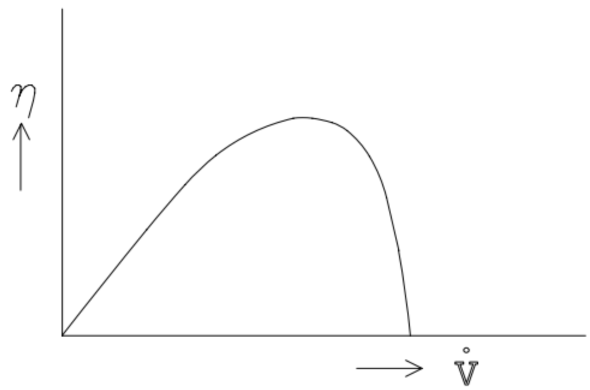

Figure 4-9. Efficiency characteristics of a centrifugal pump [21]

The required power to the pump is given by [19]

$$P_{\mathrm{pump}} = \frac{\dot{V}\Delta p}{\eta_{\mathrm{pump}}} \tag{32}$$

where η_{pump} is the efficiency factor of the pump.

Pumps in district heating networks are generally centrifugal pumps. The estimated life length of a centrifugal pump is 20 years. [1]

4.3.3. Valves

A district heating network contains a lot of different valves serving different purposes. Many of them are shut-off valves for branches, which in normal operating conditions are fully open. Shut off valves can be actuated manually or automatically. Pressure reducing valves are, to some extent, used to reduce the inlet pressure to a branch of the network. In this way, it is possible to reduce the pressure drop over the customers' control valves, still without making the differential pressure at the critical consumer too low. Other types of valves in a network are backlash valves and safety valves. The valves that determine the flow and the heat transfer in the network are the consumers' control valves. [2]

When selecting control valves of a network, it is important to choose valves of suitable capacity. Valve capacities are given by so called K_v values. The K_v value specifies the maximal flow of water expressed in m³/h through a fully open valve at a pressure drop of 100 kPa. The K_v value can be determined from [23]

$$K_v = \frac{\dot{V}\sqrt{\rho}}{\sqrt{\Delta p}} \tag{33}$$

where Δp is the pressure drop over the valve (bar)

Control valves are not made for every K_v value. Instead valves for a standardized series of K_v values are manufactured. The accessible values are called the K_{vs} values. A valve with a K_{vs} value greater than, but closest to, the calculated K_v value should be selected in the network [23]. The impact of the customer's control valves on the pressure drop should also be over half of the total available differential pressure announced by the heat seller. This can be expressed with an impact factor [1]

$$\beta = \frac{\Delta p_{\mathrm{valve}}}{\Delta p_{\mathrm{diff}}} \geq 0.5 \tag{34}$$

where $\Delta p_{\mathrm{valve}}$ is the pressure drop over the valve

Δp_{diff} is the available differential pressure

5. CASE HONKASUO

In this chapter the possibilities to improve the energy efficiency of district heating networks in low-energy building areas have been further studied by modeling and simulating the heat distribution in the upcoming low-energy residential area of Honkasuo in Helsinki.

5.1. The Honkasuo residential area

Honkasuo is an upcoming residential area in the north western part of Helsinki (Figure 5-1). The area is bordered by the city of Espoo in west and by the city of Vantaa in north. According to the plan, the construction work should have started during this autumn (2014). The settlement will be dominated by small detached houses, but also some blocks of flats are planned in the area. Honkasuo is designed to be a residential area meeting today's expectations on ecological and environmental sustainability. The clearest sign of this is the planned buildings, which will be timber constructions with low energy consumption. When constructing the area, there is also an aim to preserve the original nature-close landscape scenery as good as possible, making Honkasuo a peaceful living place close to the city center. [24]

The area of Honkasuo is 315 575 m² and the total projected building floor area is 62 671 m² of which 61 471 m² is housing area and 1 200 m² planned for public services. Honkasuo is estimated to be inhabited by 1 500 persons. The housing density can be measured in built floor area per region area, and this factor varies between 0.3 and 0.7 per housing lot in Honkasuo. Building a dense residential area with low energy consumption and with good connection to public transport indicates a clear strive for lowering emissions of greenhouse gases in the city of Helsinki. According to the city plan, the area is also prepared for an increased use of renewable energy. A detailed view of the planned buildings is provided in Figure 5-2. [24]

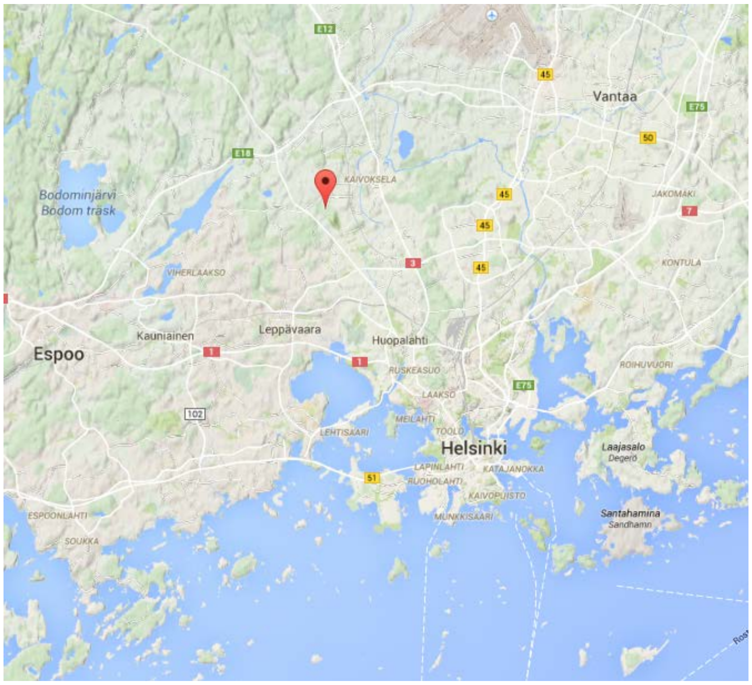

Figure 5-1. Honkasuo's location

Figure 5-2. The planned residential area of Honkasuo [24]

Helsingin Energia will provide the area of Honkasuo with district heat and by that satisfy the inhabitants' need of both space heating and domestic hot water. The distribution in this area (Figure 5-3) will slightly differ from traditional heat distribution in the city. The heat to the separate network of Honkasuo will be exchanged from one of the main heating pipes in the city. In the district heating network of Honkasuo, lower heat losses will be required to keep energy efficiency high and maintain profitability in the distribution. This is due to the low heat demands in the buildings. [24]

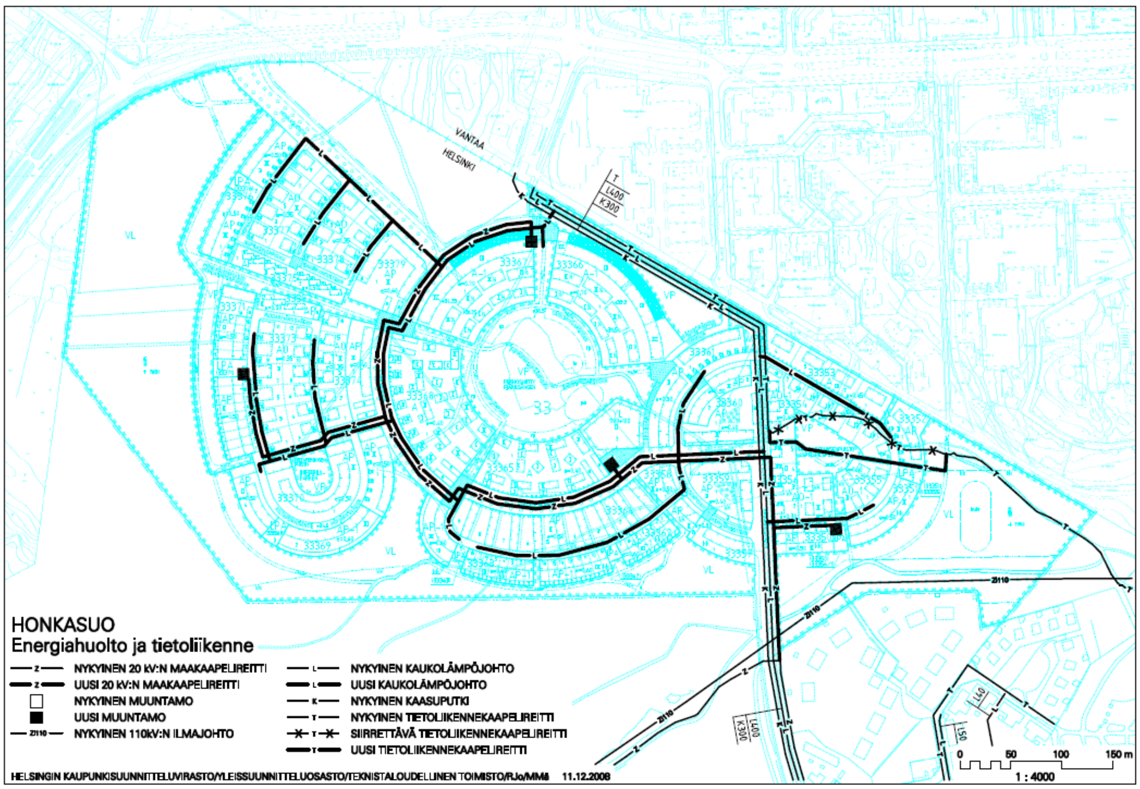

Figure 5-3. The district heating network planned for Honkasuo with heating pipes marked by "-L-" [24]

5.2. Simulation program structure

In this work, a simulation program was written in Microsoft Excel to study different heat distribution scenarios in Honkasuo, and to compare them in terms of energy efficiency. Simulations were done for a whole year, so that operational differences between seasons were considered. As a result from a simulation, the network's relative heat loss on a yearly basis was obtained. In developing the model, the heat demands of the buildings were modelled and the network was dimensioned according to the principles outlined in chapter 4.

The structure of the program is illustrated in Figure 5-4 and closer explained in subsections 5.2.1 to 5.2.3.

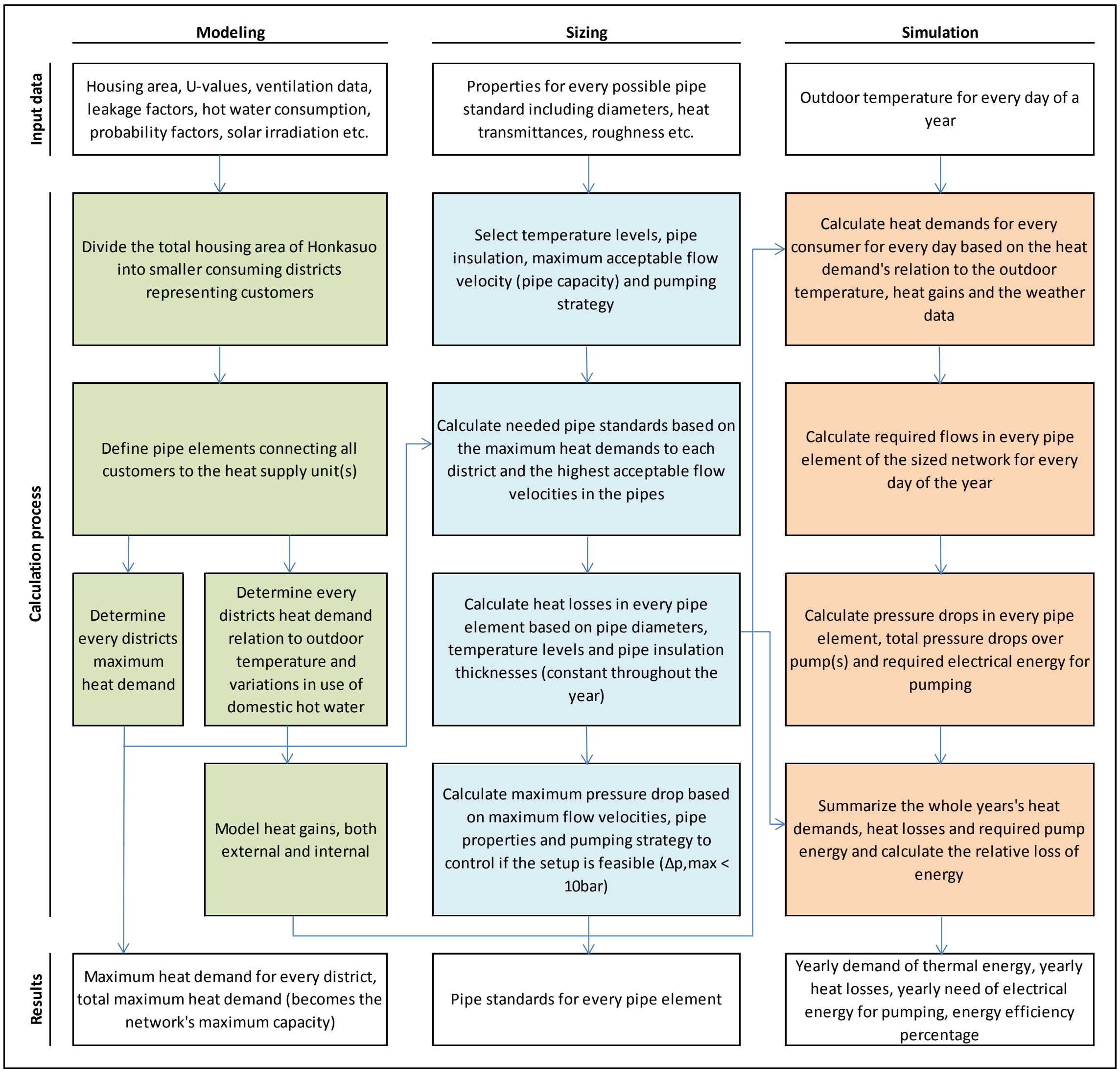

Figure 5-4. Simulation program structure

5.2.1. *Modeling heat demands*

Both the space heating demand and the heat required for domestic hot water must be satisfied with district heating. Both demands vary, but in very different ways. While the need of space heating is strongly dependent on the outdoor temperature, a yearly trend with high demand during the winter and low demand during the summer arises. The use of hot water does not depend on any physical factors, but varies due to the daily rhythm of people. Peaks in the use of hot water can typically be seen during mornings and evenings, but the simulation program simply uses daily average values for hot water consumption. Thus, such hourly trends won't be seen in the plots from the program. The daily variation trends have though been studied and will be presented later in this chapter. The modelled heat demands are in this subsection only presented for the whole district of Honkasuo. The splitting into smaller heat consuming areas, representing customers, is treated in subsection 5.2.2.

The space heating demand is based on the buildings' ability to prevent heat conduction and air leakage. In the coming low-energy buildings in Honkasuo, this ability is naturally good, but there still is a need of space heating especially during the winter months. The demand increases with lower outdoor temperatures. Based on Figure 4-1 the heat distribution should be able to keep a comfortable indoor climate with outdoor temperatures down to -26°C. A heat loss value of 0.76 W/($m^{2\circ}$C) have been obtained from calculations based on the geometry of the houses and technical data of *U* values, ventilation and leakage, given by the house providers. This value corresponds to small detached houses and naturally varies with type of buildings. Since Honkasuo is dominated by small detached houses, the value has been used for all the buildings in the simulation program.

To obtain the yearly demand of thermal energy for space heating, the demand values for every day of the year were calculated and added. Outdoor temperature data (Figure 5-5) from Helsinki, between 1.6.2013 and 31.5.2014, was used to estimate the daily demands. The internal heat gains were approximated to be constant throughout the year (≈7 W/m^2) while heat gain from solar irradiation was modelled in a way that gives it a minor impact during dark winter months and a larger impact during summer (0 W/m^2 - 6 W/m^2). Values used in the modelling can be found in Appendix A.

