The Green District Heating System

Considering Heat Pumps and Storage
as a Future Danish District Heating Solution

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Preface

This project is written as an exam project in Energy Technology at the University of Southern Denmark. It is intended for peers and other potentially interested parties. It consists of different aspects of the Danish district heating system, including political goals, legislative aspects, financial aspects, an optimisation model for estimating future price of district heating, a heat storage analysis and a pipe flow analysis.

We would like to thank our supervisor Ashok Kumar Singh, Adjunkt, ph.d at the Mærsk McKinney Møller Institute, for supervision.

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Abstract

The purpose of this project is to analyse the possibilities of replacing the heat production from the coal-fired combined heat and power plant, *Fynsværket*, with heat pumps. It includes a review of the possibilities of integrating heat pumps in a district heating network. It also includes an analysis of including a heat storage facility and the heat loss that would occur in this solution and an optimisation model that optimises the production costs and the price of district heating using MATLAB. Additionally, an analysis of the heat and pressure losses in the pipes used in a district heating system is carried out. Legislative and financial aspects of shutting down power plants and installing heat pumps are considered. It is evaluated that it is realistic to replace *Fynsværket Blok 7* with heat pumps only. Other solutions, including alternative methods of heat production and alternative means of storage, are mentioned.

Contents

1 Introduction

A completely renewable district heating system by 2035 is one of the energy milestones of the Danish government. Another goal is to remove all coal-fired energy, both electrical and district heating, from the Danish energy sector by 2030.[1] Directives from the EU and the government's own goals call for a paradigm shift in terms of moving from commercial fossil based heat production technologies to renewable production facilities. This project aims to accommodate this paradigm shift for *Fynsværket*'s *Blok 7* (FV07), the only significant non-renewable production facility left in *Fjernvarme Fyn*'s supply area in order to make *Fjernvarme Fyn*'s heat-production completely renewable and thereby meet the commitments and goals of the Danish government. The point of departure for the project is FV07 and associated data, which creates a basis for:

- The heat price optimisation model
- Legislative and financial aspects
- Heat pump analysis
- Storage analysis
- Pipe flow analysis

The project's objective is to replace the remaining non-renewable heat production at FV07 with renewable heat produced by heat pumps, using electricity. Given the 2035 goal, electricity production will be completely renewable and therefore so will the heat produced by heat pumps. When replacing all non-renewable heat production at FV07, the hourly district heating production price is found using an optimisation model. From this price, a consumer price is determined. The model will be constructed so that the minimum district heating price of the new solution is found, under the assumption that only heat pumps and a heat storage can be used to cover the FV07 district heating production of 2010. The chosen storage technology is a water reservoir, dimensioned in accordance with the current heat storage at *Fynsværket*.

Heat pumps are the chosen heat production technology. An explanation and an analysis of the heat pump production cycle are given, to better understand the main production technology. Also, an explanation and possible areas of improvement of the heat pump coefficient of performance (COP) are presented, as well as the important aspects of implementing heat pumps in the current Danish district heating system.

The model determining the production price considers various parameters such as the heat pump COP, marginal costs, the electricity spot price and the average electricity price of 2014. In addition, storage parameters such as the marginal costs of the storage and maximum amount of heat stored in and extracted from the storage will affect the final heat price. From these parameters, the model will choose the optimal mix of heat extracted directly from the heat pumps and heat extracted from the storage, to meet the heat demand for each hour of 2010, with the objective of minimising the price that the consumer pays for district heating.

When producing heat with heat pumps, and given that the future Danish electricity grid mainly relies on fluctuating wind power, means of storing heat for later use when electricity is in shortage, are needed in order to always accommodate the district heating demand and maintain a high security of supply. Such a storage facility is analysed in the project. The analysis includes dimensioning of the storage. In addition, the maximum and minimum amount of energy in the storage are found. Heat loss from the storage is found from the insulation thickness, the storage medium and the ambient temperatures. From the heat loss and maximum amount of heat stored, an overall efficiency of the storage given a full storage over the course of an entire year is determined. The minimum amount of heat needed in the storage, for the district heating system to be able to extract heat from it, is found using a temperature gradient. Using the temperature gradient an amount of stored energy and a storage efficiency that varies with storage medium temperature is determined.

An analysis of a district heating twin pipe, as used in the Danish district heating transmission system, is carried out to find the pressure and heat loss from the pipe in a per-unit length notation.

When closing down FV07 in accordance with the Danish goals for 2035, technological and legislative challenges arise. These challenges are analysed and ideas to solve them presented.

The present Danish heat price, how it is determined and what it consist of is analysed and presented. Similar parameters for the future Danish heat price in a completely renewable energy sector are analysed. Also, when using heat pumps the heat price becomes dependent on the fluctuating, renewable electricity prices. The district heat price with electricity price dependence is presented and analysed.

How the course theory of the 4th semester is used in this project is explained in Appendix B.

2 The Danish District Heating System

In Denmark 64 % of all households are connected to the district heating system, which has approximately 430 district heating production facilities located all over the country, distributing the energy in a network of 60,000 km of piping. The main reason for having so many production facilities is that, unlike electricity, it is not possible to distribute district heating over long distances, as the heat losses in the pipes would be too large. Most district heating companies have several decentralised production facilities at their disposal, making it easier for them to meet the demand in a large supply area.[2]

It is mainly the more densely populated areas of the country that are supplied with heat from the district heating network, however, the system continuously expands; even to the households in *Area 4*[1]. Expanding the network makes the overall heat production more sustainable as district heating is the form of heat-production that emits the least amount of CO_2 [2]. The reason for this is that a large part of the energy in the district heating system originates from renewable sources.

