Optimisation of district heating production by utilising the storage capacity of a district heating network on the basis of weather forecasts

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Abstract

Seasons cause large variations in heating demand for buildings, and the heat is produced for district heating (DH) with several heat production plants. The network itself can be assimilated to a thermal energy storage unit and used effectively for peak reduction purposes. The heat storage balances the operation of the system, which allows smoother running of the entire energy production process. Short- and long-term storage enables the transition of current energy systems towards the next generation of low-temperature DH and sustainable multi-energy networks.

In this study, an example district heating system with two 4 MW boilers, located in Kymenlaakso, Finland was studied. The use of DH production was optimised by charging the network via adjusting the DH supply water temperature instead of using the reserve power. The savings potential depends on the variations in heat demand at the interface where the reserve power would have to be introduced, the size of the network volume, and the increase in the DH supply water temperature. On the basis of weather forecasts with an increase in the water temperature of 15 K, the received savings potential of reserve power could have been 185 MWh and the reduction of emissions 40 tCO_2 with renewable recycling-based wood fuels during the years 2018–2020 in the environmentally friendly case network.

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Keywords: heat storage, district heating, weather forecast

Nomenclature

c_p	specific heat capacity	J/(kgK)
H	depth of pipes in the ground	m
K	heat transfer coefficient	W/(mK)
L	length	m
Q	heat energy	J
R	thermal resistance	mK/W

T	temperature	°C, K
V	volume	m^3
Δ	delta (difference)	-
λ	thermal conductivity	W/(mK)
ρ	density	kg/m^3
Φ	heat loss	W
Abbreviations		
CHP	combined heat and power	
DH	district heating	
DN	nominal diameter	
PCM	phase change material	
Subscripts		
i	insulation	
r	return side of DH network	
s	supply side of DH network	
soil	soil	

1. Introduction

In Finland, the four seasons cause large variations in the demand for district heating. Because of that, the heat is produced for the district heating network with several heat production plants. These heating plants can be divided into base load plants, which are operated constantly, and reserve load plants, which are operated when the heat demand is greater than the base load plants can produce. The operation of reserve load plants is more expensive than the use of base load plants because peak loads are often produced with fossil fuels (natural gas, oil). The reserve load plant can be commissioned quickly when needed. In addition to higher operating costs, the use of reserve power often leads to higher carbon dioxide emissions.

In district heating production, consumption and production do not have to be fully balanced at all times, unlike, for example, electricity production and consumption. Changes in DH production and consumption are not immediately reflected in the operation of the district heating system, as the DH network itself stores thermal energy. The energy stored in the district heating network can be increased by temporarily raising the flow water temperature. Such an operation is called charging the district heating network.

The district heating networks intrinsically provide an opportunity to store heat energy. In the future, the significance of storing heat energy in the district heating network will increase, as it is an economical way to level out the peaks in heat demand and to minimise the use of reserve power. Utilising the heat storage capacity of the DH network can reduce the use of peak load plants and thus make economical savings on heat production but also reduce carbon dioxide emissions if the peak heat demand is produced with fossil fuels. In the beginning some results of a literature research is discussed related to the research of the corresponding heat storages.

Korpela et al. [1] analysed dynamic operability of interconnected combined heat and power (CHP) plants and district heating (DH). They found that rapid power level changes were disturbances to CHP production and DH networks.

According to Basciotti et al. [2] the district heating network itself can be assimilated to a large thermal storage unit and used effectively for peak reduction purposes. This is not applied systematically in existing networks. A DH network of Altenmarkt Austria was modelled in the simulation environment Modelica/Dymola to study the proposed control strategy. The results show a potential reduction of 15% of the daily peaks with an increase in heat losses of only 0.3% compared to the reference scenario.

Romanchenko et al. [3] applied a techno-economic optimisation model to the district heating system of Göteborg, Sweden. They investigated the benefits of applying thermal energy storage in DH systems to decrease heat load variations, comparing storage using a hot water tank and the thermal inertia of buildings with similar storage capacity. The results show that both the hot water tank and the thermal inertia of buildings benefit the operation of the DH system and have similar dynamics of utilisation. Compared to the thermal inertia of buildings, the hot water tank stores more than twice as much heat over the modelled year, owing to lower energy losses.