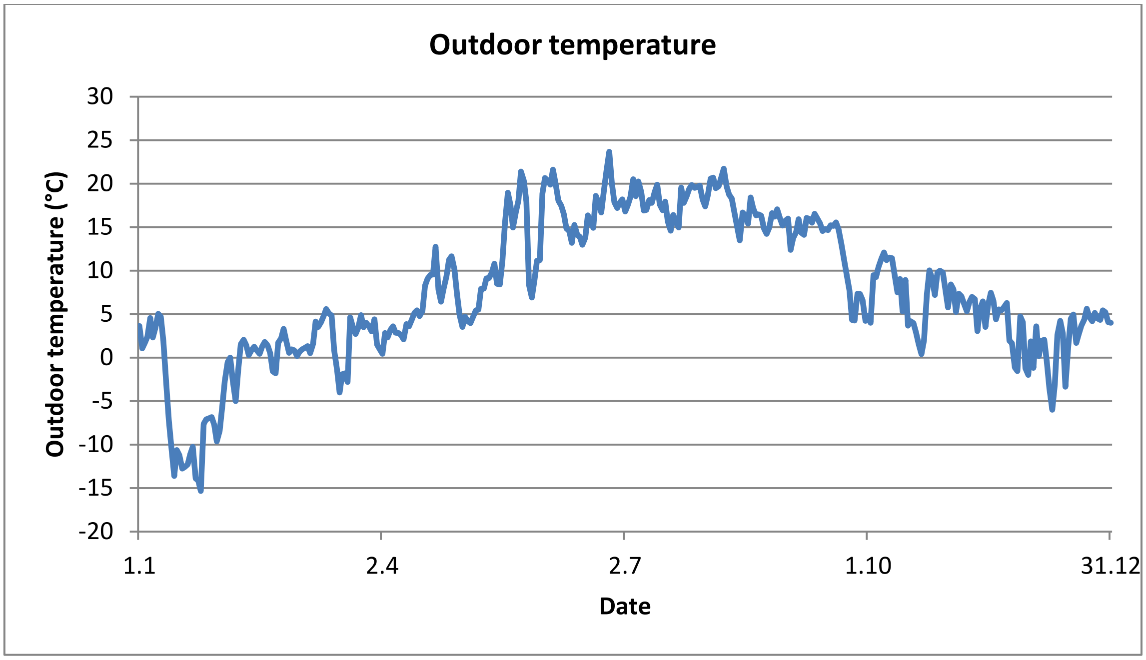

Figure 5-5. Outdoor temperature (in monthly order) used in the simulation program

The modelled need of heat for domestic hot water was based on one person's daily use of hot water. With a randomly generated hot water consumption between 35 and 65 liters a day per person, and considering the average housing area per inhabitant, the need of heat for domestic hot water was estimated and expressed as heat demand per housing area, and by that scaled to the same unit as the space heating demand. The maximum heat demand for domestic hot water is obviously much higher than the daily average values. To determine this maximum demand, one person's maximum momentary use of hot water has been used combined with a probability factor on how many inhabitants might be using hot water at the same time. In subsection 4.1.2 different formulas for determining the maximum heat demand for hot water in larger complexes of apartments were presented. The modelled maximum hot water demand for Honkasuo corresponds well with the Velander formula (Eq. 11) with the factor ε = 0.01.

The space heating demand and the heat for domestic hot water together represent the total heat demand in the area. A plot of Honkasuo's modelled total heat demand during the days of a year is presented in Figure 5-6. Note that the absolute peaks in the use of hot water are not seen due to the use of daily average values in this study. From the plot it can be seen that the low-energy buildings in Honkasuo will require space heating only about five and a half months per year, which is significantly less than traditional buildings. This is in general agreement with overall findings for low-energy buildings reported in the literature [6].

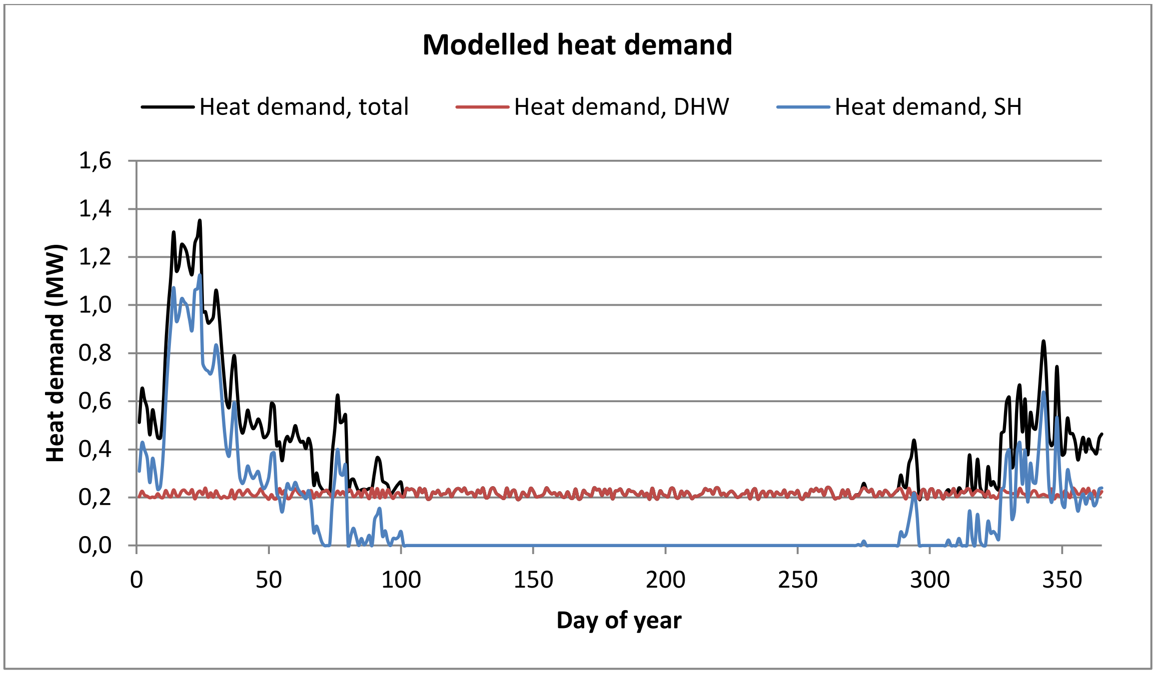

Figure 5-6. Modelled heat demand in Honkasuo for the days of one year (DHW: Domestic hot water, SH: space heating)

When the total heat demand for every day is plotted against the outdoor temperature (Figure 5-7), the figure clearly shows both the space heating demand, together with its dependence of the outdoor temperature, and the heat demand for hot water, which is independent of the outdoor temperature. The horizontal part of the figure, which lies on the magnitude of 200 kW, represents the average heat demand for hot water production while the inclined part describes the relation of the space heating demand on the outdoor temperature. As can be seen the buildings do not require space heating when the outdoor temperature exceeds 6°C. This limit is lower than for traditional buildings, which is due to the low heat loss values of the buildings and the heat gains. The heat demand for domestic hot water is obviously also kept at the same level for outdoor temperatures below 6°C, although the figure breaks at that point.

From a duration curve, it can be seen how often certain heat demands occur. A duration plot is done by sorting the daily heat demands of the year from largest to smallest values. Information about how often certain peak demands occurs can be useful for the heat production plants and their operational strategy, and the information can also benefit the planning of pump connections in the network. The duration curve of Honkasuo's total heat demand is presented in Figure 5-8.

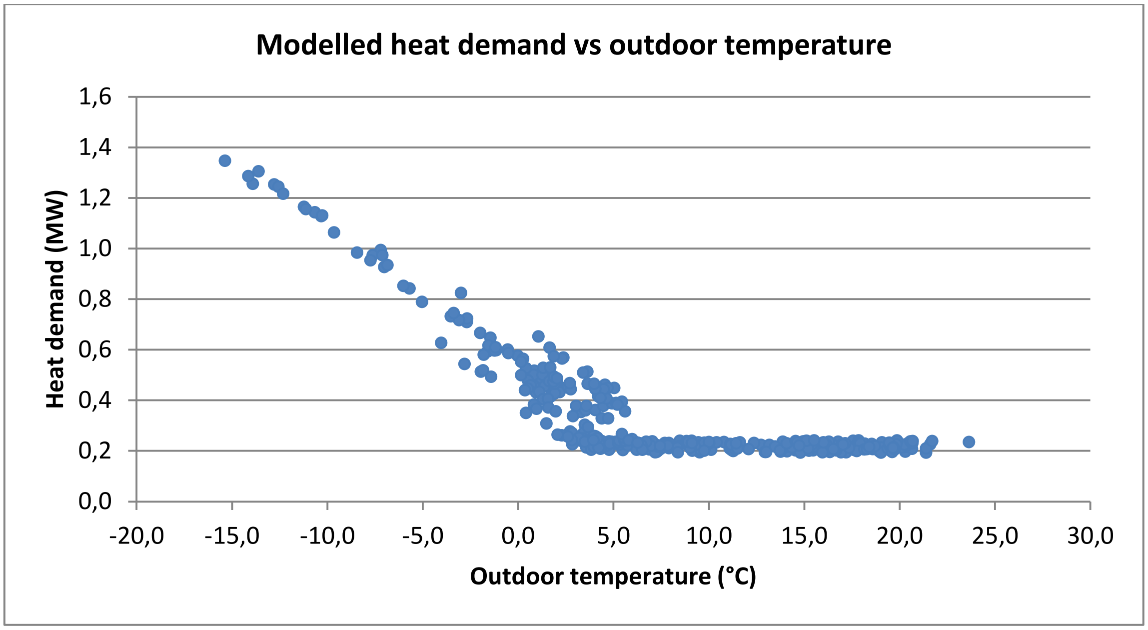

Figure 5-7. Modelled heat demand as a function of outdoor temperature for the Honkasuo residential area

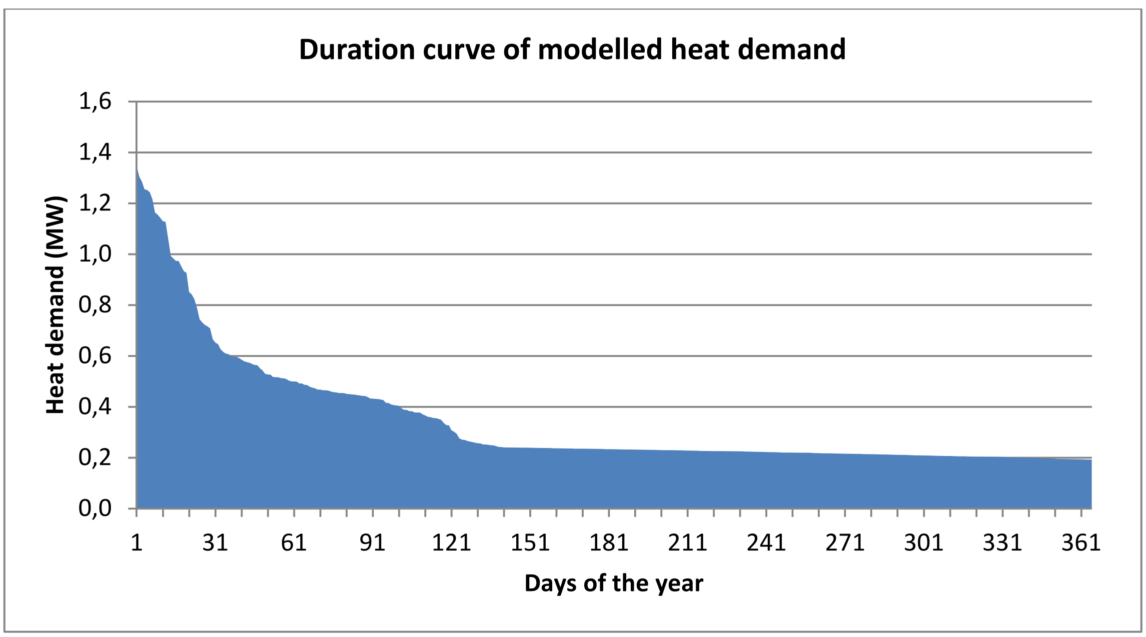

Figure 5-8. Duration curve of the modelled heat demand in Honkasuo

As can be seen from Figure 5-8 the heat demand exceeds 600 kW only just over a month per year, but the plot is not fully accurate because daily average values were used for the heat demands for domestic hot water. A plot matching reality would be more varying, or would, in other words, start from a value slightly higher than 1300 kW and end at value closer to 0 kW.

As a comparison to the modelled heat demands, plots based on data from measured heat consumption have been created. This data, provided by Helsingin Energia, contained the heat consumption of one hundred detached houses for every hour of one year. All the buildings were built in 2010 or later. Since the measured data was expressed as a total heat demand per square meter of floor area, the measurements were easily scalable to a housing area similar to that of Honkasuo.

As the buildings from where the measurements were obtained were new, their heat consumption is relatively low. These houses were still not built as low-energy buildings, which means that their heat consumption, scaled to the same housing area as in Honkasuo, will be slightly higher. Since Figures 5-9 and 5-10 are plotted for every hour of a year, they vary more and provide a more realistic view than the daily plots of the modelled heat demands.

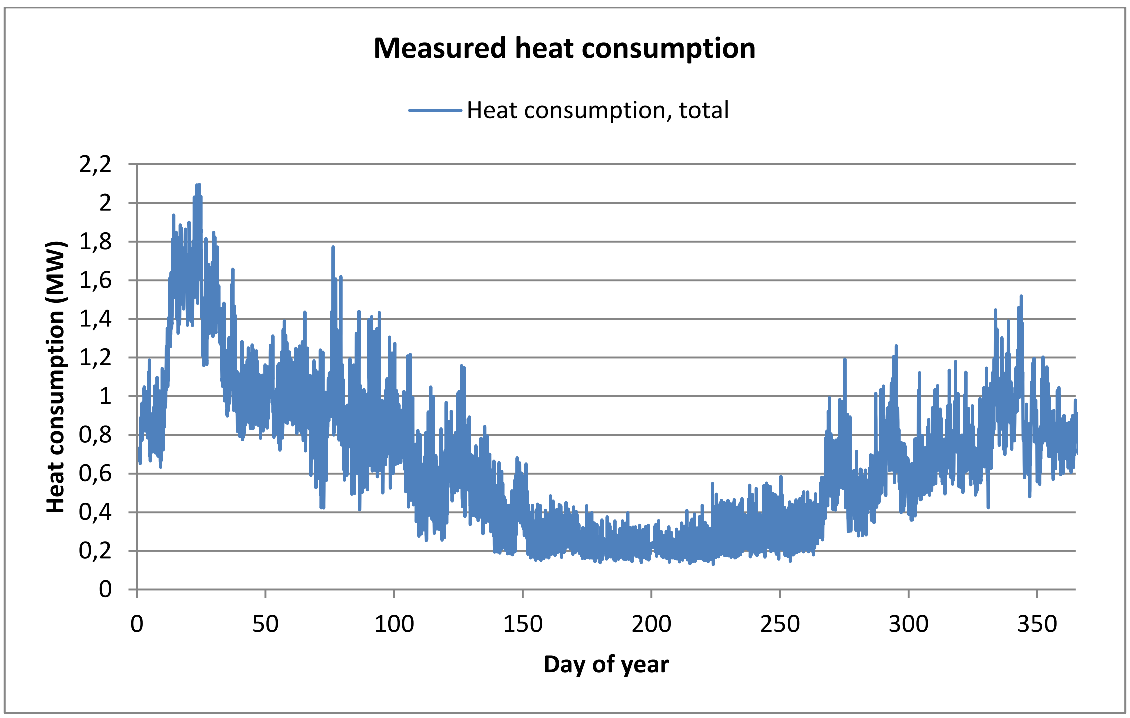

Figure 5-9. Measured heat consumption scaled to the same housing area as in Honkasuo

The measured heat consumption (Figure 5-9) is on a slightly higher level than the modelled heat demands, as expected. This can also be observed in Figure 5-10, where the measurements are plotted against the outdoor temperature.

As can be seen the level of heat for hot water matches the modelled plot well, but since hourly variations now are taken into account the plot is more noisy. The temperature limit where space heating is no longer required is for the measured houses just above 10°C.

A duration curve for the measured heat consumptions is presented in Figure 5-11.