One of the large district heating companies in Denmark is *Fjernvarme Fyn*, supplying approximately 80,000 households in Odense and environs. At *Fjernvarme Fyn*, only 35 % of the heat supply is generated from coal whilst the rest of the production originates from completely sustainable technologies. Figure 1 shows the various energy sources *Fjernvarme Fyn* uses to meet the district heating demand from the households in their supply area. This project revolves around these 35 %, supplied from FV07, at *Fynsværket* in Odense. FV07 is the only coal fired production facility in *Fjernvarme Fyn*'s supply area, so replacing its production with a renewable production technology, would make the district heating supply from *Fjernvarme Fyn* completely renewable.

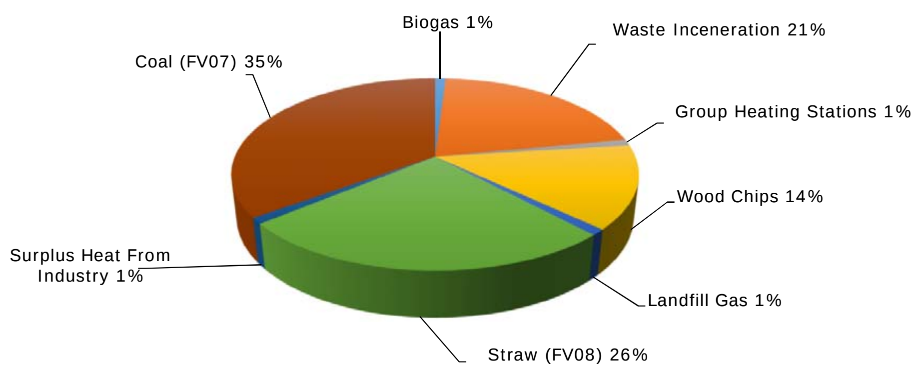


Figure 1: Illustration of the various district heating energy sources in *Fjernvarme Fyn*'s supply area in Odense and environs. [3]

[1] Area 4 (*In Danish: Område 4*): Area outside the public district heating network. Households in *Area 4* will typically provide themselves with heating from either an oil or pellet burner.

[2] Compared to heating by electricity, heat pumps and oil or natural gas boilers. The reason for heat pumps being mentioned here is that, if they are powered by energy from fossil fuelled technologies, e.g. CHP-plants, the overall emissions are not lowered. If they instead are powered by electricity from wind turbines, the overall emissions would be minimised.

In Figure 2, the boundary of the system analysed in this project is illustrated. Only FV07 and storage facilities are considered, the rest of the production facilities at *Fjernvarme Fyn*'s disposal are assumed to maintain their current production and the demand is assumed to be equal to the heat production at FV07 in 2010. The forward and return temperatures for the system are 80°C and 40°C respectively. These temperatures are chosen as they represent a valid assumption in terms of a maximum load scenario.[4] However, it is necessary to point out that these temperatures are not representative of the temperatures that actually appear in a district heating system over an entire year. Here they are used for simplification purposes, in reality, the forward temperature would fluctuate by as much as 25°C as the demand changes.

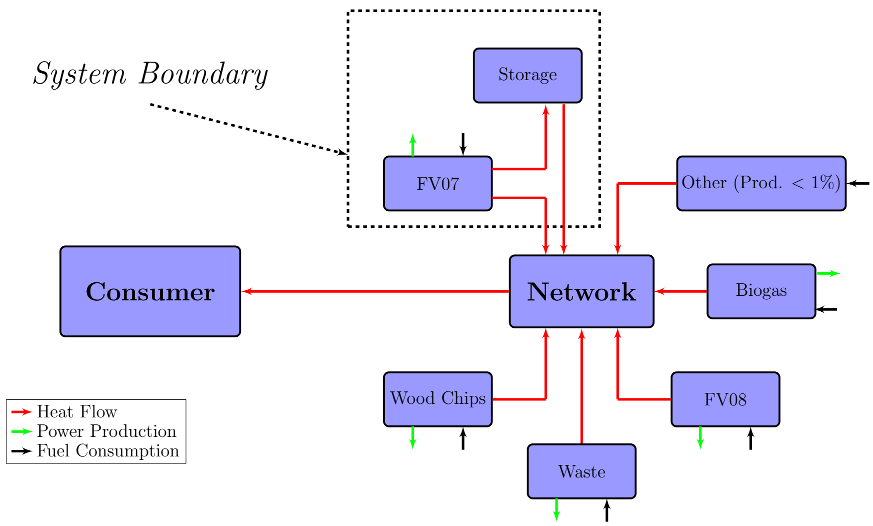


Figure 2: Illustration of the system analysed in this project. [5]

2.1 The Future District Heating Sector

The key idea in this project is to replace the heat demand covered by FV07 with renewably produced district heating. There is, however, one striking obstacle if FV07 is to be closed down. As it is a combined heat and power (CHP) production facility, a significant amount of electricity supply would be removed from the system. The solution to this problem has to be both a technologically and a politically viable solution. The legislation in the field is approaching its expiration date and needs a thorough review in order for the future district heating sector to function optimally.

The solution to the technological problems of closing down FV07 would be to install production facilities covering both the electricity and heating demand. According to *Energinet.dk*, the responsible authority for the security of supply of electricity in Denmark, a large expansion of the power grid will be completed by the year 2017, ensuring that the security of supply on Funen and in Odense is high enough for FV07 to be excluded from the power grid [6], making it unnecessary to install new electricity-producing facilities. This leaves the security of supply of district heating. To maintain a high security of supply and an optimally functioning grid, new production facilities have to be constructed. It would be optimal to construct the new facilities so that the already existing piping network could be utilised.