Gu et al. [4] proposed a model of transmission delay in district heating networks. The model of buildings was proposed and integrated as thermal storage units. A real heating system (24 nodes, 50 pipes) in Jilin province in China was used in the case study. The paper proposed an optimal operation model for an integrated energy system combining the thermal inertia of a DH network and buildings to enhance the absorption of wind power. The use of wind power is often restricted by the strong interdependence between the electricity generation and thermal energy generation of combined heat and power units, especially during winter, when CHP operates according to the heat-led mode.

Thermal storage ensures a heat reservoir for optimally tackling dynamic characteristics of district heating systems: heat and electricity demand evolution, changing energy prices, the intermittent nature of renewable sources, extreme weather conditions, and malfunctions in the systems. Guelpa & Verda [5] reviewed the implementation of thermal energy storage in district heating and cooling systems. Short- and long-term storage solutions were considered, highlighting their potential in combination with DH. The transition of current energy systems towards next generation district heating and sustainable multi-energy networks was considered.

Biomass combined heat and power plants connected to district heating networks are recognised as a very good opportunity to increase the share of renewable sources in energy systems. To extend the use of the CHP plants and reduce costs, conventional fuel use, and emissions, it is proposed to study the feasibility of using the DH network itself or additional high temperature heat storage to retrofit an existing CHP plant. Sartor & Dewallef [6] studied a method that provides accurate estimations of economic, environmental and energetic performances of CHP plants connected to DH networks. The district heating network of the University of Liège in Belgium was used as an application framework to demonstrate the effectiveness of the approach. The potential energy, pollutant emissions savings, and resulting energy costs were estimated.

Turski & Sekret [7] examined the impact of heat storage in buildings and district heating networks in terms of reducing the heat output from heat plants. In addition, the study analysed the effect of outdoor temperatures and the of duration periods of the lowest outdoor temperatures on the heat production of a district heating system. As a result, a reduction of 14.8 % in the heat output of heat sources was achieved. The results obtained were presented for the reference DH system in Poland.

Lesko et al. [8] demonstrated a mathematical model for operational optimisation of district heating. In the model, CHP production is simulated by storing the thermal energy in a hot water tank, as well as in buildings and DH network pipes.

Li & Wang [9] introduced a multi-agent (MA) approach to smooth the DH load by utilising the mass of buildings as thermal storage. The aim of the work was to equalise the heating demand of the building below the reference temperature without weakening the consumer's heat supply. The results of the study show that it is possible to achieve the mentioned goal by discharging and charging the thermal mass of the building.

In addition to traditional methods, there are reasons and benefits to using different kinds of energy storage technologies applied to buildings, including the following.

Using thermal energy storage is widely recognized to increase the efficiency of energy systems in different building topologies, to help introduce renewable energies in buildings and to reduce the energy demand for heating and cooling. Nowadays, different thermal energy storage technologies are available, including sensible, latent, and sorption and chemical reactions energy storage. [10]

Jouhara et al. [11] presented sensible heat storage, latent heat storage and thermochemical energy storage. Their article presents a classification of phase change materials (PCMs) according to their chemical nature as organic, inorganic and eutectic and by the phase transition with their advantages and disadvantages. Furthermore, the use of PCM materials, for example, in buildings was presented and the modelling tools for analysing the functionality of these materials were compared and classified.

In addition to optimising the DH production by different heat storage system on the basis of forecasts there are also methodologies for load forecasting and optimal sizing of PV (photo voltaic)/wind/battery hybrid renewable energy systems for electrification of remote areas [12].

One aspect of the issue is storing thermal energy in the district heating network for heating the areas, which has been the focus of this work.

This study is a continuation of the previous study [13]. As a one result of that study a new boiler plant was acquired that would be owned by waste company, using bio-based fuel in the Finland Kymenlaakso area. According to the study, the construction of a new boiler proved to be profitable. One of the reasons for profitability was that the waste company had a large reception of wood-based material, and it continuously receives the wood-based material for a gate fee, which means it charges for the fuel it uses for energy production. Based on the study the new boiler plant (2 x 4 MW) was built.

This study suggests how the operation of the new boiler plant can be optimised for district heating production by charging and discharging the DH network. The benefits of charging a district heating network are reviewed based on actual heat production data and outdoor temperatures from previous years. The district heating system is located in South-Eastern Finland, in Kymenlaakso.