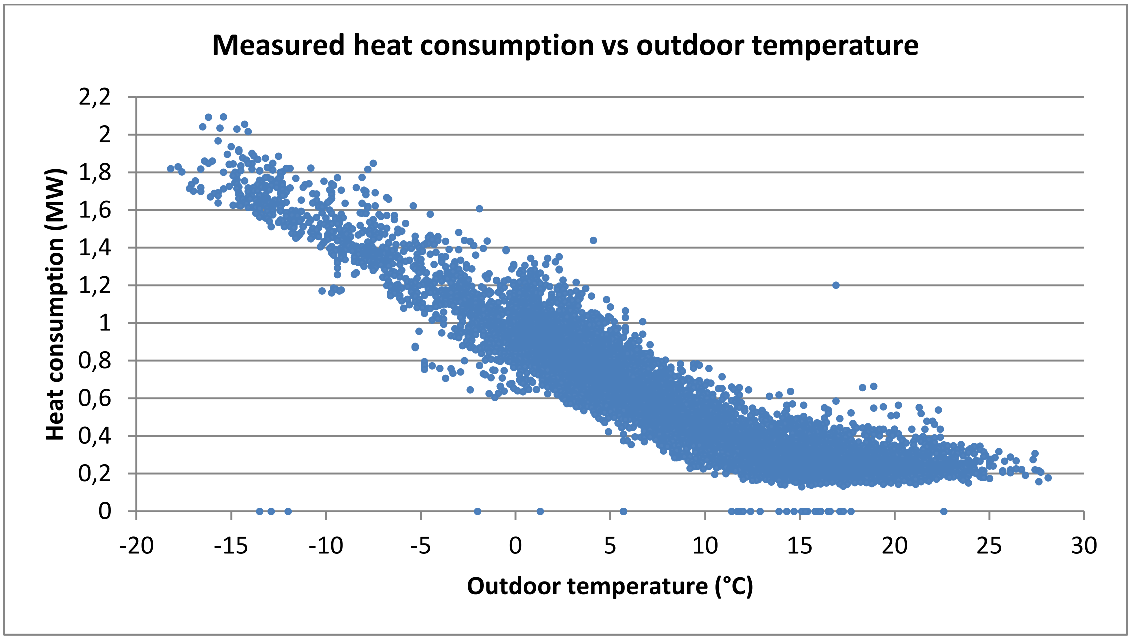

Figure 5-10. Measured heat consumption, scaled to the same housing area as in Honkasuo, as a function of outdoor temperature

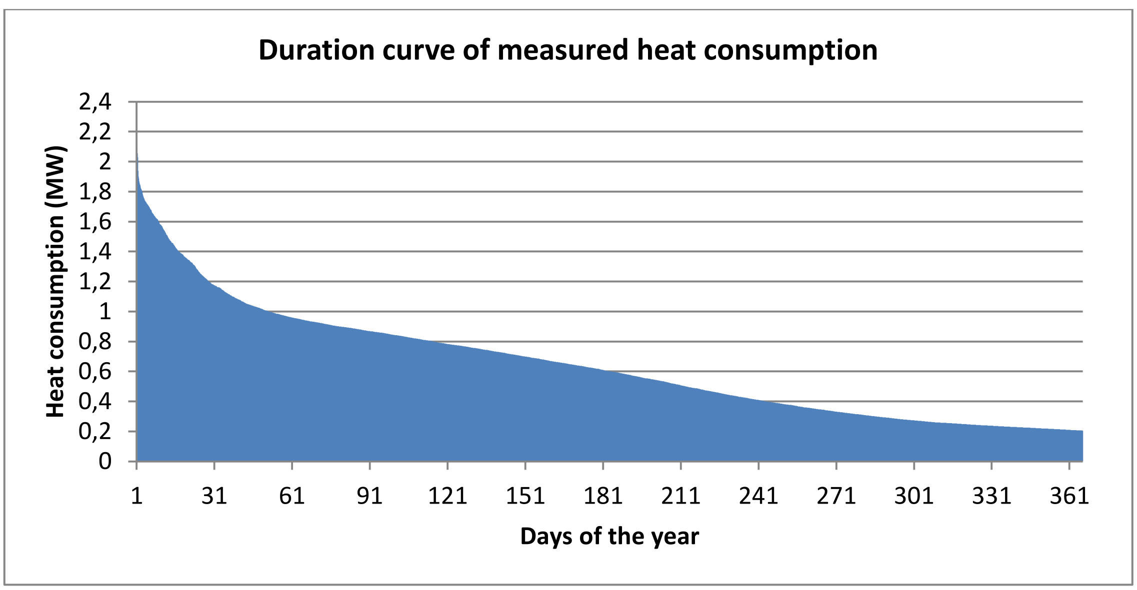

Figure 5-11. Duration curve of the measured heat consumption scaled to the same housing area as in Honkasuo

The simulation results regarding energy efficiency and yearly heat losses are expected to match reality well, even though hourly variations in the hot water use are not taken into consideration. It would still be interesting to know the magnitude of these variations. In one single house or apartment the momentary peaks in heat consumption might be ten times higher than the average value, because of typically short but intense use of hot water. With more consumers connected to the network, theses peaks will still occur, but be evened out due to the low probability that many people tap their hot water simultaneously. Figure 5-10 already indicated that the maximum use of hot water in large networks rarely becomes twice as high as the average use, but further research has still been done in order to confirm this and simultaneously determine daily trends. This was done by using the data of measured heat consumptions.

First, a summer day (17.6.2013) was studied, where all the heat consumption could be assumed to be due to heating of hot water. The measured data was scaled to the housing area of Honkasuo, and the results are presented in Figure 5-12. It should be pointed out that the variations here were based on one hundred houses, which is fewer than in Honkasuo, so the variations in Honkasuo are expected to be slightly more damped.

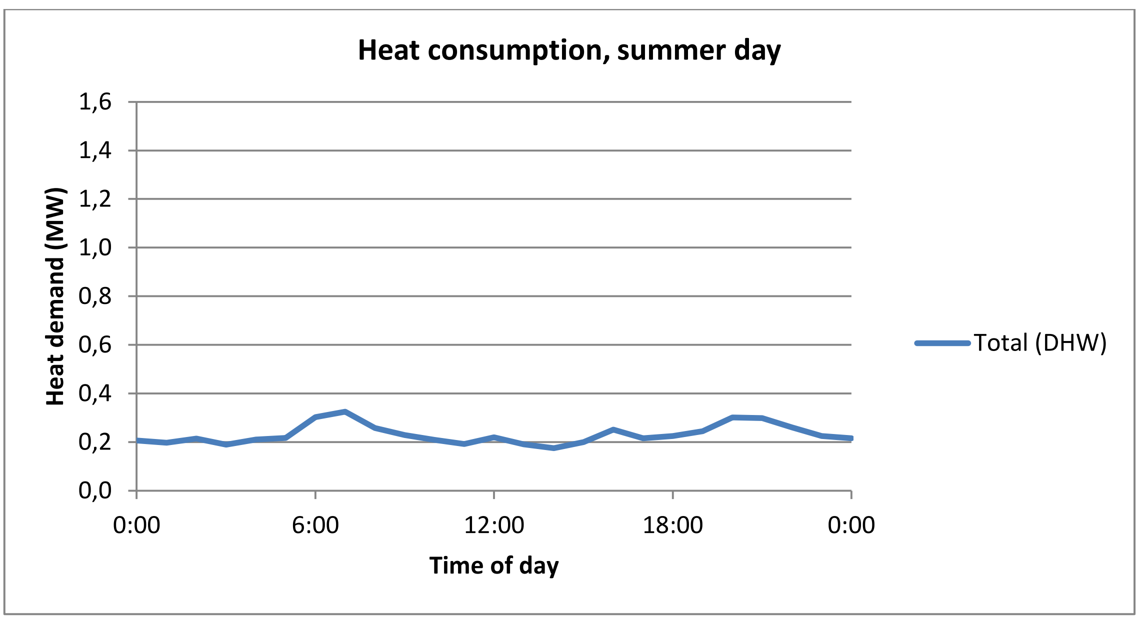

Figure 5-12. Estimated heat consumption in Honkasuo during a summer day

Although the consumption peaks have been leveled out due to the high amount of connected houses, they can be spotted. The morning hours between 6:00 and 8:00, together with the evening hours between 19:00 and 22:00, show the highest heat consumption during a day. This trend can in practice be seen for every day and is therefore not specific for the selected day. The consumption trend is simply caused by the living rhythm of the inhabitants. It should yet be mentioned that 17.6.2013 was a Monday, i.e., a working day. The consumption during weekends typically looks a bit different due to the social rhythm of the consumers.

The hourly consumption during a winter day (15.1.2014), a Wednesday, was also studied. Again, the measured hourly heat consumptions consist of both space heating and heating of the hot water, but now the former consumption cannot, naturally, be neglected. However, by using the outdoor temperature data, also available for every single hour of the year, the variations in the space heating demand can be estimated. The magnitude of the space heating consumption was determined with the assumption that the consumption level of domestic hot water lies on same level as during the summer day. With this approach both the space heating consumption and the heat consumption for domestic hot water have been extracted from the total heat consumption. When plotting the consumption in Figure 5-13, a scaling to Honkasuo's housing area has again been made to allow for comparison. The space heating consumption separated from the measurements, was multiplied by a factor of 0.75 to take into account the low-energy construction of the houses in Honkasuo.

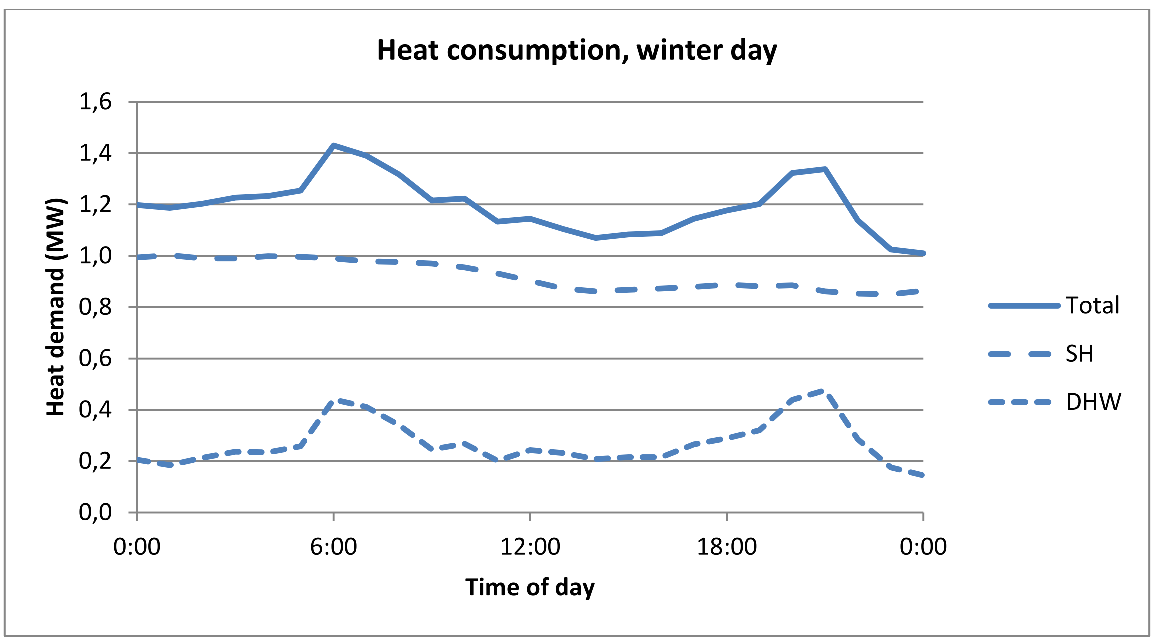

Figure 5-13. Determined heat consumption in Honkasuo during a winter day

Similar trends as during summer clearly appear also during winter, but the curve has been shifted to a higher total consumption level. The estimated domestic hot water demand actually looks very much like the consumption curve from the summer day. The peaks are slightly higher, but they occur during the same hours. The fact that the peaks are higher may depend on social factors that are difficult to determine, but may also be due to the fact that the incoming water that is heated has a slightly lower temperature in the winter time. This will shift the consumption curve somewhat upwards. The plots also confirm that the daily highest peaks in the use of hot water, in larger areas, typically are about twice as high as the average use of hot water on that day. In one single building the hot water peaks can still be about ten times higher than the average value.

The peaks in heat consumption caused by the heating of domestic hot water could be even more leveled out by using hot water storage tanks in each building. However, this will not be the case in Honkasuo, so all the heat transfer in these buildings has to be done directly. The total amount of transferred heat would still be approximately the same with installed storage tanks.

It should be noted that studying the heat consumption on an hourly basis also filters out shorter-term fluctuations: A shorter time interval used in the calculations would naturally give results that more accurately reflect the true situation. The figures with values plotted for every hour are still expected to be accurate enough to reflect the main variations in the heat consumption during a day.

Based on the measured data from one hundred recently-built small detached houses, the formulas for determining the maximum heat demand for domestic hot water in larger building complexes have also been investigated. The formulas presented in subsection 4.1.2 (Eq. 11 – 13) give quite scattered results, as can be seen from Figure 5-14, where the heat demand for making the hot water has been plotted using the formulas.

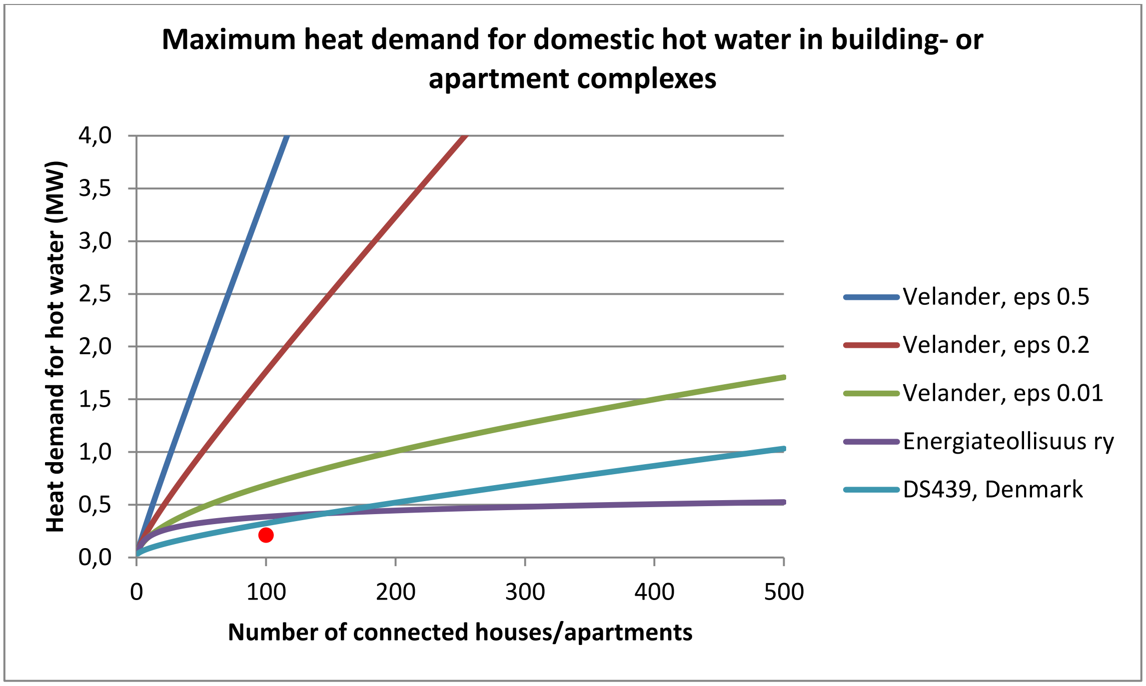

Figure 5-14. Maximum heating demand for domestic hot water in connected houses or apartments according to different formulas [1]

From the data for the 100 houses, only the total heat consumption was reported. By assuming that the need of space heating during the summer months was close to zero, the highest peaks during summer would very closely represent the maximum demand for the production of domestic hot water. The highest spike during the summer was 11.5 W/m^2 (housing area). It is still reasonable to suppose that the yearly maximum heat consumption for hot water was a little higher than this, since the incoming water during winter months has a slightly lower temperature. Therefore, the value 14 W/m^2 was taken as the maximum heat demand for hot water in 100 houses. By multiplying this value by the total housing area of the measured houses, 15 000 m^2, a maximum heat consumption of 210 kW was obtained; this value has been indicated by a solid red circle in Figure 5-14. Studying the figure, we may conclude that even the harshest formula for determining the maximum demand for domestic hot water will be sufficient with a clear safety margin. If, for instance, we use the Velander formula, the factor should not be set higher than ε = 0.01, at least not for larger networks.

The formula proposed by Energiateollisuus ry looks very reasonable for determining the maximum demand for up to 100 connected buildings. After that this curve levels out quite quickly and suggests almost the same maximum demand for 200 connected houses and 500 connected houses. The Danish analogy, which for small networks with up to 100 connected buildings is the harshest one, will be more reasonable to use for larger networks, or at least it will imply a greater safety margin. Based on the same measured data, but scaled to a housing area of 62 000 m², Figure 5-10 showed that the highest values for heat consumption occurring from hot water use would be around 700 kW during warm periods in Honkasuo. If we assume that this residential area will consist of about 400 buildings and apartments, it can be established from the plot that the formula determined in Denmark is most reasonable when it comes to large networks. The maximum heat demand for domestic hot water in 400 buildings according to the formula from Energiateollisuus ry is 500 kW, which is too low according to Figure 5-10. As stated in the figure, it is still only a few hours per year that the level of 500 kW is exceeded, but naturally the network has to be dimensioned in a way where also the maximum demands can be satisfied. One still has to keep in mind that the variations in the area corresponding to Honkasuo were estimated based on the variations observed in 100 houses. This means that that the estimated variations might be higher than what they would be in reality, since more connected houses buffer the relative variations.

It is difficult to draw any further conclusions than this, since the research was based on only one table of measured data. It is noteworthy to point out that networks with as many connected houses can differ from each other in terms of hot water use. For instance a residential area dominated by families with children probably need more hot water and require more heat than areas mostly inhabited by elderly persons.

5.2.2. Sizing the network

In the simulation program, the sizing of the network required some simplifications to be introduced. The structure of the pipelines was taken straight from the Honkasuo city plan, but a few estimated pipe elements were added since the plan did not cover the whole network yet. Naturally, the plan did not either cover the last pipe elements connecting each consumer. A simplification was introduced to lower the number of consumers by grouping several consumers into larger housing areas. This simplification of the network structure also led to fewer flow- and pressure calculations.

Heat is exchanged to the network of Honkasuo from an existing base pipeline in the city. Two heat exchangers, at different locations, will transfer heat from this pipeline into the Honkasuo system. This means that the heat supplied to the consumers can be pumped from two directions. Both pumps can then satisfy their customer's heat demands. The pipelines and pumps are still sized in the way where it is possible to supply the whole district with heat from only one pump location. With this option, service can be made at one pumping point without interrupting the heat distribution. The fact that the east side of the residential area will be built first, and the heat exchanger and pump in north will be connected at a late stage of the construction, also made it logical to carry out the dimensioning in the selected way. When operating the network from both sides, shut-off valves in the middle of the pipelines will define the two different pumping coils. In case only one pump has to supply the whole system, these valves will naturally be open. Figure 5-15 illustrates the distribution in the simplified network.