2.1.1 Climate Goals

According to the *EU Climate and Energy Package* from December 2008, Denmark is committed to have at least 30 % of their overall energy consumption covered by renewable energy sources before 2020. In addition, Denmark is also committed to cover 10 % of their energy consumption in the transportation sector with renewable sources. [7] The result of this commitment is the *Energy Agreement* of the 22nd of March 2012. The main points in this agreement are:

- A broad political support for an ambitious green transition with focus on reducing energy consumption and producing more renewable energy in form of more wind power, biomass and biogas.
- The agreement ensures a reduction of 12 % in gross energy consumption in 2020 compared to 2006, about 35 % renewable energy in 2020 and about 50 % of the Danish electricity consumption covered by wind power in 2020.
- This agreement is an important step towards the 2050 goal of converting all of Denmark's energy supply (electricity, heat, industry and transport) to renewable energy. [8]

These goals imply that a transition from fossil-fuelled production of district heating to a renewable one is necessary. If the current legislation regarding district heating and the production hereof is taken into consideration, some issues regarding the transition mentioned above begin to emerge.

Denmark is legally bound to meet the goals set forth by the EU. The government implements these goals into a national agreement. However, the Danish government has set higher goals than those they are committed to in the EU. For example, a part of the national agreement is to have 100 % renewable energy in the electricity and heat sector by 2035 and phasing out coal by 2030. This, however, is not a part of the EU package. The issue with this ambitious agreement is that the government may change its conditions at any time, by a majority in the Danish parliament. This makes Denmark an unsafe country for potential energy investors, when the circumstances for investments change in form of changing legislation and government goals.

2.1.2 The Legislative Aspects

The solution to the legislative problems of closing down FV07 would include alterations of the legislation on the area. Considering the purpose of *Varmeforsyningsloven*[3] §1 in main points, its purpose is to promote the most socio-economic and environmentally friendly supply of district heating and reduce the dependence on fossil fuels. This works well with the goals mentioned in section 2.1.1. However, *Varmeforsyningsloven* §1 art. 2 promotes co-production of electricity and heat and dictates that it has to be done as much as possible. This promotion of co-production is contradictory to the goal of district heating production by means of renewable sources because it implies the use of fossil fuels. In a future energy system, the heat production will most likely be by means of

[3] Varmeforsyningsloven - The Danish heat supply act.

converting electricity supplied by renewables into heat, i.e. with heat pumps.

Cf. *Varmeforsyningsloven* §4 the municipality has to approve new public heat supply installations or major changes in already existing installations. This means that, before closing any of the already existing plants, like FV07, it has to be approved by the municipality. Furthermore, cf. *Varmeforsyningsloven* §4 art. 2 in special cases an approval from the Minister for Energy, Utilities and Climate is needed, see also *Elforsyningsloven*[4] §11. This is because the security of supply of electricity and district heating has the highest priority and has to be maintained at a very high level at all times. From this, it can be seen that this transition is more of a political problem than a question of technical capacity.

2.1.3 The Dying Power Plants

Another aspect and problem with several central power plants in Denmark is that they need a lifetime extension within the next 5-15 years. A CHP plant is estimated to have a lifetime of 40 years, however, after about 25-30 years it is necessary to invest in a comprehensive lifetime extension. Focusing on *Fynsværket*, which was constructed in 1991, it is noticed that FV07 needs a lifetime extension within the next 5 years. However, regarding the energy package and government's energy policy goals, the plan is to phase out all coal-fired plants by 2030. This creates a major conflict for FV07. The extension has a cost of 400-800 million DKK depending on conditions and size. It is an enormous investment and risk and it is necessary to make a decision on whether to extend the lifetime of the power plants or to replace them with a renewable solution instead. [9]

2.2 Price Determination

The price of district heating for the consumer can vary a lot depending on the supplying district heating plant. The reason for this is mainly that all of the district heating companies are obligated, by law, to operate financially under the self-sustained principle, as all of the district heating companies are natural monopolies. This means that the price of district heating from each plant varies with its marginal costs for fuel, maintenance, investments and the supply area in relation to large-scale production advantages. Based on these expenditures each plant sets its own heat price, ensuring that the income equals the expenditures on a yearly basis. This heat price will be fixed for an entire year. In case the annual settlement gives a deficit or a profit, the divergence is to be taken account for in the proceeding year's heat price. The total price of district heating for the consumer consists of four parts: the energy charge, the transportation charge, the effect charge and the meter charge. Every part has its own significance.

The Energy Charge is determined from the temperature difference of the inlet and outlet flow for each household, that is the amount of energy extracted from the water. This charge is essentially the only income the district heating companies have to cover their marginal costs and this is therefore, the main reason that the district heating price varies from supplier to supplier.

[4] Elforsyningsloven - The Danish Electricity supply act.

The Transportation Charge is determined from the amount of water flowing through the household. The point of this charge is to create an incentive for a lower water consumption. This should increase the market for more efficient household appliances, that use less energy and also extract as much energy from the water as possible. This would result in the district heating companies having to circulate and heat less water.

The Effect Charge is a fixed annual contribution determined from the living floor space registered in *The Danish Building and Home Register* (BBR) [5]. This charge covers the expenses on maintenance of the network and the production facilities.

The Meter Charge is simply a fixed annual charge of rental and service of the measuring equipment in each household.

Fjernvarme Fyn provides district heating at a relatively low price. The main reasons for this are large-scale production advantages at *Fynsværket* and relatively low fuel costs for the various renewable production technologies. The total price for a standard household at *Fjernvarme Fyn* was 510 DKK/MWh in 2015.[10] This is the fixed price for an entire year and *Fjernvarme Fyn* must therefore predict their expenses a year ahead, as they must operate under the self-sustained principle. As the average price in Denmark is 546 DKK/MWh [11] the households in Odense and environs have a relatively low price for district heating.