2. District heating network in Kymenlaakso, Finland

The DH network located in Kymenlaakso, Finland, consists of a heating plant with two 4 MW boilers. The heating plant uses recycling-based wood fuels. The peak power for heating is produced with natural gas. The length of the district heating route is 21 940 m, and the total pipe volume of the network topology is 942.4 m^3. The network connection, location of the heating plant and reserve plants, as well as the main consumers are shown in Figure 1.

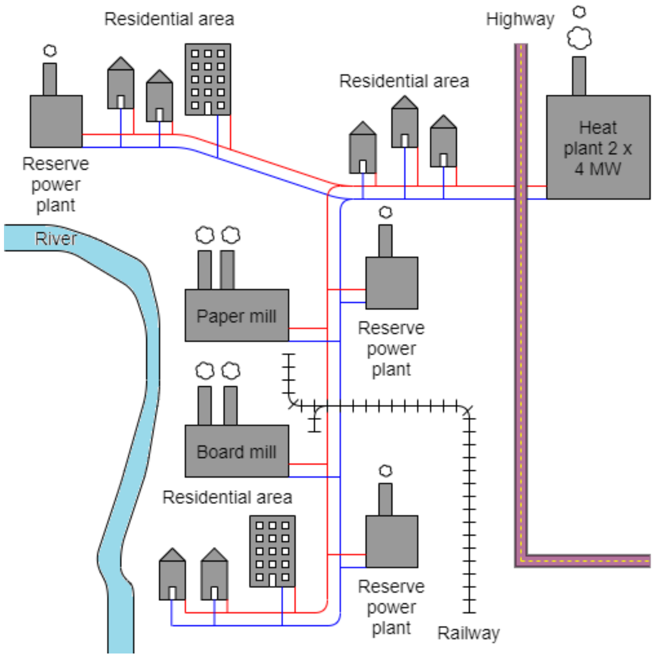

Figure 1. DH network located in Kymenlaakso Finland.

The heating area consists of three residential areas, where the district heating customers are residential and commercial buildings. Also, there are three reserve power plants in the district heating system, which acted as base load producers before the merging of the three regional district networks and the completion of the new heating plant. In addition, the district heating network is connected to plants in the paper and board industry, which supply the surplus heat generated in the process to the district heating network.

District heating power of the case network as MW (measured power) at different outdoor temperatures is presented in Figure 2. The heating power varied during the years 2018–2020 in different ambient conditions between 1 and 13 MW. In 2018, the need for heating was the highest and in 2020 the lowest. In 2018, the total production of the district heat in the area was 39 502 MWh and 34 591 MWh in 2020.