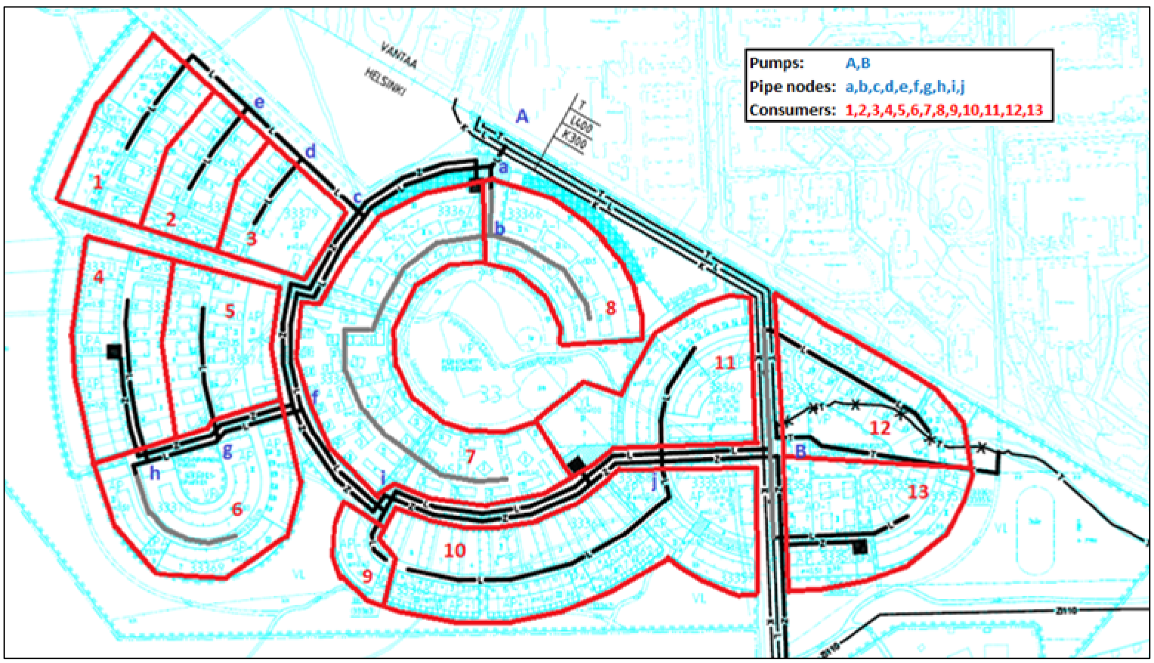

Figure 5-15. Simplified model of the heat distribution in Honkasuo

The 13 modelled heat consuming districts in the area were drawn logically and with consideration of the already planned pipeline. The 13 areas together form the total housing area of 62 000 m² but individually their housing area varies. The smallest modelled district have a housing area of 1 500 m² and the largest an area of 11 000 m². The pipe elements in Figure 5-15, defined by nodes, vary when it comes to both length and capacity. The longest pipe in the network is the one connecting the both pump locations, and it has a length of about 750 meters. Data for all districts, and also for all pipe elements, are given in Appendix A. In the same appendix calculations for maximum heat loads are shown.

The selection of pipe diameters in the network was based on the maximum heat demand to each consumer and the highest allowed flow velocities. In other words, the upper limit on the flow velocity is reached when the modelled maximum heat demand occurs in the area. Since the recommendations on maximum flow velocity strictly will constrain the option to select smaller pipe diameters, scenarios, where the recommended maximum velocity is momentary exceeded, were also simulated. Allowing for exceeding the recommended maximum flow velocities temporarily, smaller pipe diameters can be selected and the heat losses can be reduced. According to the duration plot of the yearly heat demand (Figure 5-8), the times when really high peaks occur are quite few, which means that the flow velocities will still be kept at levels satisfying the recommendations most of the year. A decrease in pipe diameter also causes higher pressure drops in the pipes, which, in turn, means that the pumping power increases. Later in this chapter an analysis is presented on whether exceeding the recommended maximum flow velocities can improve the energy efficiency of the network.

The selection of pipe insulation class is also set as a changeable design parameter in the simulation program. Different insulation thicknesses can be chosen for each simulation in order to see how much the loss of thermal energy is affected. The fact that better insulated pipes have higher investment costs has not been taken into consideration in the simulation, since the program focuses mainly on energy efficiency. The increased need of electrical power for pumping, which arises from higher allowed maximum flow velocities, has not been given a direct cost. Still, in the calculations of energy efficiency, the pumping power has been valued 2.5 times higher than the thermal energy, where the factor was chosen on the basis of typical conditions in combined heat and power plants, where 2.5 times more heat than electricity is produced.

Whether to pump only from one pump location or from both is, likewise, a parameter in the simulation program. The simulation program reports if maximum allowed pressure drops are exceeded in the system.

An important parameter that has to be selected before the network is dimensioned is the temperature level. Lower temperatures gives rise to less heat losses, but an increase in the supply temperature gives lower flow rates so smaller pipe diameters can be selected.

5.2.3. Simulating the outcome

When the buildings have been modelled, the heat demand in the area is determined and the network can be sized after selecting a few model parameters. The model then calculates the heat demand for every consumer for every day of the year based on weather data used (Figure 5-5). The heat demands stand as basis for the calculations of flows, pressures and pumping power. The heat losses are taken to be constant during the year since they do not depend on the magnitude of the flow in the pipes; this is so because the cooling along the pipeline was neglected, as it turned out to be in the order of a few degrees only. The summarized amount of distributed thermal energy, and likewise the summarized amount of lost energy, is the basis for the determination of energy efficiency.

The purpose of the simulations was to investigate how the energy efficiency of the network can be improved. Naturally, the energy efficiency is not the only factor studied in the simulations. Also, the estimated heat consumption of the buildings is a result of the simulation, but this result stays the same even though design parameters of the networks are changed. The buildings' yearly demand of both space heating and domestic hot water heating has been divided with the total housing area to obtain a yearly consumed amount of thermal energy per square meter. Table 5-1 presents the buildings yearly heat demand per square meter.

Table 5-1. Modelled yearly heat demand in the low-energy buildings in Honkasuo

Space heating	19.8	kWh/(m²a)
Domestic hot water	29.6	kWh/(m²a)
Total	**49.4**	**kWh/(m²a)**

The yearly need of thermal energy for domestic hot water might be slightly lower than in traditional buildings but generally speaking the value in the table corresponds very well to typical heat consumptions for domestic hot water. The need for space heating, on the other hand, is significantly reduced in comparison to traditional buildings. The value might even be a bit lower than the actual space heating consumption in the buildings of Honkasuo, since the weather data was taken from a relatively warm year. A model giving an underestimated value on the heat demand is still better than the opposite, since a lower heat demand makes it even more difficult to distribute heat efficiently. In other words, it is easier to make the heat distribution efficient during cold years than during warm years. Therefore, if the network is efficient under these conditions it surely works during colder years. The network is, naturally, still sized in a way were it can handle high heat demands arising at very low outdoor temperatures. The total heat demand of about 50 kWh/(m^2a) easily places the houses in the category low-energy buildings, and if the yearly space heating demand in reality will be kept below 20 kWh/(m^2a) also the criteria for passive housing is met .

The energy efficiency analysis is based on the modelled yearly supply to the consumers, the calculated yearly loss of thermal energy and the electrical energy for pumping, scaled in the way explained earlier. The energy efficiency is assessed by illustrating the percentage of yearly lost energy of total energy delivered to the customers. Thus, the lower the percentage is, the better the energy efficiency in the network. Naturally the efficiency percentage is better during the winter months when more heat is supplied to the consumers and the heat losses are still kept at their stable level (as the ground temperature was taken to be constant). The electrical energy for pumping has, even after being scaled to the corresponding amount of thermal energy, a minor impact on the total heat lost in the system, which can be seen from Figure 5-16, where the monthly supply of heat and the energy losses are presented. The supplied heat is divided into heat for domestic hot water and space heating. The losses in the plot will naturally vary depending on how the design parameters are selected. The plot in Figure 5-16 presents the distribution with a district heat supply temperature of 70°C, a return temperature of 30°C, pipe insulation class 3, flow velocities not exceeding the recommended maximum velocities at any time and the pumping strategy using both pump locations selected.

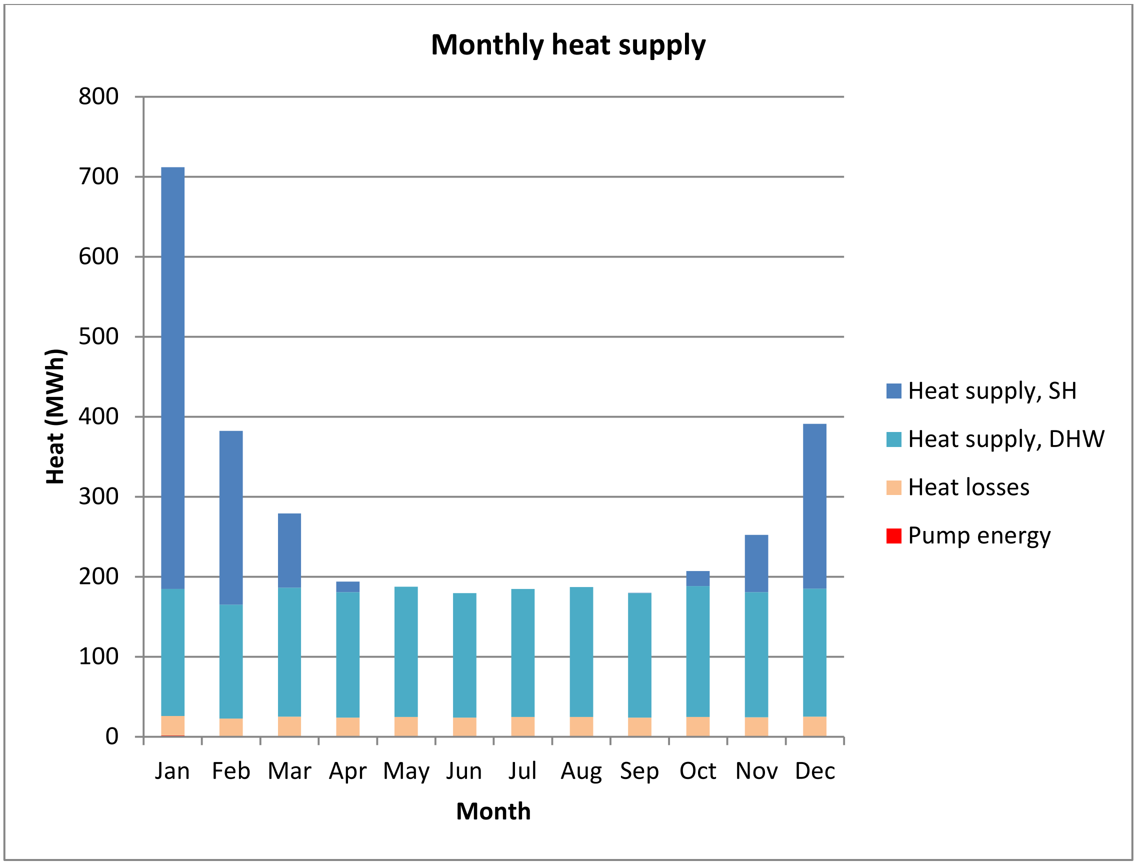

Figure 5-16. Simulated heat supply and energy losses in Honkasuo

Other results of the program are the pipe diameters used and the network volume. From the network volume and the heat demand also an average exchange time of the water in the network has been calculated to analyze if there is a correlation between the exchange time and the energy efficiency. If too high pressure drops occur in the network, the program reports it among the results.

Values used for running the simulations are listed in Appendix A.

5.3. Simulation of different distribution scenarios

By changing temperature levels, insulation thicknesses and allowed maximum flow velocities, different distribution scenarios can be studied. The results in terms of energy efficiency have been compared and also the pressure levels have been investigated for both pumping alternatives in order to verify, whether the scenario is feasible in practice.

A so called start scenario was first created. This scenario was in no way chosen to be the most efficient setup for heat distribution, but was rather selected as it reflects today's heat distribution relatively well. In the start scenario, the supply temperature was set to 90°C and the return temperature to 50°C. These values have been chosen as yearly average values, since the real temperature levels in district heating networks in Finland vary depending on the outdoor temperature (cf. Eq. 28). The third insulation class has been chosen in the start scenario and the flow velocities were kept under recommended maximum limits at all times during the year. Both pump stations were in use in the start scenario. Figure 5-17 presents the result sheet of the simulation, but the results will be discussed later.

Scenario		
Supply temperature level	*90*	*°C*
Return temperature level	*50*	*°C*
Insulation class	*Mpuk3*	
Allowed maximum flow velocity	*Recommended*	
Way of pumping	*Only from B*	

Results: Heat		
Max space heating demand	*2 228*	*kW*
Max heat demand for domestic hot water	*1 426*	*kW*
Max total heating demand	*3 654*	*kW*
Max heat loss	*47,6*	*kW*
Space heating demand per year	*1 185 004*	*kWh/a*
Domestic hot water heating demand per year	*1 776 407*	*kWh/a*
Total heating demand per year	*2 961 410*	*kWh/a*
Total heat loss per year	*416 810*	*kWh/a*
Total pump energy per year	*2 038*	*kWh/a*
Space heating demand per square meter per year	*19,8*	*kWh/m²/a*
Domestic hot water heating demand per square meter per year	*29,6*	*kWh/m²/a*
Total heating demand per square meter per year	*49,4*	*kWh/m²/a*
Total heat loss per square meter per year	*6,9*	*kWh/m²/a*
Top usage time	*810,5*	*h*
Network volume	*33,51*	*m³*
Average exchange time of water	*4,56*	*h*
Max condition pressure drop check	*OK*	
Relative loss of energy	*12,5*	*%*

Results: Pipes	
A-a	*DN125*
a-c	*DN125*
c-f	*DN125*
f-i	*DN125*
i-j	*DN125*
j-B	*DN125*
a-b	*DN65*
b-7	*DN65*
b-8	*DN50*
c-d	*DN65*
d-e	*DN50*
d-3	*DN40*
e-2	*DN40*
e-1	*DN50*
f-g	*DN65*
g-h	*DN65*
g-5	*DN50*
h-4	*DN50*
h-6	*DN50*
i-9	*DN40*
j-10	*DN65*
j-11	*DN50*
B-12	*DN50*
B-13	*DN50*

Figure 5-17. Results from start scenario

5.3.1. Insulation thickness impact

The first design parameter studied was the thickness of the insulation. In Finland, there are four standard classes of insulation thickness, but the first (i.e. thinnest) layer of insulating polyurethane has not been considered due to its insufficient ability to prevent heat loss. Two new scenarios were studied to assess the impact of the thickness of insulation on energy efficiency, cf. Figures 5-18 and 5-19. In the first scenario, the insulation class standard with slightly less insulating material was selected while the rest of the design parameters were as in the start scenario. In the second scenario, the fourth (and thickest) insulation class was selected. The simulations were done only for twin pipe constructions (Mpuk) since their ability to prevent heat loss is better than that of single pipes.

Scenario		
Supply temperature level	90	°C
Return temperature level	50	°C
Insulation class	Mpuk2	
Allowed maximum flow velocity	Recommended	
Way of pumping	From both sides	

Results: Heat		
Max space heating demand	2 228	kW
Max heat demand for domestic hot water	1 426	kW
Max total heating demand	3 654	kW
Max heat loss	57,4	kW
Space heating demand per year	1 185 004	kWh/a
Domestic hot water heating demand per year	1 776 407	kWh/a
Total heating demand per year	2 961 410	kWh/a
Total heat loss per year	502 724	kWh/a
Total pump energy per year	2 034	kWh/a
Space heating demand per square meter per year	19,8	kWh/m²/a
Domestic hot water heating demand per square meter per year	29,6	kWh/m²/a
Total heating demand per square meter per year	49,4	kWh/m²/a
Total heat loss per square meter per year	8,4	kWh/m²/a
Top usage time	810,5	h
Network volume	33,51	m³
Average exchange time of water	4,56	h
Max condition pressure drop check	OK	
Relative loss of energy	14,6	%

Results: Pipes	
A-a	DN125
a-c	DN125
c-f	DN125
f-i	DN125
i-j	DN125
j-B	DN125
a-b	DN65
b-7	DN65
b-8	DN50
c-d	DN65
d-e	DN50
d-3	DN40
e-2	DN40
e-1	DN50
f-g	DN65
g-h	DN65
g-5	DN50
h-4	DN50
h-6	DN50
i-9	DN40
j-10	DN65
j-11	DN50
B-12	DN50
B-13	DN50

Figure 5-18. Results from first scenario with changed insulation class

Scenario		
Supply temperature level	90	°C
Return temperature level	50	°C
Insulation class	Mpuk4	
Allowed maximum flow velocity	Recommended	
Way of pumping	From both sides	

Results: Heat		
Max space heating demand	2 228	kW
Max heat demand for domestic hot water	1 426	kW
Max total heating demand	3 654	kW
Max heat loss	41,3	kW
Space heating demand per year	1 185 004	kWh/a
Domestic hot water heating demand per year	1 776 407	kWh/a
Total heating demand per year	2 961 410	kWh/a
Total heat loss per year	361 430	kWh/a
Total pump energy per year	1 950	kWh/a
Space heating demand per square meter per year	19,8	kWh/m²/a
Domestic hot water heating demand per square meter per year	29,6	kWh/m²/a
Total heating demand per square meter per year	49,4	kWh/m²/a
Total heat loss per square meter per year	6,0	kWh/m²/a
Top usage time	810,5	h
Network volume	33,51	m³
Average exchange time of water	4,56	h
Max condition pressure drop check	OK	
Relative loss of energy	11,0	%

Results: Pipes	
A-a	DN125
a-c	DN125
c-f	DN125
f-i	DN125
i-j	DN125
j-B	DN125
a-b	DN65
b-7	DN65
b-8	DN50
c-d	DN65
d-e	DN50
d-3	DN40
e-2	DN40
e-1	DN50
f-g	DN65
g-h	DN65
g-5	DN50
h-4	DN50
h-6	DN50
i-9	DN40
j-10	DN65
j-11	DN50
B-12	DN50
B-13	DN50

Figure 5-19. Results from the second scenario with changed insulation class

5.3.2. Temperature level impact

In the next scenarios studied, the energy efficiency was improved by lowering the temperature levels in the system. In all the following simulations with changed temperature levels, the insulation class giving the best result so far (Mpuk4) was used.