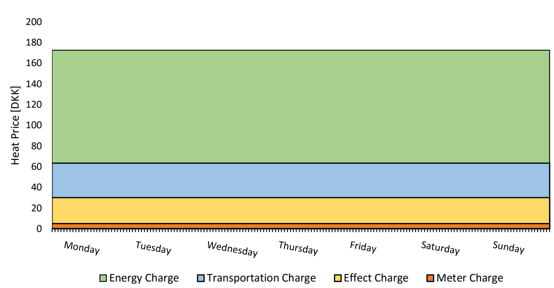
To lower the price at *Fjernvarme Fyn* even more, it is necessary to reduce the marginal costs. The marginal costs mainly consist of fuel costs, investment costs and maintenance costs. Since the latter is practically unchangeable and the investment costs are inevitable in an industry undergoing constant expansion, it could be interesting to lower or perhaps even eliminate the fuel costs. These fuel costs can, for FV07, essentially be divided into 2 parts; expenditures from buying coal and expenditures from purchasing CO_2-quotas. As FV07, in this project, will be shut down, these expenditures on fuel will no longer be due to purchasing coal as the energy source. The optimal solution for a new renewable production facility would be the one having the lowest fuel costs. One solution could be to construct another block at *Fynsværket* incinerating straw like *Blok 8* already does. This would require a large increase in the straw production solely for energy production purposes. This might raise ethical issues regarding the incineration of food and the prices within the food sector would end up competing with the heating sector for the available straw. This would most likely make the price of straw increase. Another way to meet the demand could be to increase the heat production from biogas or wood chips, but in both cases the fuel costs are relatively high.

In order to minimise the fuel costs the most, utilising the increasing electricity production could be a viable solution. According to the government's *Energy Political Statement 2015* the electricity production from wind turbines continues to increase and the price continues to decrease.[12] Essentially, the Danish energy sector will become completely electrified. Instead of exporting the excess electricity it could be utilised within the Danish borders, providing electricity to large industrial heat pumps. The fuel costs will then originate in the *Nord Pool* electricity price, making the price of district heating vary with time.

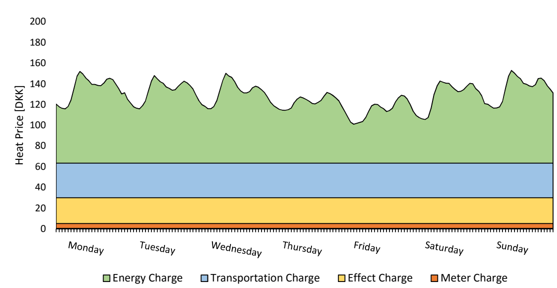
[5] In Danish: Bygnings- & Boligregistret (BBR).

2.2.1 A Fluctuating Heat Price

When the price of district heating varies with the electricity price, an extra cost will be added to the elaboration of the price of district heating from above. The price of district heating will still consist of four parts, but in the energy charge the fuel costs will be replaced with an electricity cost. By constructing the price like so, the energy charge will be much lower in 2035. In Figure 3a, the district heating price for a household of 130 m^2 is illustrated. In 2035 the district heating price mainly covers maintenance costs and electricity costs and therefore fluctuates with time due to electricity prices fluctuating with time, making it higher during the day than at night, as shown in Figure 3b. It shows how much of a difference the new constellation of the district heating price makes for an average household. At this point, the exact 2035-price is yet unknown, but an average value for the electricity price, based on the hourly electricity prices from 2014 and a heat pump efficiency of 3.5, is determined and used for illustrative purposes. In chapter 3.3 an optimisation model will determine the exact heating price, taking into account both marginal costs and the electricity price.



(a) Constant district heating price 2014.



(b) Estimated district heating price 2035.

Figure 3: Illustration of the various parts of the heat price in 2014 and in 2035. The charges are accumulated and are calculated as an average weekly price throughout the course of a year for a household of 130 m^2. [13]

It is assumed that the transportation charge, the effect charge and the meter charge will be the same in 2035 as in 2014. These parts do not depend on where the energy comes from, but cover essential costs within the grid and promote energy efficiency. Furthermore, it is assumed that the investment costs for the heat pumps and storage facilities are excluded from the price of district heating. These investments are assumed to be covered through other channels than the heating price.

3 Optimisation model

In this chapter, the technical aspects of replacing the heat production from FV07 with large industrial heat pumps as the heat production technology and heat storage for regulatory energy are analysed in order to determine various technological parameters. These parameters are then used in a mathematical optimisation model minimising the heat price by minimising the costs of supplying heat.

3.1 Heat Pump Analysis

This section provides a short explanation of how heat pumps work. The coefficient of performance (COP) is addressed and it is discussed how it can be improved. The implementation of heat pumps and some of the difficulties involving this are also mentioned. [14]

Heat pumps are designed to move thermal energy in the opposite direction of spontaneous heat flow. They transfer heat from a low-temperature location, the heat source, to a warmer location. To be able to do this a small energy input is needed, see Figure 4. In the case of this project, this energy is provided by electricity. Heat pumps make good use of the flexibility and high quality of electric energy, in that they can use one unit of electric energy to transfer more than one unit of thermal energy from a cold area to a hot area.

Figure 4: A simple schematic of the heat pump conversion process. [15]

There are two main types of heat pumps, absorption and compression. Absorption heat pumps operate with heat as the energy source. This heat may come from burnable fuels. Compression heat pumps run on mechanical energy, typically driven by electricity. Some new heat pumps use a combination of the absorption and compression technologies and are simply called hybrid heat pumps. Absorption heat pumps are used to increase the energy gained from the used fuel at a district heating plant. As this project aims to replace the present production of FV07 with standalone heat pumps driven by electricity, the best solution will be to use compression heat pumps.