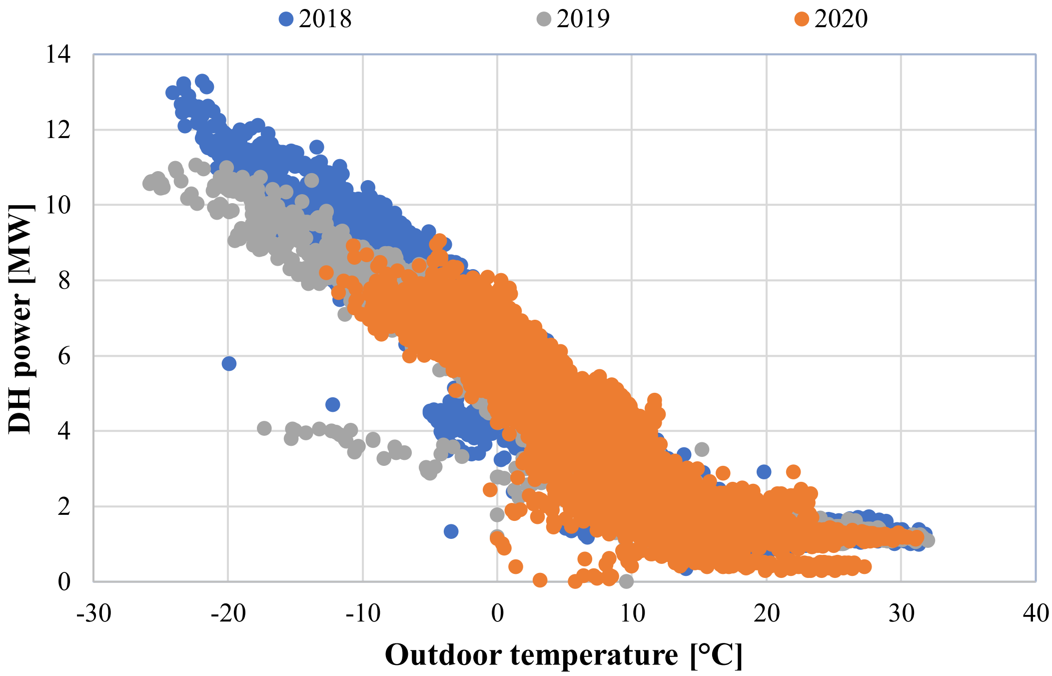

Figure 2. District heating power at different outdoor temperatures during 2018–2020.

Based on the actual heat productions (Figure 2) at the corresponding outdoor temperatures and the storage capacity of the DH network, the amount of energy that can be loaded in advance into the DH network in situations where reserve power should be used (heat demand > 8 MW) is determined. Actual, measured heat production data from 2018 to 2020 are used as initial values in the study.

3. Heat losses in the network

The storage of the heating energy in the district heating network causes increasing heat losses due to the higher flow water temperatures, which have to be taken into account when examining the storage of heat energy in the DH network. The magnitude of heat losses in the district heating network is affected by the temperature of the supplied water flow, the size of the district heating pipe, the thickness of the insulation and the location depth of the pipes. Smaller DH pipes (< DN150) have relatively higher heat losses than larger pipes due to the larger surface area in relation to heat energy transfer [14]. In this study, the heat loss calculations are performed for the DN100 pipe size, because it is an assumption of the average pipe size in this case for the entire district heating network.

The following initial values were used to calculate the heat losses in the district heating network: H = 0.9 m (depth of the district heating line in the ground), λ_{soil} = 2 W/(mK) (thermal conductivity of soil), λ_i = 0.029 W/(mK) (thermal conductivity of the polyurethane insulation), T_{soil} = 5 °C (temperature of the soil), and T_r = 50 °C (DH return water temperature). The dimensions of the inner and outer diameters of the insulation and the distance between the centres of the pipes for the DH pipe sizes DN25–DN200 are shown in Table 1 [14].

Table 1. Thicknesses of thermal insulation of district heating pipes and distances between centres of the supply and return pipes for DN25 – DN200

Pipe dimension	Insulator inner diameter [m]	Insulator outer diameter [m]	Distance between centres of pipes [m]
DN25	0.0337	0.1181	0.275
DN50	0.0603	0.1531	0.31
DN100	0.1143	0.2403	0.40
DN200	0.2191	0.3841	0.60

To determine the heat losses on the basis of the initial data, the thermal resistance of the soil R_{soil}, the thermal resistance of the insulator R_i, the mutual thermal resistance of supply and return pipes R_m and their inverses, and the heat transfer coefficients K_1 and K_2 were calculated [14], [15]. The thermal resistances and the heat transfer coefficients are shown in Table 2. In this case, the heat loss calculation was made for the average pipe size of the district heating network, DN100.

Table 2. Thermal resistances and heat coefficients for the heat loss calculation

R_{soil}	0.2154	[mK/W]
R_i	4.0780	[mK/W]
R_m	0.1216	[mK/W]
K_1	0.2331	[W/(mK)]
K_2	0.0066	[W/(mK)]

The heat losses in the district heating pipe can be determined from Equation 1:

$$\Phi = \Phi' \cdot L \tag{1}$$

where	Φ	heat loss	[W]
	Φ'	loss of heat flow per pipe length	[W/m]
	L	pipe length to be examined	[m]

The heat losses in supply and return pipes towards the pipe length can be determined from Equations 2 and 3 [14]:

$$\Phi_s' = (K_1 - K_2) \cdot (T_s - T_{soil}) + K_2 \cdot (T_s - T_r) \tag{2}$$

$$\Phi_r' = (K_1 - K_2) \cdot (T_r - T_{soil}) - K_2 \cdot (T_s - T_r) \tag{3}$$

where	Φ_s'	heat losses at supply side	[W/m]

Φ_r'	heat losses at return side	[W/m]
T_{soil}	temperature of the soil	[°C]
T_s	DH supply water temperature	[°C]
T_r	DH return water temperature	[°C]

The supply water temperatures and the heat losses in the district heating network based on the above formulas for normal operation (water temperature 90 °C) and for charging the district heating network (15 °C increase to flow water temperature) are presented in Table 3 as °C, W/m, kW/km and kWh/km (with 10 hours of charging time).