The temperature levels were lowered stepwise from 90°C (supply)/50°C (return) to 80°C/40°C and 70°C/30° in order to study how much the relative loss of thermal energy was decreased. The lowest temperatures chosen are already close to the minimum levels, because the network has to be able to heat the consumers' domestic hot water to 58°C and 30°C is stated in Finnish regulations as the set point for return temperatures on the primary side of a district heating network [25]. These scenarios have the same difference between supply temperatures and return temperatures, which means that the same amount of heat can be extracted at equally large water flows. The results are presented in Figures 5-20 and 5-21. To study whether a larger temperature drop would be beneficial, a scenario with a higher temperature difference was also simulated. In this scenario, the supply temperature was 80°C and the return temperature 30°C. Since more heat is available in this setup, it will require lower flow rates, which will allow for smaller pipe diameters. The use of smaller pipes naturally generates less heat loss, but at the same time the potential to lower the supply temperature is smaller. Figure 5-22 presents the results of this simulation.

Scenario		
Supply temperature level	*80*	*°C*
Return temperature level	*40*	*°C*
Insulation class	*Mpuk4*	
Allowed maximum flow velocity	*Recommended*	
Way of pumping	*From both sides*	

Results: Heat		
Max space heating demand	*2 228*	*kW*
Max heat demand for domestic hot water	*1 426*	*kW*
Max total heating demand	*3 654*	*kW*
Max heat loss	*34,9*	*kW*
Space heating demand per year	*1 185 004*	*kWh/a*
Domestic hot water heating demand per year	*1 776 407*	*kWh/a*
Total heating demand per year	*2 961 410*	*kWh/a*
Total heat loss per year	*305 825*	*kWh/a*
Total pump energy per year	*1 917*	*kWh/a*
Space heating demand per square meter per year	*19,8*	*kWh/m²/a*
Domestic hot water heating demand per square meter per year	*29,6*	*kWh/m²/a*
Total heating demand per square meter per year	*49,4*	*kWh/m²/a*
Total heat loss per square meter per year	*5,1*	*kWh/m²/a*
Top usage time	*810,5*	*h*
Network volume	*33,51*	*m³*
Average exchange time of water	*4,56*	*h*
Max condition pressure drop check	*OK*	
Relative loss of energy	*9,5*	*%*

Results: Pipes	
A-a	*DN125*
a-c	*DN125*
c-f	*DN125*
f-i	*DN125*
i-j	*DN125*
j-B	*DN125*
a-b	*DN65*
b-7	*DN65*
b-8	*DN50*
c-d	*DN65*
d-e	*DN50*
d-3	*DN40*
e-2	*DN40*
e-1	*DN50*
f-g	*DN65*
g-h	*DN65*
g-5	*DN50*
h-4	*DN50*
h-6	*DN50*
i-9	*DN40*
j-10	*DN65*
j-11	*DN50*
B-12	*DN50*
B-13	*DN50*

Figure 5-20. Results from first scenario with lowered temperature levels

Scenario		
Supply temperature level	*80*	*°C*
Return temperature level	*30*	*°C*
Insulation class	*Mpuk4*	
Allowed maximum flow velocity	*Recommended*	
Way of pumping	*From both sides*	

Results: Heat		
Max space heating demand	*2 228*	*kW*
Max heat demand for domestic hot water	*1 426*	*kW*
Max total heating demand	*3 654*	*kW*
Max heat loss	*30,3*	*kW*
Space heating demand per year	*1 185 004*	*kWh/a*
Domestic hot water heating demand per year	*1 776 407*	*kWh/a*
Total heating demand per year	*2 961 410*	*kWh/a*
Total heat loss per year	*265 583*	*kWh/a*
Total pump energy per year	*1 486*	*kWh/a*
Space heating demand per square meter per year	*19,8*	*kWh/m²/a*
Domestic hot water heating demand per square meter per year	*29,6*	*kWh/m²/a*
Total heating demand per square meter per year	*49,4*	*kWh/m²/a*
Total heat loss per square meter per year	*4,4*	*kWh/m²/a*
Top usage time	*810,5*	*h*
Network volume	*25,46*	*m³*
Average exchange time of water	*4,33*	*h*
Max condition pressure drop check	*OK*	
Relative loss of energy	*8,3*	*%*

Results: Pipes	
A-a	*DN100*
a-c	*DN100*
c-f	*DN100*
f-i	*DN100*
i-j	*DN100*
j-B	*DN100*
a-b	*DN65*
b-7	*DN65*
b-8	*DN50*
c-d	*DN50*
d-e	*DN50*
d-3	*DN32*
e-2	*DN40*
e-1	*DN40*
f-g	*DN65*
g-h	*DN65*
g-5	*DN40*
h-4	*DN50*
h-6	*DN50*
i-9	*DN32*
j-10	*DN65*
j-11	*DN50*
B-12	*DN50*
B-13	*DN50*

Figure 5-21. Results from second scenario with lowered temperature levels

Scenario	
Supply temperature level	70 °C
Return temperature level	30 °C
Insulation class	Mpuk4
Allowed maximum flow velocity	Recommended
Way of pumping	From both sides

Results: Heat		
Max space heating demand	2 228	kW
Max heat demand for domestic hot water	1 426	kW
Max total heating demand	3 654	kW
Max heat loss	28,6	kW
Space heating demand per year	1 185 004	kWh/a
Domestic hot water heating demand per year	1 776 407	kWh/a
Total heating demand per year	2 961 410	kWh/a
Total heat loss per year	250 221	kWh/a
Total pump energy per year	1 883	kWh/a
Space heating demand per square meter per year	19,8	kWh/m²/a
Domestic hot water heating demand per square meter per year	29,6	kWh/m²/a
Total heating demand per square meter per year	49,4	kWh/m²/a
Total heat loss per square meter per year	4,2	kWh/m²/a
Top usage time	810,5	h
Network volume	33,51	m³
Average exchange time of water	4,56	h
Max condition pressure drop check	OK	
Relative loss of energy	7,9	%

Results: Pipes	
A-a	DN125
a-c	DN125
c-f	DN125
f-i	DN125
i-j	DN125
j-B	DN125
a-b	DN65
b-7	DN65
b-8	DN50
c-d	DN65
d-e	DN50
d-3	DN40
e-2	DN40
e-1	DN50
f-g	DN65
g-h	DN65
g-5	DN50
h-4	DN50
h-6	DN50
i-9	DN40
j-10	DN65
j-11	DN50
B-12	DN50
B-13	DN50

Figure 5-22. Results from third scenario with lowered temperature levels

5.3.3. Maximum flow velocity impact

Next, the effect of exceeding the recommended maximum flow velocities temporarily was studied. Every pipe diameter standard has its own recommendation regarding flow velocity (Table 4-2), but scenarios where these limits are multiplied by factors of 1.1, 1.3 and 1.5 were created to study the impact on energy efficiency of a relaxation of the constraints. As explained earlier, higher flow velocities give an option to use smaller pipe standards, which, in turn, leads to less heat loss. Since the network is dimensioned so that the highest acceptable flow velocity is reached during the modelled absolute peak demand, where the network's capacity is used to its maximum, the flow velocity would typically exceed the recommended limits by some tens of hours per year. If the outdoor temperature during a year does not go down to values around -26°C, the recommendations need not be exceeded at all, although the model allows higher velocities than recommended.

The problem arising from higher flow velocities is an increased pressure drop. Although all simulations indicate that increased flow velocities improve the network's total energy efficiency, also taking the pumping power requirement into account, the pressure limits were reached quite quickly when increasing flow velocities. Typically, the static pressure in a network is set to 6 bar while the maximum allowed pressure in the pipes is 16 bar. This means that a pressure drop of 10 bar is the highest acceptable one. A drop of 10 bar was therefore set as limit in the simulation program, and if this value is exceeded when distributing heat during the modelled maximum heat demand, the program will report it in the result sheet.

Even if the program reports that the pressure drop is too high, it does not mean that it is impossible to fulfill the scenario, but, rather, that some additional actions have to be taken during peak conditions. For example another pump, connected in series, can be placed at the point where the pressure level becomes critical. Another solution is to temporarily transfer more heat to the network of Honkasuo, and thus reach a higher supply temperature. This solution might be better, since heat is always available in the main pipeline from where heat is transferred and it does not require the investments an additional pump would. Peak conditions where a 10 bar pressure drop would be exceeded occur so rarely that it is expected that an increased allowed maximum flow velocity would improve the energy efficiency on a yearly basis.

Results of the three scenarios where the maximum acceptable flow velocity was stepwise increased are illustrated in Figures 5-23, 5-24 and 5-25. All these scenarios are based on the best simulation so far, in other words, the one where the supply temperature is set to 70°C, the return temperature to 30°C and the thickest insulation class is used. Larger factors than 1.5 were not studied due to the high pressure drops that were obtained.

Scenario		
Supply temperature level	70	°C
Return temperature level	30	°C
Insulation class	Mpuk4	
Allowed maximum flow velocity	Recommended*1,1	
Way of pumping	From both sides	

Results: Heat		
Max space heating demand	2 228	kW
Max heat demand for domestic hot water	1 426	kW
Max total heating demand	3 654	kW
Max heat loss	27,5	kW
Space heating demand per year	1 185 004	kWh/a
Domestic hot water heating demand per year	1 776 407	kWh/a
Total heating demand per year	2 961 410	kWh/a
Total heat loss per year	240 609	kWh/a
Total pump energy per year	1 908	kWh/a
Space heating demand per square meter per year	19,8	kWh/m²/a
Domestic hot water heating demand per square meter per year	29,6	kWh/m²/a
Total heating demand per square meter per year	49,4	kWh/m²/a
Total heat loss per square meter per year	4,0	kWh/m²/a
Top usage time	810,5	h
Network volume	25,97	m³
Average exchange time of water	3,53	h
Max condition pressure drop check	OK	
Relative loss of energy	7,7	%

Results: Pipes	
A-a	DN100
a-c	DN100
c-f	DN100
f-i	DN100
i-j	DN100
j-B	DN100
a-b	DN65
b-7	DN65
b-8	DN50
c-d	DN65
d-e	DN50
d-3	DN40
e-2	DN40
e-1	DN50
f-g	DN65
g-h	DN65
g-5	DN40
h-4	DN50
h-6	DN50
i-9	DN32
j-10	DN65
j-11	DN50
B-12	DN50
B-13	DN50

Figure 5-23. Results from first scenario with increased flow velocities

Scenario		
Supply temperature level	70	°C
Return temperature level	30	°C
Insulation class	Mpuk4	
Allowed maximum flow velocity	Recommended*1,3	
Way of pumping	From both sides	

Results: Heat		
Max space heating demand	2 228	kW
Max heat demand for domestic hot water	1 426	kW
Max total heating demand	3 654	kW
Max heat loss	27,1	kW
Space heating demand per year	1 185 004	kWh/a
Domestic hot water heating demand per year	1 776 407	kWh/a
Total heating demand per year	2 961 410	kWh/a
Total heat loss per year	237 493	kWh/a
Total pump energy per year	1 906	kWh/a
Space heating demand per square meter per year	19,8	kWh/m²/a
Domestic hot water heating demand per square meter per year	29,6	kWh/m²/a
Total heating demand per square meter per year	49,4	kWh/m²/a
Total heat loss per square meter per year	4,0	kWh/m²/a
Top usage time	810,5	h
Network volume	25,13	m³
Average exchange time of water	3,42	h
Max condition pressure drop check	OK	
Relative loss of energy	7,6	%

Results: Pipes	
A-a	DN100
a-c	DN100
c-f	DN100
f-i	DN100
i-j	DN100
j-B	DN100
a-b	DN65
b-7	DN65
b-8	DN50
c-d	DN50
d-e	DN50
d-3	DN32
e-2	DN40
e-1	DN40
f-g	DN65
g-h	DN65
g-5	DN40
h-4	DN50
h-6	DN50
i-9	DN32
j-10	DN65
j-11	DN50
B-12	DN50
B-13	DN40

Figure 5-24. Results from second scenario with increased flow velocities

Scenario	
Supply temperature level	70 °C
Return temperature level	30 °C
Insulation class	Mpuk4
Allowed maximum flow velocity	Recommended*1,5
Way of pumping	From both sides

Results: Heat		
Max space heating demand	2 228	kW
Max heat demand for domestic hot water	1 426	kW
Max total heating demand	3 654	kW
Max heat loss	26,8	kW
Space heating demand per year	1 185 004	kWh/a
Domestic hot water heating demand per year	1 776 407	kWh/a
Total heating demand per year	2 961 410	kWh/a
Total heat loss per year	234 534	kWh/a
Total pump energy per year	2 062	kWh/a
Space heating demand per square meter per year	19,8	kWh/m²/a
Domestic hot water heating demand per square meter per year	29,6	kWh/m²/a
Total heating demand per square meter per year	49,4	kWh/m²/a
Total heat loss per square meter per year	3,9	kWh/m²/a
Top usage time	810,5	h
Network volume	23,25	m³
Average exchange time of water	3,16	h
Max condition pressure drop check	TOO HIGH	
Relative loss of energy	7,5	%

Results: Pipes	
A-a	DN100
a-c	DN100
c-f	DN100
f-i	DN100
i-j	DN100
j-B	DN100
a-b	DN65
b-7	DN50
b-8	DN50
c-d	DN50
d-e	DN50
d-3	DN32
e-2	DN32
e-1	DN40
f-g	DN65
g-h	DN50
g-5	DN40
h-4	DN40
h-6	DN50
i-9	DN32
j-10	DN65
j-11	DN50
B-12	DN40
B-13	DN40

Figure 5-25. Results from third scenario with increased flow velocities

5.3.4. Pumping strategies

The scenario giving the best result, without the pressure drop at any time becoming too high, was the one where the recommended maximum velocities multiplied by a factor of 1.3 were allowed, the thickest insulation class was chosen and the temperature levels were set to 70°C (supply) and 30°C (return). This setup would thereby work efficiently when supplying the consumers from both pump locations. As explained earlier, the network still has to be functioning also if only one pump location is in use. By changing the last parameter, this scenario was created and simulated to find out if the pressure drop exceeded acceptable level, when supplying all the customers only from one pump location. Also the other scenarios with different flow velocities were tested to control if they were implementable in practice, when using one pump location.

For all scenarios, the maximum pressure drop will be slightly higher when using only one pump location. This would have a negative impact on the energy efficiency, since more electrical power would be needed for pumping, but the impact would still be small. The fact that the maximum pressure drop increases when using only one pump location is mostly due the longer distances between pumping point and consumer. The consumer that causes the highest pressure drop in the system is called the critical consumer, and usually placed furthest away from the pumping point.