Compression heat pumps are the most commonly used type. The cycle of a heat pump can be seen in Figure 5. The refrigerant inside the closed circuit of the heat pump is responsible for transferring and transporting the heat. In step 1 the refrigerant gets heated in the evaporator by the heat source until it evaporates. In step 2 the gaseous refrigerant is compressed in the compressor, which is driven by electricity. This increases the pressure of the refrigerant and thus also its temperature. In step 3 the heated refrigerant then flows to the condenser, a heat exchanger, in which the heat is extracted from the refrigerant and transferred to the heating system. In this step, the refrigerant liquefies due to the heat release. In step 4 an expansion valve causes a reduction in temperature and pressure and the cycle starts over.

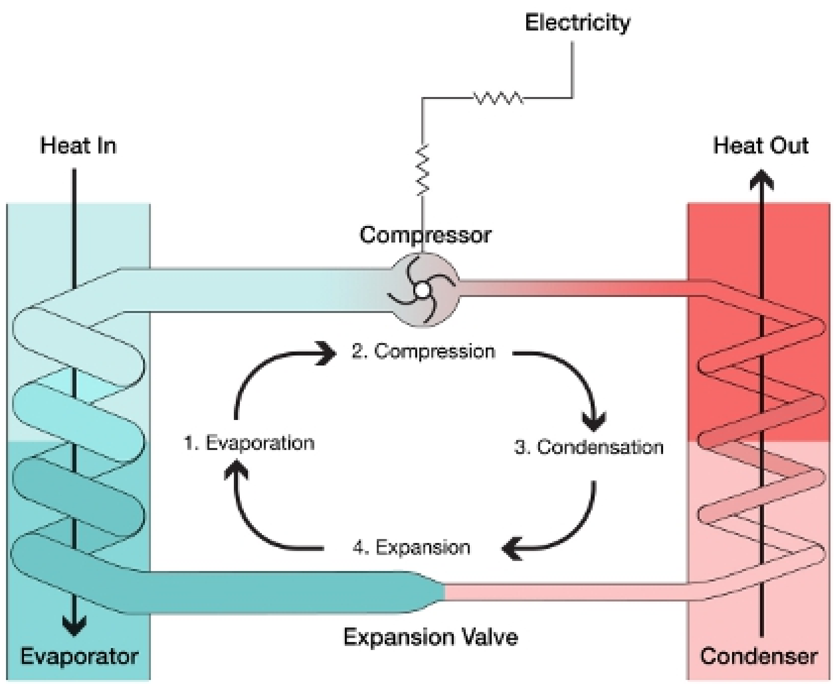


Figure 5: Compression and expansion cycle of a heat pump. [16]

3.1.1 Coefficient of Performance

The energy efficiency of a heat pump is characterised by the COP. The COP is the ratio of the heat output to the input electric energy used in the process. The theoretical maximum efficiency for a compression heat pump can be calculated with the Lorentz efficiency equation:

$$COP_L = \frac{T_{mh}}{T_{mh} - T_{ml}}, \tag{1}$$

where COP_L is the Lorentz efficiency, T_{mh} is the mean temperature on the hot side and T_{ml} is the mean temperature on the cold side. When calculating, the temperatures are in Kelvin. For this project the district heating water is expected to have a return flow temperature of 40°C and a supply temperature of 80°C, these are the hot side temperatures. It is also assumed that the heating source is sea water from textitOdense Fjord, which will be explained further in section 3.1.2. The sea water is assumed to be cooled from 8.4°C [17] to 2°C, these are the cold side temperatures. This would yield a Lorentz efficiency of

$$COP_L = 6.08. \tag{2}$$

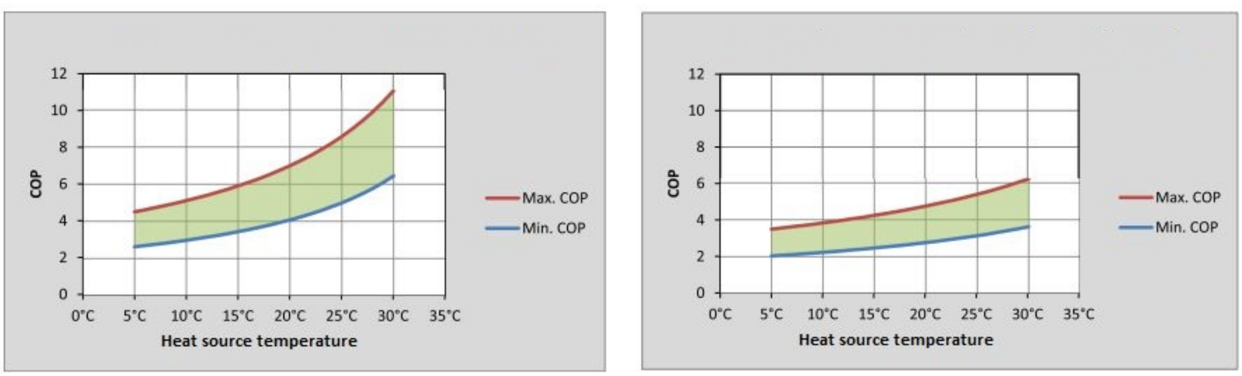
In practice, heat pumps powered by electricity typically have a COP between 3 and 5 due to both thermal and mechanical losses in the different components. In district heating, these numbers can be even lower and the COP of the most efficient heat pumps is at about 50-60 % of the Lorentz efficiency. The actual COP is calculated by multiplying the Lorentz efficiency with the efficiency of the heat pump:

$$COP = COP_L \times \eta_{HP}, \tag{3}$$

where η_{HP} is the efficiency of the heat pump. It is assumed, that the heat pumps that will be used in this project have a COP of 60 % of the Lorentz efficiency, which is the COP of the most efficient heat pumps available. This would yield a COP of

$$COP = 6.01 \times 0.6 = 3.65. \tag{4}$$

Typical COP values for heat pumps used in district heating can be seen in the graphs in Figure 6. The higher COP numbers are often reached in facilities with large compressors and small distances from the heat pump to the district heating water and the heat source. The two graphs show that the temperature levels of the district heating water have a large influence on the COP. The temperature of the heat source is also reflected in the COP and thus, it changes with the seasons, especially if water is used as a heat source, which is the case in this project.