Table 3. Supply water temperatures 90 °C and 105 °C and heat losses as W/m, kW/km and kWh/km

Supply temperature	Heat losses		
°C	W/m	kW/km	kWh/km
90	29.45	29.45	294.5
105	32.84	32.84	328.4

Raising the district heating supply temperature from 90 °C to 105 °C increases the heat losses 33.9 kWh per one kilometre (11.5 %) in a DN100 pipe when the time frame for charging the district heating network is ten hours. Upon examination the total heat losses for the district heating network covered in the study were determined to be 0.74 MWh for the 10 hours' charging time.

4. DH network as a heat storage

Heat can be charged to the district heating network by raising the supply water temperature higher than the driving situation normally requires. The total amount of heat energy that can be stored in the DH network depends on the heat energy storage capacity of the network, which is affected by the volume of the DH network and the increase in the flow water temperature during storage compared with normal operation. The amount of energy that can be stored in the district heating network can be determined from Equation 4 [14] (equation modified).

$$Q = c_p \cdot \frac{V}{2} \cdot \rho \cdot (\Delta T) \tag{4}$$

where			
	Q	heat energy	[kJ]
	c_p	water specific heat capacity	[kJ/kgK]
	V	volume of the DH network	[m^3]
	ρ	density of water	[kg/m^3]

ΔT increase of water temperature [K]

The heat is stored solely in the pipe volume of the supply line, not in the volume of the return line. Therefore, in Equation occurs V/2, not V. The consumer devices regulate the flow so that the return water temperature remains almost unchanged [14].

The heat storage capacity for the district heating network was first calculated to be 151.67 kWh/km while using the average size of the studied district heating pipe (DN100). The increased heat losses caused by charging the network (33.9 kWh/km) were deducted from the charged energy and the final heat storage capacity was obtained (117.77 kWh/km). The final amount of the thermal energy stored in the district heating network in this example case is shown in Table 4 for the real pipes. The largest pipe lengths were implemented with pipe sizes of DN200, DN150, DN100 and DN250, respectively, in the network (Table 4). The temperature increase is always set to be 15 K in the calculations. However, even with lower temperature increases, the heat storage capacity of the district heating network can be utilised.

Table 4. Heat storage capacity of the case study's district heating network with a temperature increase ΔT of 15 K.

Diameter nominal	Length [m]	Volume [m^3]	Heat storage [MWh]
DN25	260	0.17	0.00
DN32	660	0.72	0.01
DN40	1820	2.66	0.04
DN50	1730	4.04	0.07
DN65	1050	4.08	0.07
DN80	520	2.78	0.05
DN100	2560	23.06	0.39
DN125	1590	21.92	0.37
DN150	2950	59.54	1.00
DN200	6400	221.88	3.74
DN250	2400	130.38	2.20

The total heat storage capacity of the DH network with the real pipes in the study was 7.19 MWh with the 15 K temperature increase. The heat losses were calculated for the DN100 pipe, when considering the entire district heating network area.

The potential of savings depends on the volume of the heat storage/district heating network, as well as the heat demand variation at the critical consumption point. *The critical consumption point refers to the consumption where the heat output produced by the base load plant is no longer sufficient to cover the heat demand.* In that case reserve power plants will have to be introduced to cover the heat demand. The savings potential also depends on the cost of heat production between base and peak load production, which is most affected by the price of the fuels used. Almost without exception, the heat production is cheaper when it is produced in base load plants compared to peak load plants.

The most significant benefit of charging a district heating network is cutting consumption peaks in situations where the consumption of heat energy from time to time exceeds the maximum capacity of the base load plants. *In this case, instead of using the reserve power, the district heating network could be alternately charged and discharged to obtain the necessary heat energy to the DH network.* The storage capacity can also be utilised in levelling out daily consumption peaks, as well as in situations where only one boiler is operated in spring and autumn or during maintenance and repair work.