Scenario		
Supply temperature level	70	°C
Return temperature level	30	°C
Insulation class	Mpuk4	
Allowed maximum flow velocity	Recommended	
Way of pumping	Only from B	

Results: Heat		
Max space heating demand	2 228	kW
Max heat demand for domestic hot water	1 426	kW
Max total heating demand	3 654	kW
Max heat loss	28,6	kW
Space heating demand per year	1 185 004	kWh/a
Domestic hot water heating demand per year	1 776 407	kWh/a
Total heating demand per year	2 961 410	kWh/a
Total heat loss per year	250 221	kWh/a
Total pump energy per year	1 933	kWh/a
Space heating demand per square meter per year	19,8	kWh/m²/a
Domestic hot water heating demand per square meter per year	29,6	kWh/m²/a
Total heating demand per square meter per year	49,4	kWh/m²/a
Total heat loss per square meter per year	4,2	kWh/m²/a
Top usage time	810,5	h
Network volume	33,51	m³
Average exchange time of water	4,56	h
Max condition pressure drop check	OK	
Relative loss of energy	7,9	%

Results: Pipes	
A-a	DN125
a-c	DN125
c-f	DN125
f-i	DN125
i-j	DN125
j-B	DN125
a-b	DN65
b-7	DN65
b-8	DN50
c-d	DN65
d-e	DN50
d-3	DN40
e-2	DN40
e-1	DN50
f-g	DN65
g-h	DN65
g-5	DN50
h-4	DN50
h-6	DN50
i-9	DN40
j-10	DN65
j-11	DN50
B-12	DN50
B-13	DN50

Figure 5-26. Results from the first scenario where only one pump was in use

Scenario		
Supply temperature level	70	°C
Return temperature level	30	°C
Insulation class	Mpuk4	
Allowed maximum flow velocity	Recommended*1,1	
Way of pumping	Only from B	

Results: Heat		
Max space heating demand	2 228	kW
Max heat demand for domestic hot water	1 426	kW
Max total heating demand	3 654	kW
Max heat loss	27,5	kW
Space heating demand per year	1 185 004	kWh/a
Domestic hot water heating demand per year	1 776 407	kWh/a
Total heating demand per year	2 961 410	kWh/a
Total heat loss per year	240 609	kWh/a
Total pump energy per year	2 137	kWh/a
Space heating demand per square meter per year	19,8	kWh/m²/a
Domestic hot water heating demand per square meter per year	29,6	kWh/m²/a
Total heating demand per square meter per year	49,4	kWh/m²/a
Total heat loss per square meter per year	4,0	kWh/m²/a
Top usage time	810,5	h
Network volume	25,97	m³
Average exchange time of water	3,53	h
Max condition pressure drop check	TOO HIGH	
Relative loss of energy	7,7	%

Results: Pipes	
A-a	DN100
a-c	DN100
c-f	DN100
f-i	DN100
i-j	DN100
j-B	DN100
a-b	DN65
b-7	DN65
b-8	DN50
c-d	DN65
d-e	DN50
d-3	DN40
e-2	DN40
e-1	DN50
f-g	DN65
g-h	DN65
g-5	DN40
h-4	DN50
h-6	DN50
i-9	DN32
j-10	DN65
j-11	DN50
B-12	DN50
B-13	DN50

Figure 5-27. Results from the second scenario where only one pump was in use

Scenario	
Supply temperature level	70 °C
Return temperature level	30 °C
Insulation class	Mpuk4
Allowed maximum flow velocity	Recommended*1,3
Way of pumping	Only from B

Results: Heat		
Max space heating demand	2 228	kW
Max heat demand for domestic hot water	1 426	kW
Max total heating demand	3 654	kW
Max heat loss	27,1	kW
Space heating demand per year	1 185 004	kWh/a
Domestic hot water heating demand per year	1 776 407	kWh/a
Total heating demand per year	2 961 410	kWh/a
Total heat loss per year	237 493	kWh/a
Total pump energy per year	2 135	kWh/a
Space heating demand per square meter per year	19,8	$kWh/m^2/a$
Domestic hot water heating demand per square meter per year	29,6	$kWh/m^2/a$
Total heating demand per square meter per year	49,4	$kWh/m^2/a$
Total heat loss per square meter per year	4,0	$kWh/m^2/a$
Top usage time	810,5	h
Network volume	25,13	m^3
Average exchange time of water	3,42	h
Max condition pressure drop check	TOO HIGH	
Relative loss of energy	7,6	%

Results: Pipes	
A-a	DN100
a-c	DN100
c-f	DN100
f-i	DN100
i-j	DN100
j-B	DN100
a-b	DN65
b-7	DN65
b-8	DN50
c-d	DN50
d-e	DN50
d-3	DN32
e-2	DN40
e-1	DN40
f-g	DN65
g-h	DN65
g-5	DN40
h-4	DN50
h-6	DN50
i-9	DN32
j-10	DN65
j-11	DN50
B-12	DN50
B-13	DN40

Figure 5-28. Results from the third scenario where only one pump was in use

5.4. Results and discussion

To be able to analyze the results from all simulations more easily, a table (Table 5-2) summarizing the most important results from every simulation has been made. The scenarios presented so far have been made according to the principle that a new case is based on the scenario with the least energy loss so far. However, the result table also presents a few other scenarios as it may be interesting to know how much the losses can be reduced, for instance without investing in pipes with the thickest and most expensive insulation. Insulation class 3 can be seen as the choice of today, while insulation class 4 might become conventional in the future.

In the table the pipe insulation class has been shortened to only a number between two and four, two being the next thinnest standardized layer of insulation and four the thickest. The highest allowed flow velocities have not been listed for every pipe standard in every simulation, but have instead been expressed with the factor by which the recommended maximum velocities are multiplied to obtain the modelled peak conditions. A unity factor thus indicates that recommended maximum velocities are not exceeded even at peak conditions.

The most important results from each simulation are presented in the colored cells of the table. The main purpose of the simulations is to determine the relative loss of energy and to reduce it, but also the pipe standard in the main pipeline is presented. The main pipeline is the largest pipeline in the network, connecting both pump locations. The relative loss of energy has only been presented for the cases where the pumps operate at both pumping points, but the value would be very similar for the case where only one pump is used. The maximum pressure drop presented in the table is based on the maximum peak values of the flows. Pressure drops exceeding 10 bar are colored red, indicating that the scenario in question is not feasible in practice without taking additional actions during absolute peak demands.

Table 5-2. Result summary of the heat distribution scenarios

Scenario		Supply temperature (°C)	Return temperature (°C)	Pipe insulation class	Max allowed flow velocity factor	Relative loss of energy (%)	Pipe standard in main pipe	Max pressure drop, 2 pump points (bar)	Max pressure drop, 1 pump point (bar)
Start	0	90	50	3	1	12,5	DN125	5,5	7,3
Insulation thickness impact	1	90	50	2	1	14,6	DN125	5,5	7,3
	2	90	50	4	1	11	DN125	5,5	7,3
Temperature level impact	3	80	40	3	1	10,8	DN125	5,5	7,3
	4	80	30	3	1	9,5	DN100	6,4	9,7
	5	70	30	3	1	9	DN125	5,5	7,3
	6	80	40	4	1	9,5	DN125	5,5	7,3
	7	80	30	4	1	8,3	DN100	6,4	9,7
	8	70	30	4	1	7,9	DN125	5,5	7,3
Max flow velocity impact	9	70	30	3	1,1	8,7	DN100	8,3	13,8
	10	70	30	3	1,3	8,6	DN100	9,3	14,5
	11	70	30	3	1,5	8,5	DN100	12,2	19,3
	12	70	30	4	1,1	7,7	DN100	8,3	13,8
	13	70	30	4	1,3	7,6	DN100	9,3	14,5
	14	70	30	4	1,5	7,5	DN100	12,2	19,3

The effect of added insulation thickness is clearly seen from the results. An increased insulation thickness yields a lower heat loss. Whether to choose the best insulated pipes is a question of investment cost. It can still definitely be said that the pipe type with the thinnest insulating should not be used since its heat loss factor is high.

As expected, the lower temperature levels reduce the losses. Interestingly, however, the scenario with a supply at 80°C and a return at 30°C is almost as energy efficient, since a smaller flow can carry the same energy, so smaller pipe diameters can be used. It can also be established that it is advantageous to cool down the flow as much as possible. In the scenarios, 30°C has been selected as the lowest return temperature. Colder return flows would naturally improve the energy efficiency even more, but in practice further cooling is not available as the temperature is close to the return temperature from the secondary circuit even in the case of underfloor heating.

It would still be realistic to assume a return temperature of 30°C and then plan for a sufficient, but not overestimated, temperature gap between supply- and return flows. The temperature gap that can be utilized is normally around 40°C, but at high demands also larger utilizable temperature differences would be possible. In essence, a higher design difference between the supply- and return temperatures also places higher requirements on the heat exchanging equipment.

To temporarily allow flow velocities exceeding recommendations would improve energy efficiency, but as can be seen from the table, problems with too high pressure drops will occur at peak conditions. Still, scenarios where the recommended velocities have been multiplied by 1.5 could be considered, as if pumps at the two locations were used simultaneously and the supply temperature were lifted. Note that the peak demand at which the maximum pressure drop was calculated is the modelled maximum demand, where the outdoor temperature is –26°C, the internal heat gains are absent and the use of hot water is at its maximum. According to the simulation, the maximum acceptable level of the pressure drop was not exceeded for any daily average heat demand value during the whole year, even though the network was dimensioned for a flow velocity exceeding recommendations by 50 % (i.e. a factor of 1.5). This indicates that only on few occasions additional heat would have to be transferred to the network and the supply temperature be increased. The required increase in the supply temperature under such conditions could be rather moderate, since the pressure drop limit was exceeded by only 2.2 bar when pumping from both directions. This scenario might be the most beneficial one, since it improves the energy efficiency to a very tolerable level and the option to temporarily exceed recommended maximum flow velocities allows for constructing the main pipeline of DN100 pipes instead of DN125 pipes, which lowers the investment costs.

Furthermore, it should be stressed that, due to the lowest temperatures in the consumers' secondary coils, it is easier to utilize an extended temperature interval between the supply- and return flows when the heat demand for hot water is high than when the space heating demand is high.

The simulations with higher flow velocities clearly indicated that there is a correlation between the water exchange time in the network and the thermal energy lost from the system. When contemplating this, the reasons become obvious. The shorter exchange time of water is caused by the smaller volume of the network, which, in turn, is due to the possibility to construct the network with smaller pipe standards causing less heat loss.

Two pump locations can naturally supply the area with heat more efficiently than one, according to all the simulations. Especially during peak conditions it is important to use both pumps in order to avoid critical pressure drops, particularly in cases where the supply temperature is not increased to extend the temperature interval.

The yearly energy for pumping presented in the simulation result sheets varies slightly even between scenarios where the flow velocities and utilizable temperature interval are kept the same. In theory, though, the energy should stay unchanged, but in implementing the model heat losses in the pipelines were compensated for by a slightly increased flow instead of taking into account that the water reaching the last consumer would be of slightly lower temperature. In other words, the required energy for the pumps will be lower for a setup where heat losses are prevented. The effect of the approximation introduced is still marginal.

Table 5-3 compares the simulated heat distribution scenarios with the heat distribution of today (selected as Scenario 0 in Table 5-2), illustrating how much room for improvement there is when it comes to heat distribution.

Summarizing the findings, the heat distribution in Honkasuo can, with smarter design and operation, be made up to 40 % more efficient compared to networks traditionally designed and operated. Even without investing in pipes with the thickest insulation, the energy efficiency can be improved by over 30 %. Since some of the scenarios with increased flow velocities indicated that additional actions have to be taken during peak conditions to avoid critical pressure drops, the efficiency improvement estimated for these scenarios will be somewhat exaggerated. This is so because the analysis has not taken into account the hours of the year when additional actions are needed. During these hours the energy efficiency of the system is lower, but the time is probably so short that the negative impact would be minor, and thus not affect the performance indices reported in the table.

Table 5-3. Comparison with heat distribution today

Scenario		**Supply temperature (°C)**	**Return temperature (°C)**	**Pipe insulation class**	**Max allowed flow velocity factor**	**Comparison with distri-bution today**
Heat distri-bution today	0	90	50	3	1	0,0 %
Insulation thickness impact	1	90	50	2	1	16,8 %
	2	90	50	4	1	-12,0 %
Temperature level impact	3	80	40	3	1	-13,6 %
	4	80	30	3	1	-24,0 %
	5	70	30	3	1	-28,0 %
	6	80	40	4	1	-24,0 %
	7	80	30	4	1	-33,6 %
	8	70	30	4	1	-36,8 %
Max flow velocity impact	9	70	30	3	1,1	-30,4 %
	10	70	30	3	1,3	-31,2 %
	11	70	30	3	1,5	-32,0 %
	12	70	30	4	1,1	-38,4 %
	13	70	30	4	1,3	-39,2 %
	14	70	30	4	1,5	-40,0 %

6. CONCLUSIONS

In building areas with decreased heat demands, it is important to distribute heat as efficiently as possible. With lowered heat demands, the relative share of heat loss increases, so especially in areas with low-energy buildings, actions to improve energy efficiency are essential. However, many of the simulated scenarios of heat distribution in the Honkasuo residential area indicated that district heating can be a highly competitive method for satisfying heat demands also in low-energy building areas, if the network is properly designed and operated smartly.

The distribution becomes less efficient, if the temperatures are kept at higher levels than 70°C (supply) and 30°C (return), especially during periods of low heat demands. In practice, it may be difficult to cool down very small flows to 30°C, but heat providers should always strive for reaching as low return temperatures as possible. According to Finnish regulations, this temperature is also the set point for the return flow. To reach this value in a short time, though, requires efficient heat exchanging equipment and correctly designed secondary coils. This explains why the return temperatures are often slightly higher in today's networks.

When the temperature levels' effect on energy efficiency was studied, the calculations showed that a system with a supply temperature of 80°C and a return temperature of 40°C results in 22 % higher heat loss than in a network with temperature levels set to 70°C and 30°C respectively. The traditional supply temperature setting in district heating networks in Finland gives a supply temperature of 110°C when the outdoor temperature reaches –22°C. As the return temperature is estimated to be only 40°C lower, the momentary heat loss in the network is almost 90 % higher compared to the case where the supply temperature is 70°C and the return temperature 30°C. This confirms the importance of not keeping unnecessarily high temperature levels in a district heating network. The results from an analysis on how to reduce heat losses in pipes can be studied in Appendix B.

Another conclusion that can be drawn from the simulations is that increased insulation thickness brings about a significant improvement in the energy efficiency of the district heating network. Still, also economic aspects have to be considered when the insulation thickness is selected.

The network should be constructed of pipes that have a sufficient diameter to be able to satisfy high heat demands, but an oversizing of the network has a clear negative impact on the energy efficiency, since larger pipes generate a greater loss of thermal energy. The relative heat loss during every month will be higher if unnecessarily large pipes are used; particularly during summer, when the heat distribution in the network is least efficient, the relative loss of thermal energy can reach intolerable levels. An undersized network is, of course, not anything to strive for, but if the capacity is not high enough at a demand peak, there is always the possibility to transfer more heat to the system by increasing the supply temperature. Supply temperature control could be an efficient means of coping with large spikes in the daily use of hot water, and also with exceptionally cold winter weather.

To stress the importance of not selecting too large pipe standards in a network, a few general comparisons were made. For instance, a single pipe of standard DN200, and in the insulation class with the thinnest insulation layer gives rise to up to 50 % more heat losses than a DN100 pipe in the same insulation class and that contains a flowing media of the same temperature. For twin pipes in a high insulation class, a DN200 pipe results in about 30 % more heat losses than a DN100 pipe. It is important to keep in mind that heat losses do not depend on the magnitude of the flow in a network. The heat losses as a function of pipe diameter are illustrated for different types of pipes in Appendix B.

When constructing a network with smaller pipe standards, there is still an increase in the required electrical power for pumping. However, as the analysis presented in chapter 5 demonstrated, this increase, even after scaling the power to heat by a factor of 2.5, is clearly lower than the thermal energy that would be lost if using pipe standards large enough to keep the flow velocity under recommended limits at all time. Of course, there is a limit below which it is no longer profitable to decrease the pipe diameters, but according to the simulations, the constraint regarding unacceptably high pressure drops will be violated earlier.

In general, it can be said that small pipe diameters and low temperature levels minimize the heat losses of the heat distribution system. As long as the difference between supply- and return temperature is kept unchanged, larger flows are not needed to transfer the same amount of heat as in traditional networks. It might be possible to lower the supply temperature below 70°C, but not much, since this heat source must be able to heat the domestic hot water to at least 58°C and some superheat is always required.

Although the relative loss of energy in the modelled district heating network in Honkasuo could be decreased to the tolerable level of about 8 %, it cannot be concluded whether district heating is efficient in any low-energy building area dominated by small detached houses. Every district heating network must be investigated separately, because the building- or inhabitation density plays a very important role for both energy efficiency and profitability. Although Honkasuo is not comparable to the city center in terms of inhabitation density, the buildings are smartly planned to be located close to each other to avoid long pipe stretches which would be detrimental for the energy efficiency. Also, the blocks of flats planned in the otherwise detached house-dominated region make the area denser and improves its energy efficiency. In sparsely populated areas, pipe distances become longer and the relative losses of energy may become unacceptably high, even if every design parameter is chosen optimally.

A higher level of everyday heat demand in the low-energy buildings would make the area denser in terms of energy and profit the distribution of district heat. This is why possibilities to operate appliances such as fridges and refrigerators with district heat are currently studied, for example in Sweden [10]. This would result in an increased heat demand, but the additional demand would be constant throughout the year and decrease the relative losses of thermal energy, especially during the summer months.

The energy efficiency improvements that made the simulated heat distribution in Honkasuo up to 40 % more efficient than with a traditional design and operation are not only transferable to low-energy building areas. Also traditional networks would be more efficient with lower temperature levels, thicker insulation and smaller pipe diameters.

7. SUMMARY

There are possibilities to make the distribution of district heat more efficient. As houses today are built more energy efficient and need less heat, higher requirements will be set on the future distribution of district heating to maintain both energy- and cost efficiency. With such efficiency-improving actions the concept of district heating can be maintained as a competitive heat source in areas with decreasing energy density.

In this thesis, the impact on energy efficiency of lowered temperature levels, thicker insulation and higher flow velocities in the district heating network was studied. By simulating different distribution scenarios for satisfying the heat demand in an area (Honkasuo), it was established that the relative loss of energy could be decreased to an acceptable level.

The selection of temperature levels clearly affects the energy efficiency in a district heating network. The lower the levels are set, the smaller is the heat loss. It is profitable for heat suppliers to strive for as low return temperatures as possible, but in practice it might be difficult to reach values below 30°C due to heat transfer limitations. The temperature in the supply pipes should be selected so that sufficient amounts of heat can be extracted from the flowing media. Assuming a temperature difference of 40°C between the supply- and return pipes would be logical, and this would mean that the supply temperature should be set to around 70°C.