(a) District heating water heated from 30 °C to 60 °C.

(b) District heating water heated from 40 °C to 80 °C.

Figure 6: Expected COP for different district heating water temperatures. [14]

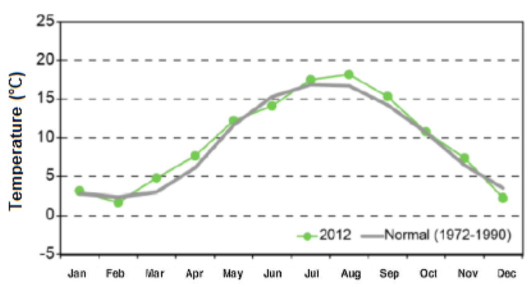
One way of improving the COP is to reduce the temperature difference between the heating source and the district heating water. Reducing the needed supply temperature of the district heating water could improve the COP significantly, as can be seen in the difference between the two graphs in Figure 6. Another possible way of improving the COP is to connect several heat pumps in series. The series connection applies especially to systems with large temperature differences between the heat source and the district heating water, and if the used refrigerant is not suitable for large temperature changes. Connecting heat pumps in series could be a possibility for *Fjernvarme Fyn*. It will require extensive research to improve the efficiency of existing heat pumps and it is not expected that they will become more efficient in the near future.

3.1.2 Implementing Heat Pumps Into District Heating

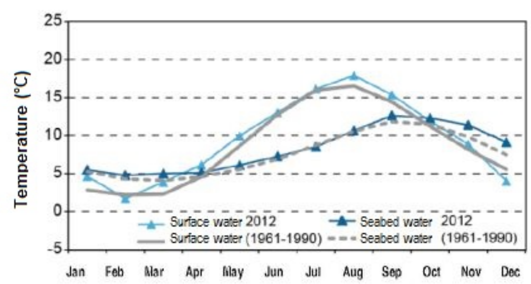
The first step of implementing heat pumps into a district heating system is to identify the available heat source and its potential. In the following sections, a couple of heat source possibilities and their advantages and disadvantages are mentioned.

Sea water

In principal, sea water has no limitations in capacity. Most larger cities are situated close to the sea. The temperature of the water in the coastal regions can come close to zero as seen in Figure 7a, and some components of the heat pump will have to be built specially to be able to handle low temperatures without freezing. Technologies that are capable of handling the low water temperatures in the winter, are being developed and will make sea water as a heat source very attractive. The problem could also be handled with different depths of inlets from the sea water. Surface water could be used in the summer and water from greater depths in the winter, see Figure 7b. This could also secure a more constant temperature of the inlet of the heat source. When using sea water as the heat source, fouling growth also has to be taken into consideration.



(a) In fiords and close to the coast.



(b) At open sea: surface (≤ 10m) and seabed (≥ 20m).

Figure 7: Mean sea water temperatures from 1961-1990 and 2012. [14]

Groundwater

The Danish groundwater reservoirs are suitable as a heat source. The temperature of the groundwater is almost constant throughout the year at about 8-10°C, which is a big advantage compared to many other heat sources. There are a lot of data from drilling for drinking water that indicate the groundwater's suitability for use as a heat source, but exploratory drilling is needed to confirm the necessary flow to facilitate enough heat transfer to the heat pump refrigerant for a given heat load. This is both time consuming and expensive. As with all water heat sources, fouling growth could be a problem. Aside from that there are also a lot of ethical and environmental issues when using groundwater.

River and lake water

Larger rivers and lakes can be used as a heat source. Especially in Denmark they are suitable since a large amount of water runs through the Danish rivers and lakes. The temperature of the water led back into rivers and lakes, after transferring heat to the heat pump refrigerant, may not have been decreased more than 5°C or be below 2°C. This limits the use of this heat source in the winter and makes another production facility necessary. Fouling growth might also be a problem, which has to be handled with detailed maintenance and maybe also special components.

For the heat pumps used in this project, it is assumed, that sea water taken from *Odense Fjord* will be used as a heat source, since the facility is already established at the fiord and using its water for cooling at FV07.

Heat pumps used in district heating use plate heat exchangers in the evaporator and condenser. It is common to use several heat exchangers to reduce the thermal losses. Some also use more than one compressor, to divide the process into more pressure and temperature steps.

In Denmark it is only legal to use natural refrigerants, thus, the components developed for synthetic refrigerants cannot be used in heat pumps in the Danish district heating system. Heat pumps using natural refrigerants have the same performance and efficiencies as those using synthetic refrigerants and in general more and more of the developed technology aims to use natural refrigerants and thus, this should not be a problem looking forward.

Large heat pumps used in district heating are expected to be able to run indefinitely, as long as they are serviced and maintained regularly. In Sweden, some large heat pumps have been used for 25-30 years with only minor renovations.

When integrating heat pumps into a district heating system it can be difficult to predict how the system parameters will affect the COP and performance of the heat pump. The chosen heat pump and its COP will be different for every system and has to fit its needs. The system and the heat pump have to be chosen and altered to fit each other and thus create the highest possible overall system efficiency. Future changes and developments, including technological, in the system in which the heat pumps are to be applied also need to be considered, to ensure an optimal solution.