5. Exploiting the potential for savings on the basis of weather forecasts

On the basis of the weather forecasts, consciousness added by the experience of operating the district heating system, and past heat production data, it is possible to anticipate changes in increasing heat demand by making the necessary changes to the heat production by charging the district heating network. By anticipating for changes in heat demand in advance, the customers are guaranteed an adequate supply of heat and thus the heat supplier can save on heat production costs by avoiding the use of reserve power. Figure 3 presents the district heating power of the case network as a function of the time, February 3-7, 2019. It shows how consumption peaks of more than 8 MW can be levelled out by importing the additional heat from the district heating network, when the DH network has been loaded in advance.

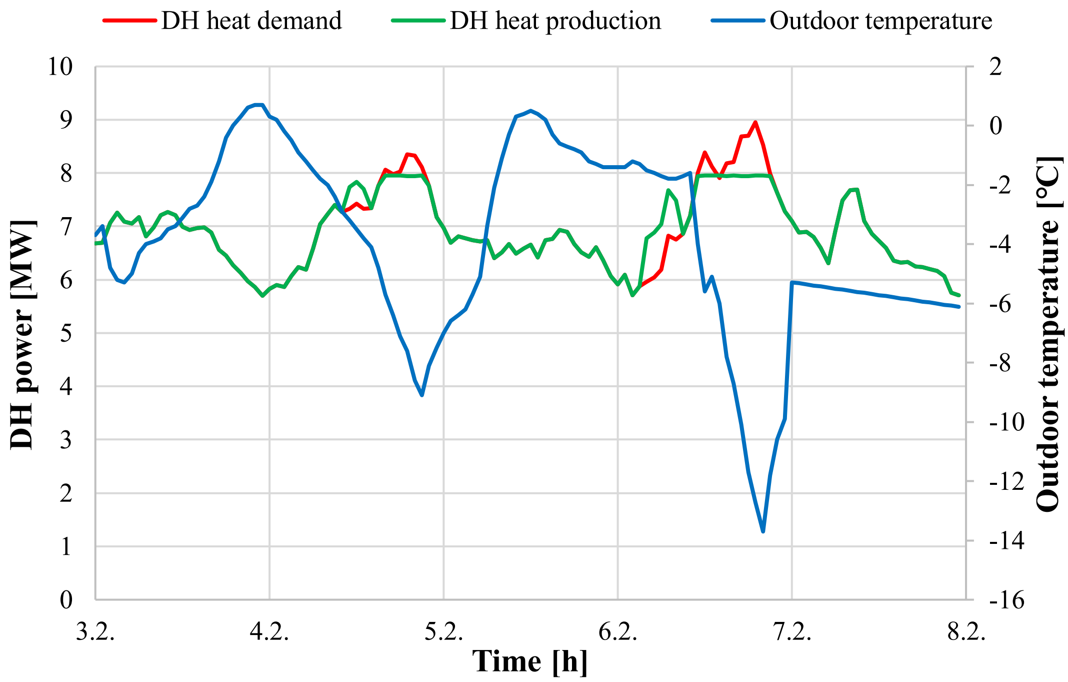

Figure 3. District heating power of the case network as a function of the time, February 3-7, 2019, and the levelling out of the consumption peaks by utilising district heating network storage capability.

The green line in Figure 3 represents the extra energy brought into the district heating network by charging it in advance. That extra energy is later utilised during the peak consumption period (more than 8MW of power). The areas formed between the green and red lines are the same size: when the green line is above the red line, the district heating network is charged, and when the green line is below the red, the energy is discharged from the district heating network (in which case the consumption peaks are leveled out).