The impact of the insulation thickness on energy efficiency was also clearly demonstrated. By adding insulation material, heat losses can be significantly reduced but naturally added insulation also leads to increased investment costs. By temporarily allowing for higher flow velocities than the recommended ones, smaller pipe diameters can be selected and also this would reduce heat losses. The conclusion that can be drawn here is that heat suppliers should be careful with oversizing a network, since unnecessarily large pipe diameters result in larger heat loss and higher investment costs. In the Honkasuo case, the maximum acceptable pressure drop dictated the limitation on how small the pipe diameters could be. Also, the increased power demand for pumping that is a result of the smaller pipe diameters and higher flow velocities might become the limiting factor.

Since the energy density varies in different types of residential areas, every district heating network should be investigated separately with respect to energy efficiency and profitability. Although the simulated heat distribution to Honkasuo must be considered efficient, one cannot make a general claim that district heating is a competitive heat source in all residential areas dominated by low-energy buildings because of variations in energy density. Long distances between buildings lead to longer pipe stretches, which, in turn, increase the loss of energy. However, with certainty it can be said that district heating should be included as an option when efficient heat sources for a residential area with low-energy buildings are evaluated.

SWEDISH SUMMARY

SVENSK SAMMANFATTNING

Byggnader görs idag allt energitätare och värmebehovet i nybyggda hus blir ständigt lägre än tidigare. Det kan leda till att valet av lämpliga värmekällor förändras, och det kommer framför allt kräva att distribution av fjärrvärme görs effektivare för att både energi- och kostnadseffektivitet ska kunna bibehållas för leverantörer av fjärrvärme. Orsakerna till att ett minskat värmebehov hos fjärrvärmeanslutna kunder leder till sämre effektivitet och lönsamhet hos leverantörer bottnar i de ökade relativa värmeförlusterna. Effektivare fjärrvärme skulle också göra metoden för uppvärmning konkurrenskraftigare i områden med allt glesare bebyggelse och energitäthet.

Syftet med denna avhandling var att kartlägga möjligheterna att förbättra energieffektiviteten i framtida fjärrvärmenät. Efter att ha begrundat lågenergibebyggelse i allmänhet och redogjort för grundläggande teori om hur fjärrvärmenät dimensioneras, har fjärrvärmedistributionen till ett planerat område med lågenergihus simulerats. Området i fråga är Honkasuo, som är beläget i norra Helsingfors, och enligt planerna skulle de första husen i området byggas redan under den gångna hösten. Helsingfors Energi, som varit samarbetspartner i detta diplomarbete, kommer att förse området med fjärrvärme.

Innan någon simulering över värmetillförseln till Honkasuo kunde göras, modellerades värmebehoven för både rumsuppvärmning och bruksvatten. Både det maximala totala värmebehovet och variationerna i båda typerna av värmelaster fastställdes. Fjärrvärmenätet dimensionerades utgående från stadsplanens kartor, men vissa designparametrar programmerades som ställbara för att möjliggöra olika tänkbara distributionsscenarier. De ställbara designparametrarna i simuleringsprogrammet var temperaturnivåer, rörisoleringstjocklek och maximal flödeshastighet. Genom att simulera och jämföra olika distributionsscenarier för att tillfredsställa det modellerade värmebehovet i området, kunde det konstateras att de relativa energiförlusterna gick att sänka till en acceptabel nivå.

Simuleringar och beräkningar visade tydligt att valet av temperaturnivåer påverkar energieffektiviteten i ett fjärrvärmenät. Ju lägre temperaturnivåerna ställs, desto mindre blir värmeförlusterna. Det är lönsamt för värmeleverantörer att sträva efter så låga temperaturer som möjligt i returledningarna, men i och med värmetekniska begränsningar är värden under 30 °C svåra att uppnå. Temperaturen i framledningen bör i sin tur väljas så att tillräckligt med värme kan tas tillvara från det strömmande mediet. En temperaturdifferens på cirka 40 °C mellan framledning och returledning är ett logiskt antagande och detta skulle innebära att framledningstemperaturen bör vara kring 70 °C.

Rörisoleringens inverkan på energieffektiviteten är även den tydlig. Genom att öka rörens isoleringstjocklek går värmeförlusterna att få ner märkbart, men naturligtvis medför ökad isoleringstjocklek även ökade investeringskostnader. Att i fjärrvärmenäten tillfälligt tillåta högre flödeshastigheter än de rekommenderade skulle innebära att mindre rördiametrar kunde användas och även detta skulle ge upphov till mindre värmeförluster. Slutsatsen som kan dras här är dock enbart den att värmeleverantörer ska akta sig för att överdimensionera fjärrvärmenät eftersom onödigt stora rördiametrar innebär både högre värmeförluster och investeringskostnader. Det maximalt tillåtna tryckfallet i fjärrvärmenätet fungerade i Honkasuos fall som en begränsning för hur små rördiametrar som kunde väljas. Också det ökade behovet av pumpenergi som högre flödeshastigheter medför kan komma att bli den avgörande begränsningen för hur små rörstandarder som kan väljas.

Då fjärrvärmetillförseln till Honkasuo simulerades på ett sätt som representerade dagens designval och driftinställningar, blev den relativa förlusten av energi under ett år 12,5 %. Med lägre temperaturnivåer, tjockare isolering och en aningen högre tillåten maximal flödeshastighet indikerade simuleringar att de relativa energiförlusterna gick att få ner till en nivå under 8 %. Det finns alltså möjligheter att minska de relativa energiförlusterna med upp emot 40 %. Förlusterna i fjärrvärmenät i dagsläget varierar inte bara under årets gång, utan även sinsemellan, beroende på olika faktorer. Energiateollisuus ry uppger dock att de relativa förlusterna i fjärrvärmenät i Finland varierar mellan 4 % och 10 %, och den simulerade värmetillförseln till Honkasuo kunde också placeras innanför det intervallet efter bättre designval och smartare drift.

I och med att energitätheten varierar i olika bostadsområden bör varje fjärrvärmenäts energieffektivitet och lönsamhet undersökas separat. Trots att den simulerade distributionen kunde göras effektiv i Honkasuo kan man inte med säkerhet säga att fjärrvärme är en konkurrenskraftig värmekälla för alla bostadsområden som domineras av lågenergihus då energitätheten kan variera. Långa avstånd mellan byggnader innebär längre rörsträckor och därmed större värmeförluster. Det som dock med säkerhet kan fastställas är att fjärrvärmedistributionen kan göras effektivare än vad den är på många håll i dagsläget och fjärrvärme kan vara ett effektivt alternativ även för bostadsområden med låg-energibebyggelse.

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APPENDIX A – Tables from simulation program

Tables from the simulation program are presented in this Appendix. Table A-1 contains determined parameters used in the calculations. These parameters can, however, vary from one case to another, and some parameters, like for instance the heat transmittances, will certainly change in the future.

In Table A-2 the maximum heat loads are listed for every heat consuming district. The area and the inhabitation of each district are approximated from the city plan. The maximum heat loads are decisive when dimensioning.

Table A-3 presents the determined length, capacity and maximum flow for each pipe element illustrated in Figure 5-15.

Table A-1. Calculation data in simulation program

Calculation data		
Parameter	Value	
Thermal conductivity of pipe insulation	0,03	W/(m°C)
Thermal conductivity of the ground	2	W/(m°C)
Heat transfer coefficient of the ground	12	W/(m²°C)
Depth of heat pipe	0,8	m
Average ground temperature	5	°C
Outdoor dimensioning temperature	-26	°C
Indoor temperature	21	°C
Average temperature of incoming water (DHW)	8	°C
Temperature of provided domestic hot water	58	°C
Variance in heat required for domestic hot water	256	kW²
Specific heat capacity for water	4,18	kJ/(kg°C)
Specific heat capacity for air	1,005	kJ/(kg°C)
Density of water	990	kg/m³
Density of air	1,2	kg/m³
Heat transmittance value for roofs	0,06	W/(m²°C)
Heat transmittance value for walls	0,1	W/(m²°C)
Heat transmittance value for floors	0,09	W/(m²°C)
Heat transmittance value for windows and doors	0,85	W/(m²°C)
Ceiling hight	3,2	m
Heat recovery efficiency	0,65	
Air exchange for ventilation	0,4	1/h
Leakage factor	0,18	1/h
Kinematic viscosity of water	6E-07	m²/s
Pipe roughness	0,0001	m
Pump efficiency	0,6	
Max allowed pressure drop over pumps	1000	kPa
Pressure drop in network heat exchanger	50	kPa
Heat gain, people	1,4	W/m²
Heat gain, electricity	5	W/m²
Heat gain, DHW	1,7	W/m²
Heat gain, solar	Varying	

Table A-2. Maximum heat load calculations in simulation program

District data				Max heat load, space heating				
District	Area [m²]	Inhabitation density [m²/pers]	Inhabitants [pers]	Heat loss, conduction [W/(m²,°C)]	Heat loss, ventilation [W/(m²,°C)]	Heat loss, leakage [W/(m²,°C)]	Heat loss, total [W/(m²,°C)]	Max SH demand [kW]
1	3600	41,3	87	0,42	0,15	0,19	0,76	129,4
2	2300	41,3	56	0,42	0,15	0,19	0,76	82,7
3	2000	41,3	48	0,42	0,15	0,19	0,76	71,9
4	4000	41,3	97	0,42	0,15	0,19	0,76	143,8
5	2800	41,3	68	0,42	0,15	0,19	0,76	100,6
6	6000	41,3	145	0,42	0,15	0,19	0,76	215,6
7	9550	41,3	231	0,42	0,15	0,19	0,76	343,2
8	5800	41,3	140	0,42	0,15	0,19	0,76	208,5
9	1500	41,3	36	0,42	0,15	0,19	0,76	53,9
10	11025	41,3	267	0,42	0,15	0,19	0,76	396,3
11	5565	41,3	135	0,42	0,15	0,19	0,76	200,0
12	3990	41,3	97	0,42	0,15	0,19	0,76	143,4
13	3870	41,3	94	0,42	0,15	0,19	0,76	139,1
1...13	62000	41,3	1500	0,42	0,15	0,19	0,76	2228,4
1, 2, 3	7900	41,3	191	0,42	0,15	0,19	0,76	283,9
4, 5, 6	12800	41,3	310	0,42	0,15	0,19	0,76	460,0
1, 2	5900	41,3	143	0,42	0,15	0,19	0,76	212,1
4, 6	10000	41,3	242	0,42	0,15	0,19	0,76	359,4
7, 8	15350	41,3	371	0,42	0,15	0,19	0,76	551,7
Total	62000		1500					2228,4

	Max heat load, domestic hot water					Max heat load, total	
District	Max hot water flow per pers [l/(s,pers)]	Avg hot water flow per pers [l/(s,pers)]	Max heat for DHW per pers [kW/pers]	Avg heat for DHW per pers [kW/pers]	Max DHW demand [kW]	Max total heat demand [kW]	Max flow to disrict [l/s]
1	0,2	0,0006	41,4	0,124	309,5	438,9	2,65
2	0,2	0,0006	41,4	0,124	245,6	328,3	1,98
3	0,2	0,0006	41,4	0,124	228,6	300,5	1,82
4	0,2	0,0006	41,4	0,124	326,8	470,6	2,84
5	0,2	0,0006	41,4	0,124	271,8	372,4	2,25
6	0,2	0,0006	41,4	0,124	403,6	619,2	3,74
7	0,2	0,0006	41,4	0,124	515,1	858,4	5,19
8	0,2	0,0006	41,4	0,124	396,5	605,0	3,65
9	0,2	0,0006	41,4	0,124	197,3	251,2	1,52
10	0,2	0,0006	41,4	0,124	555,8	952,0	5,75
11	0,2	0,0006	41,4	0,124	388,0	588,1	3,55
12	0,2	0,0006	41,4	0,124	326,4	469,8	2,84
13	0,2	0,0006	41,4	0,124	321,3	460,4	2,78
1...13	0,2	0,0006	41,4	0,124	1425,6	3654,0	22,07
1, 2, 3	0,2	0,0006	41,4	0,124	466,1	750,1	4,53
4, 5, 6	0,2	0,0006	41,4	0,124	601,6	1061,6	6,41
1, 2	0,2	0,0006	41,4	0,124	400,1	612,1	3,70
4, 6	0,2	0,0006	41,4	0,124	527,8	887,2	5,36
7, 8	0,2	0,0006	41,4	0,124	662,8	1214,5	7,34
Total	0,2	0,0006	41,4	0,124	1425,6	3654,0	22,07

Table A-3. Pipe element data in simulation program

Pipe element data			
Pipe element	Length [m]	Max heat distribution [kW]	Max flow for heat distribution [l/s]
A-a	20	3654,0	22,1
a-b	60	1214,5	7,3
b-8	80	605,0	3,7
b-7	320	858,4	5,2
a-c	120	3654,0	22,1
c-d	65	750,1	4,5
d-3	60	300,5	1,8
d-e	60	612,1	3,7
e-2	80	328,3	2,0
e-1	150	438,9	2,7
c-f	185	3654,0	22,1
f-g	65	1061,6	6,4
g-5	110	372,4	2,2
g-h	65	887,2	5,4
h-4	125	470,6	2,8
h-6	110	619,2	3,7
f-i	105	3654,0	22,1
i-9	45	251,2	1,5
i-j	250	3654,0	22,1
j-10	260	952,0	5,8
j-11	95	588,1	3,6
j-B	85	3654,0	22,1
12-B	235	469,8	2,8
13-B	190	460,4	2,8

APPENDIX B – Heat losses for different types of pipes

Figures B-1 to B-8 show heat losses for different pipes and insulation classes, as a function of pipe diameter. The impact of the temperature levels chosen is illustrated with different curves in the figures.

The calculations behind the results depicted in the figures are based on the theory of section 4.2 with some approximated values. The thermal conductivity of the ground was estimated to 2 W/(m°C) and the thermal conductivity of the insulation to 0.03 W/(m°C). The heat transfer coefficient of the ground was set at 12 W/(m^2°C), the approximated depth of the pipe was 80 cm and the ground temperature was 5°C.

The first four figures (Figures B1 to B4) represent single pipe structures, abbreviated 2Mpuk, in four different insulation classes, while the last four figures represent twin pipe structures, Mpuk, likewise, in four different insulation classes. The insulation class is expressed with a number after the abbreviation of the pipe type. Number 1 denotes the thinnest layer of insulation while 4 denotes the thickest layer.