Choosing the best-fit heat pump for district heating will be different for every scenario. Especially the type of heat source, the temperature of that heat source and the planned temperature of the produced district heating influence the final choice. There is not a lot of experience using heat pumps in district heating and they are thus still at an early point on their learning curve. In the future, it can be expected that more possible usages and ways of implementing heat pumps will emerge.

3.2 Heat Storage Analysis

To support the heat produced in the heat pumps with a regulatory capability, a heat storage facility is analysed. *Fjernvarme Fyn* already has a storage unit. This heat storage analysis takes its point of departure in this already existing facility in terms of volume. The current storage facility has been chosen as it can be expected that its volume is dimensioned to meet *Fynsværket*'s heat storage needs. Since the report aims to replace all non-renewable heat produced at FV07, using only heat pumps and storage, the already existing storage facility's capacity is an ideal point of departure.

3.2.1 Storage Specification

The heat storage has a volume of 65,000 m^3 and uses water as the storage medium. It is dimensioned based on the optimal ratio between height and width for cylindrical heat storage tanks, which is 0.45 for a 65,000 m^3 tank.[18] The height is chosen to be 14 m, in accordance with the world's largest heat storage facility in Vojens. From this optimal ratio and the overall volume of the rectangular tank the length and width of the tank are found, as seen in Appendix G. Here the width of the tank is determined to be 31.1 m and the length of the tank is 149.2 m. The storage tank itself is assumed to be build in steel and insulated with Rockwool.

3.2.2 Storage Efficiency

The first efficiency investigated is the year-round efficiency of the storage, assuming a completely full storage. Having determined the dimensions, the storage medium and the materials incorporated in the tank, a heat loss analysis using thermal resistance theory can be conducted. For such an analysis the thermal conductivity for both the insulation and the storage wall material itself are needed.

The thermal conductivity of steel is $\kappa_{steel} = 16\frac{W}{m\times K}$ and the thermal conductivity of Rockwool is $\kappa_{rockwool} = 0.045\frac{W}{m\times K}$.[19] Knowing the thermal conductivities and the area of an arbitrarily chosen storage wall, as the area will not affect the end result, from the dimensions mentioned above, the thermal resistance of the storage wall can be found using Equation 5:

$$R_{thermal} = \frac{1}{\kappa_{steel} \times A_{wall}} \times L_{steel} + \frac{1}{\kappa_{Rockwool} \times A_{wall}} \times L_{Rockwool}. \tag{5}$$

This will be the thermal resistance for a storage wall under the assumption that there is no convection heat transfer. Therefore, heat transfer from the heated water on the inside of the storage wall to the surrounding soil is only composed of conduction. Thus, there is no airflow, which in this case would be the primary cause of convection heat transfer. This is a valid assumption as there will be no airflow in soil, in which the storage is completely buried as well as the fact that Rockwool is designed to prevent airflow.

In Equation 5, A_{wall} is the surface area of the arbitrarily chosen storage wall, in this case the height of the storage times the width of the storage, which is 435.556 m^2. L_{steel} is the thickness of the steel wall and $L_{Rockwool}$ is the insulation thickness. L_{steel} is assumed to be 2 cm and the insulation thickness, which has a great impact on the thermal resistance, is chosen to be 70 cm in accordance with the insulation thickness of Vojens heat storage facility.[20]

When inserting the values in Equation 5 a thermal resistance of $1.55 \times 10^{-3} \frac{K}{W}$ for the chosen wall is found. Initially assuming a completely full storage, the temperature of the entire storage medium will be $T_{water} = 80°C$, the forward flow temperature. The surrounding temperature used to calculate the heat loss due to conduction through a storage wall is the soil temperature of $T_{ambient} = 9°C$ at a depth of 10 meters, which varies very little over the course of a year.[21]

The overall heat transfer coefficient, U, is calculated using Equation 6,

$$U = \frac{1}{R_{thermal} \times A_{wall}}. \tag{6}$$

Knowing the temperatures of the storage medium and the ambient soil temperature, the storage heat flux can be found in Equation 7,

$$q_{storage} = U \times (T_{water} - T_{ambient}). \tag{7}$$

Having the heat flux for one wall, and assuming that the steel and insulation thickness is uniform around the storage, the total heat loss through the storage walls can be determined by multiplying the storage heat flux with the total storage surface area. The total surface area of the rectangular tank is found from Equation 8,

$$A_{total} = L_{height} \times L_{width} \times 2 + L_{length} \times L_{width} \times 2 + L_{height} \times L_{length} \times 2. \tag{8}$$

Now, the total heat loss rate can be calculated from Equation 9,

$$Q_{loss} = q_{storage} \times A_{total}. \tag{9}$$

Since the heat loss over an entire year is of interest, the total heat loss is multiplied by the number of hours in a year to yield a total heat loss of 401.2 MWh.

In order to find an overall storage efficiency the total heat content of a full storage is found using Equation 10,

$$E_{content} = V \times (T_{forward} \times C_{p80°C} \times \rho_{80°C} - T_{return} \times C_{p40°C} \times \rho_{40°C}, \tag{10}$$

where V is the storage volume, $T_{forward}$ is the forward district heating temperature of $80°C$, $C_{p80°C}$ is the specific heat of water at $80°C$ and $\rho_{80°C}$ is the density of water at that temperature. Similarly, T_{return} is the temperature of water flowing back into the heat pumps after having supplied the consumer with district heating. $C_{p40°C}$ is the specific heat of water at $40°C$ and $\rho_{40°C}$ is the density of water at that temperature. Equation 10 gives 2532 MWh as the maximum energy content of the storage.