The blue line of Figure 3 presents outdoor temperature, the red line the momentary district heating heat power demand (produced by the charged heat), and the green line the heat power production in the example situation, where the district heating network has been charged before the consumption peaks. In this example, on the morning of February 4, it is noticed that according to the weather forecast, frost is expected to intensify towards evening. Charging of the district heating network will start at 11:00 in the morning and about 1.2 MWh of heat energy will be charged into the network. The district heating network is discharged between 16:00 and 21:00 when the heat demand and the frost are at their strongest. Furthermore, it can be seen from the weather forecast that February 6 will be a particularly cold day. Charging of the district heating network will then start at four o'clock in the morning, and this time about 4.1 MWh of heat energy will be charged into the network. The charged heat energy is discharged evenly during the cold day. The district heating power thus remains below eight megawatts at all times, so there is no need to introduce reserve power plants. In Figure 3 the red heat demands (MWh) over the 8 MW are levelled out by the (green) power peaks (with the same MWh areas) charged moments before.

The annual energy savings potential of reserve power resulting from charging the district heating network can be determined by examining the heat production data for the entire year at a critical consumption point where the base load is no longer sufficient to cover the heat demand.

The savings potential to be achieved by charging the district heating network was determined from the hourly district heat production data for years 2018–2020. The heat production data were reviewed throughout the year, and whenever the need for heat production exceeded 8 MW (when the reserve power plant had to be commissioned), it was calculated how much the district heating network's own heat reservation (7.19 MWh/one charging cycle) could delay the commissioning of the backup heat plant. Or for shorter frost periods, no reserve power deployment would be required at all, as in Figure 3.

Table 5 shows how much energy savings could be made when the consumption peaks of more than 8 MW are levelled out with the stored heat energy in the district heating network throughout the years 2018 – 2020 (compare Figure 3) as follows: total DH production, DH production with reserve power, and the savings potential from the reserve power. However, it must be remembered that recharging the DH network with base power also consumes renewable fuel energy.

Table 4. Savings potential of reserve power and fuel costs from charging the district heating network in the years 2018 – 2020 in MWh/ and in €/a

Year	Total DH production [MWh/a]	DH production with reserve power [MWh/a]	Savings potential from reserve power [MWh/a]	Savings potential from fuel costs [€/a]
2018	39 501.80	1526.31	120.70	5983.10
2019	36 169.50	336.31	53.82	2780.88
2020	34 590.80	10.41	10.41	494.37

Table 5 depicts the available savings potential of the reserve power, which is possible to achieve by charging the district heating network and by using the weather forecasts. The total savings potential of reserve power (from natural gas) for the years 2018–2020 in the studied DH system was 185 MWh (Table 5). This equates to a total savings of around €9260 in fuel costs over the three-year period under review, using historical natural gas prices from the years 2018–2020 [16]. In calculating fuel cost savings, the price of the main boiler fuel (wood-based waste material) is assumed to be 0 €/MWh. In this case study they receive wood-based waste material for a gate fee, which thus means even greater savings in euros.

In the examined DH network, the significance of the storage of the heat will be small at the annual level due to the size of the DH network. However, the principle of heat storage presented in this study is suitable for use in any DH network. The significance of reducing CO_2 emissions and the energy savings potential is considerably bigger when operating bigger DH networks.

According to the results, the reserve power was used a lot in 2018 (1526 MWh) compared to other years. For this reason, 2018 would have had the greatest savings potential (120.70 MWh) in terms of minimising the use of reserve power (and emissions).

The savings potential really depends a lot on how much the heat demand fluctuates during the year at the critical consumption point. In 2018, there was significantly more variation in heat demand at the critical consumption point than in 2019 and 2020, which explains the difference in savings potential between these years. The year 2020 was an exceptionally warm year with only a few periods of severe frost. As a result, reserve power was not needed almost at all throughout the year, leaving the savings potential very low.

As summed from Table 5, the total savings potential from the years 2018 – 2020 in this district heating system could have been 185 MWh. The total CO_2 emissions could have been reduced by approximately 40 tons due to the charging of the district heating network, since the required heat power would have been produced with renewable fuels. To calculate the emissions, an emission factor of 199.1 g_{CO2}/kWh was used for the use of the natural gas and an emission factor of 0 for the wood-based fuel [17].

The amount of heat produced in the district heating network in normalised form and the corresponding outdoor temperatures arranged from the lowest to the highest value during the year 2019 are presented in Figure 4. Also indicative areas (heat production with the base power, from the charged the DH network, and with the reserve power) and their relations to each other are drawn in the figure, from each heating source.