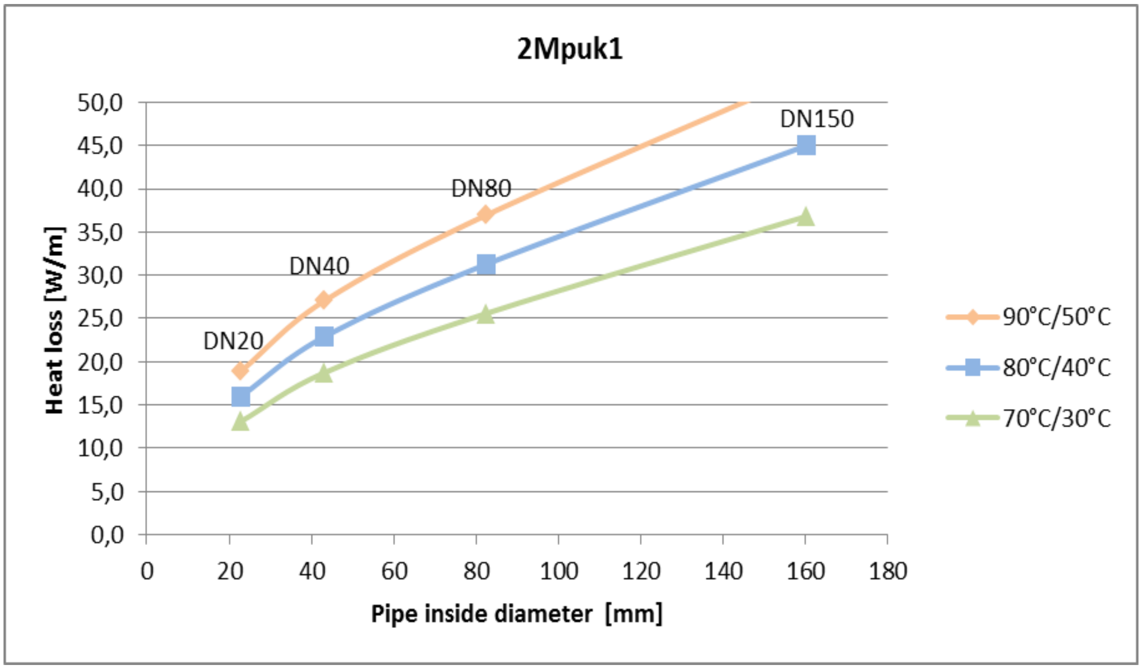

Figure B-1. Heat loss in single pipes of insulation class 1

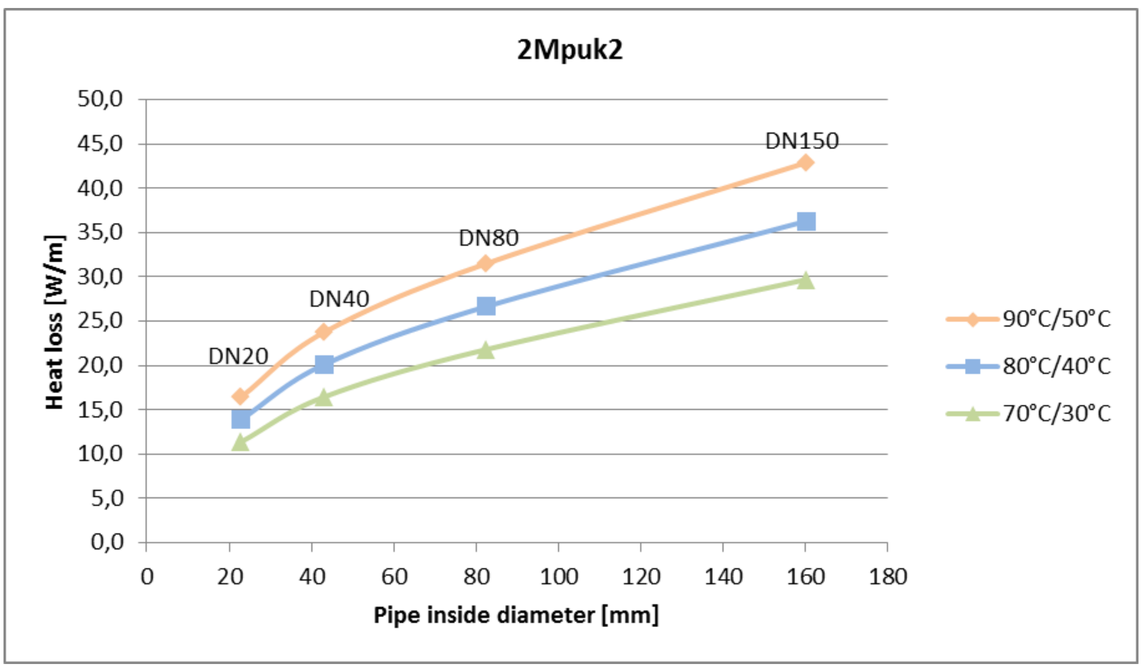

Figure B-2. Heat loss in single pipes of insulation class 2

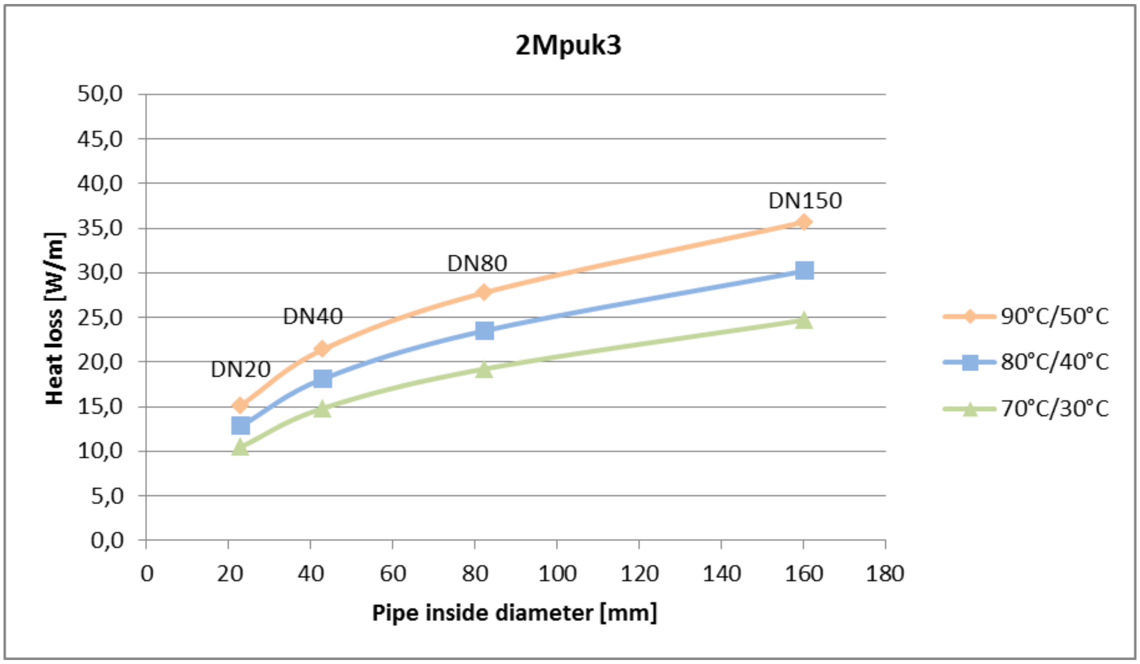

Figure B-3. Heat loss in single pipes of insulation class 3

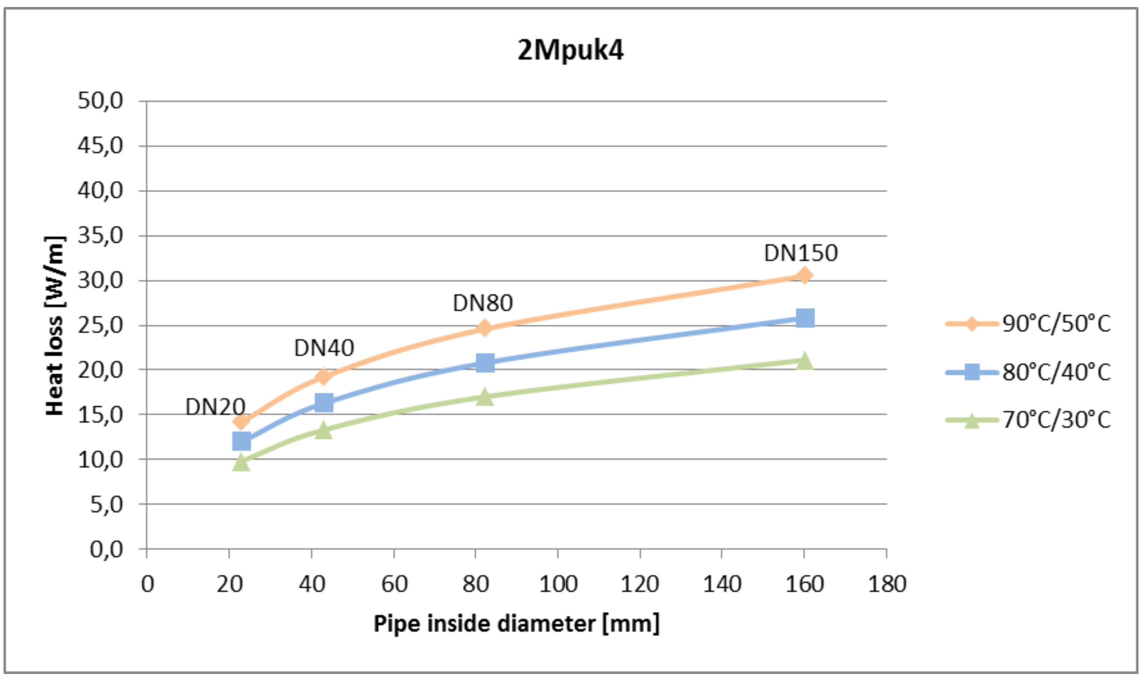

Figure B-4. Heat loss in single pipes of insulation class 4

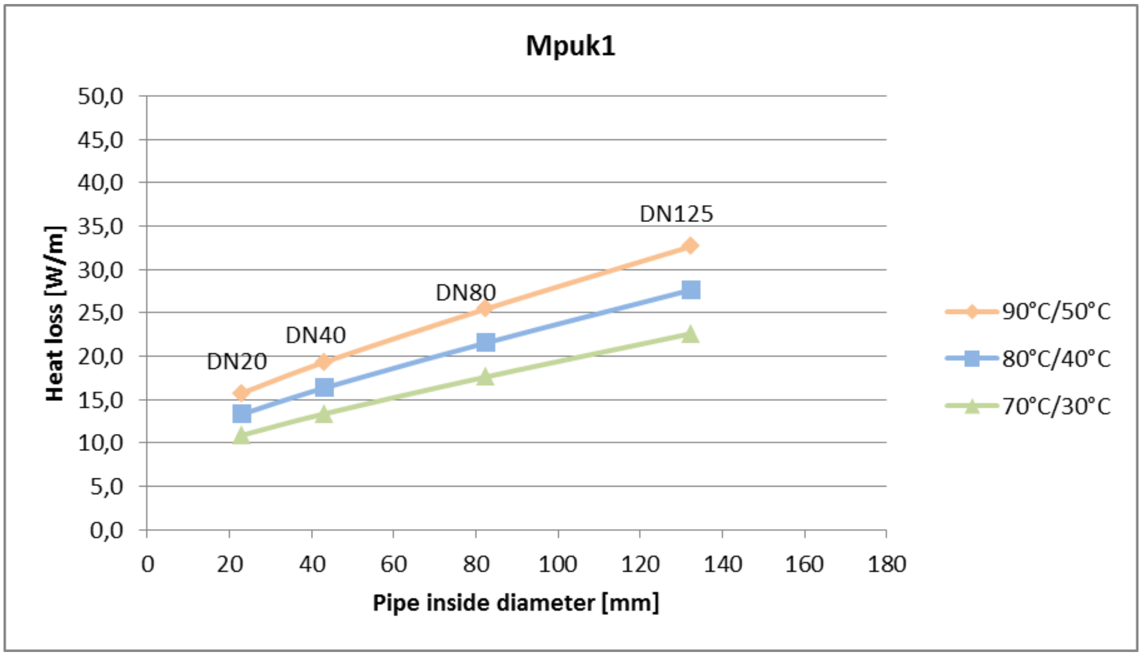

Figure B-5. Heat loss in twin pipes of insulation class 1

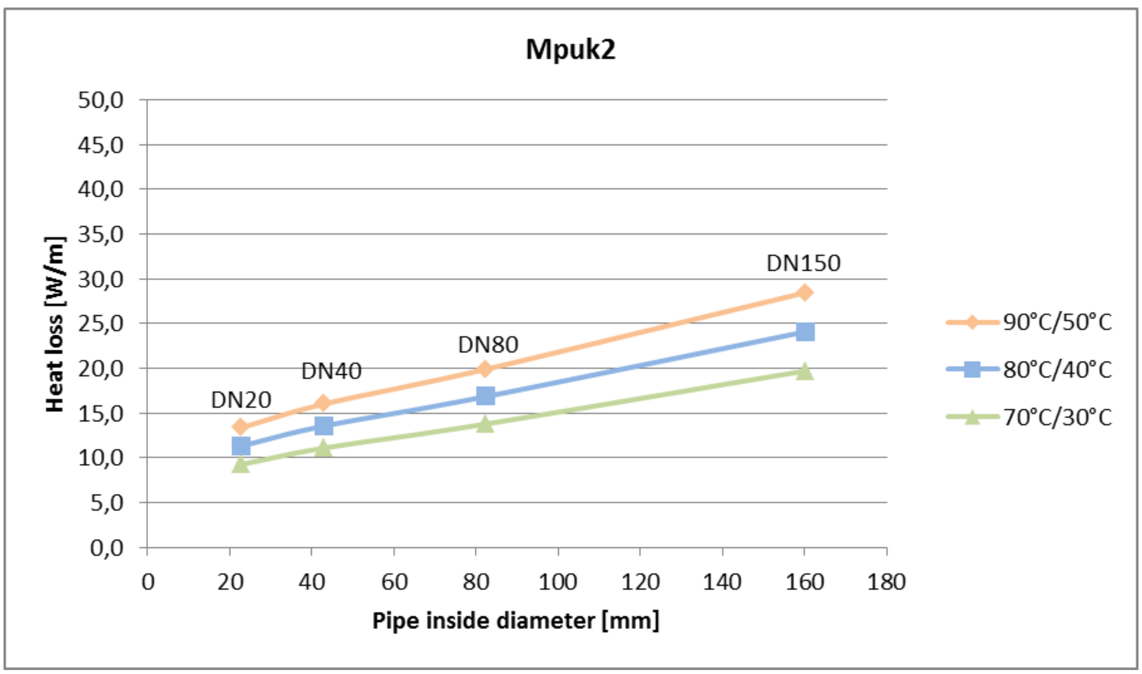

Figure B-6. Heat loss in twin pipes of insulation class 2

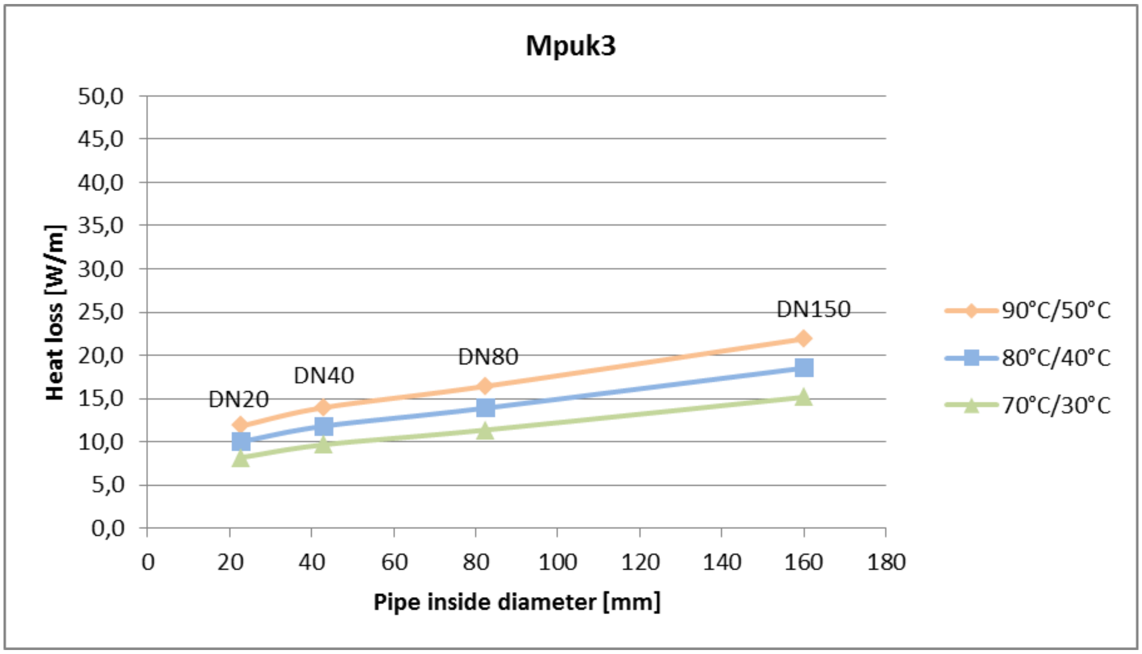

Figure B-7. Heat loss in twin pipes of insulation class 3

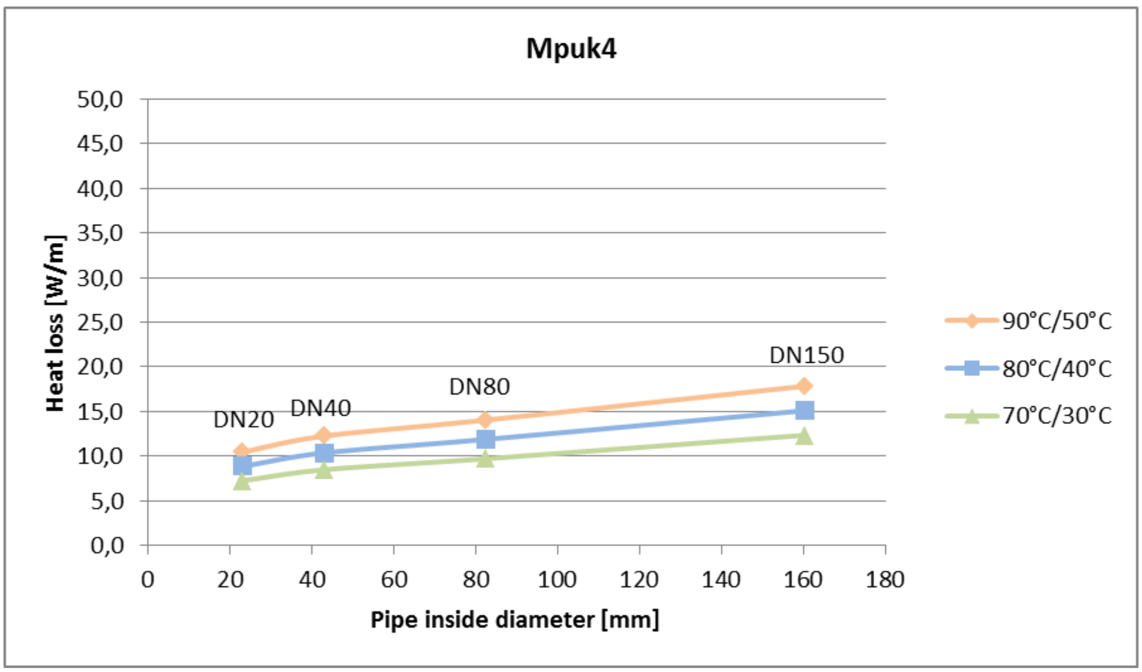

Figure B-8. Heat loss in twin pipes of insulation class 4