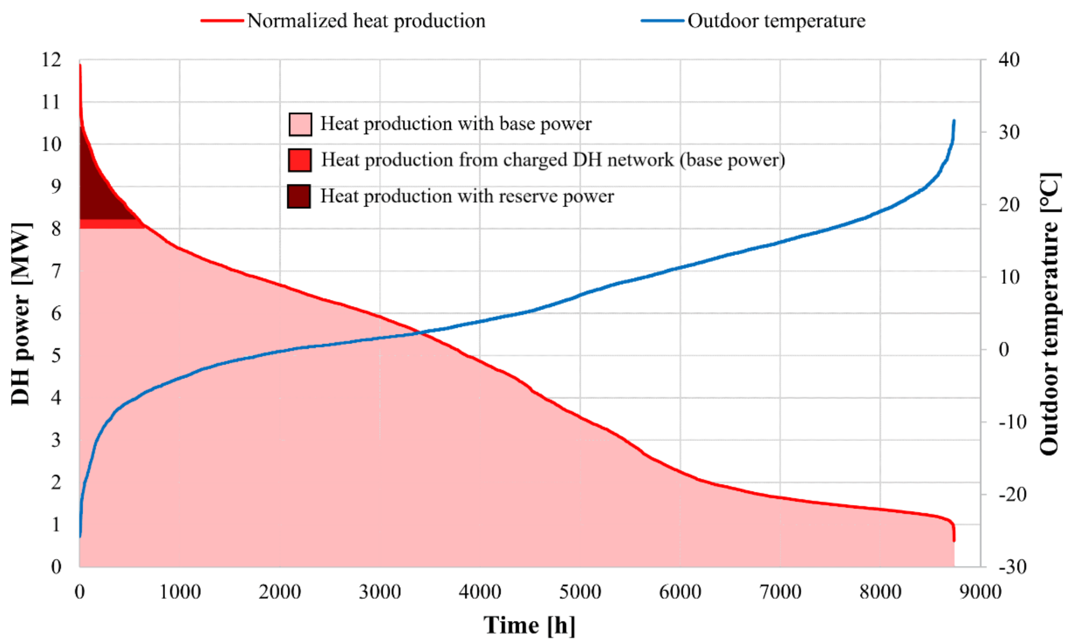

Figure 4. Normalised DH heat production and outdoor temperatures

The average amount of heat energy stored in the district heating network in one year is about 0.16 % of the total district heat production and about 41.3 % of the required reserve power production. The results presented above have been calculated with the production data from 2018–2020.

Figure 4 shows that the DH power demand is about 700 hours more than 8 megawatts over one year; converted into a continuous time, it makes about a month. During this time period, reserve power should be used to ensure sufficient heat for the customers. In actual fact, the real amount of the demand for reserve power varies from year to year mainly according to outdoor temperatures. Depending on the outdoor temperatures of the year and the length of the coldest periods, it is possible to reduce the use of reserve power produced by fossil fuels as sketched in Figure 3 and Table 5. As explained in the chapter, the annual amount of the heat production from the charged DH network was small due to the small size of the case network in the study, as shown in Figure 4.

6. Conclusions

A district heating (DH) system in Kymenlaakso, Finland, was investigated to minimise the use of reserve power, often produced by fossil fuels. The aim of the study was to optimise the production of DH systems by increasing the use of base load plants by charging the district heating network. The use of DH production was optimised by adjusting the DH supply water temperature.

The total heat storage capacity of the network was 7.19 MWh with the temperature rise of 15 K above the normal supply water temperature. Heat losses were calculated by using a mean diameter of pipes (DN100) for the entire DH topology. These heat losses increased by 11.5 % during the charging.

An economic savings potential depends on the cost of heat production between base and peak loads, which is affected by the price of the used fuels. The storage capacity of the network was utilised in levelling out daily consumption peaks, in situations where only one boiler is operated, or during maintenance and repair work.

The savings potential of reserve power and fuel costs from charging the DH network in the years 2018–2020 were calculated based on actual heat production data and outdoor temperatures from previous years. The total savings potential for the years 2018–2020 was 185 MWh, and €9260. The reduction of CO_2 emissions was 40 tCO_2 due to charging of the studied DH network with thermal power produced by renewable fuels.

The results of this study may prove to be useful for operating environmentally friendly DH systems in the future, leading to savings in heat production costs and the reduction of CO_2 emissions.

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