Knowing the total energy content, and the total energy loss over the course of a year, it is possible to determine the year-round efficiency for the storage, from Equation 11,

$$\eta_{storage} = \frac{E_{content} - Q_{loss}}{E_{content}} \times 100 = 84.15\%. \tag{11}$$

This efficiency of 84.15 % assumes ideal conditions in that the supply and return temperatures are constant at 80°C and 40°C, respectively and that the entire storage is heated to and maintained at 80 °C. A more detailed efficiency is presented in section 3.2.5.

3.2.3 Temperature Gradient

When the storage is not completely full, the storage water will not have a uniform temperature. Dividing the storage tank into 14 intervals, each of a depth of 1 meter, setting the temperature at the top to be 80°C and the temperature at the bottom to be 40°C and including the heat loss per unit volume of the storage, the temperature gradient can be found by first writing the differential equation for heat diffusion:

$$q_{loss} = -\kappa_{water} \frac{\delta}{\delta z} \frac{\delta T}{\delta z}. \tag{12}$$

Equation 12 is now solved under the assumption that at a storage depth of zero the temperature of the storage water is the forward flow temperature of the district heating system, or $T_{s1} = T(z=0)$. The other assumption of the equation is that at the full depth of the storage, L_{height}, the temperature of the storage water is the return flow temperature of the district heating system, or $T_{s2} = T(z = L_{height})$. This return flow temperature of the district heating system is 40°C. Also, κ_{water} is the thermal conductivity of water, which is $0.58 \frac{W}{m \times K}$. To solve Equation 12, both sides are integrated:

$$\int -\kappa_{water} \frac{\delta}{\delta z} \frac{\delta T}{\delta z} dz = \int q_{loss} dz. \tag{13}$$

This gives

$$-\kappa_{water} \frac{\delta T}{\delta z} = q_{loss} \times z + C_1, \tag{14}$$

where C_1 is the first constant of integration. When Equation 14 is integrated again it gives the overall temperature gradient equation:

$$-\kappa_{water} \times T = q_{loss} \times \frac{z^2}{2} + C_1 \times z + C_2. \tag{15}$$

Now, this overall temperature gradient equation is solved in terms of the first assumption made above, that is $T_{s1} = T(z=0)$. Inserting this into Equation 15 and reducing gives

$$-\kappa_{water} \times T_{s1} = C_2. \tag{16}$$

If Equation 16 is inserted into Equation 15, C_1 can be determined under the assumption that $T_{s2} = T(z = L_{height})$:

$$-\kappa_{water} \times T_{s2} = q_{loss} \times \frac{L_{height}^2}{2} + C_1 \times L_{height} - \kappa_{water} \times T_{s1}. \tag{17}$$

Solving Equation 17 for C_1 gives

$$C_1 = \frac{(T_{s1} - T_{s2}) \times \kappa_{water}}{L_{height}} - \frac{L_{height} \times q_{loss}}{2}. \tag{18}$$

Inserting C_1 into Equation 15 gives

$$-\kappa_{water} \times T = q_{loss} \times \frac{z^2}{2} + \frac{(T_{s1} - T_{s2}) \times \kappa_{water}}{L_{height}} - \frac{L_{height} \times q_{loss}}{2} \times z - \kappa_{water} \times T_{s1}. \tag{19}$$

Now, the temperature, $T(z)$, is determined. $T(z)$ signifies the temperature gradient of the storage water as a function of the storage depth, when heat loss per unit volume is accounted for:

$$T(z) = \frac{(T_{s2} - T_{s1}) \times \kappa_{water} \times 2 \times z - L_{height} \times q_{loss} \times z^2 + L_{height}^2 \times q_{loss} \times z + 2 \times L_{height} \times T_{s1} \times \kappa_{water}}{2 \times L_{height} \times \kappa_{water}}. \tag{20}$$

In Equation 20, q_{loss} is the storage heat loss expressed in watts per cubic-meter and is found as

$$q_{loss} = \frac{Q_{loss}}{V_{storage}}, \tag{21}$$

where $V_{storage}$ is the total volume of the storage, which is 65,000 m^3. The temperature gradient is illustrated as a function of the storage water depth in Figure 8.

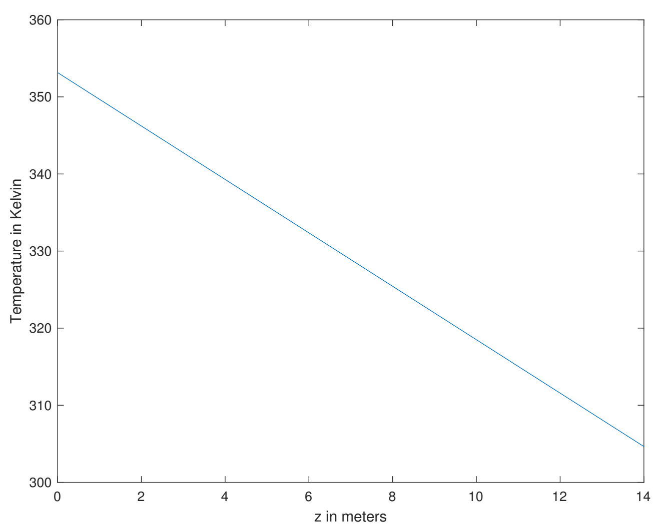


Figure 8: The temperature gradient depicted here is linear. The maximum and minimum temperatures of the gradient are 80°C and 31.5°C, respectively.

As can be seen in Figure 8 the temperature gradient is linear, as there is no convection heat transfer due to no mixing of the water, as the lighter, warmer water is at the top of the tank and therefore no buoyancy force in the water develops. Hence, heat transfer between the interval-layers is pure conduction through a “wall of water”. Figure 8 shows the minimum temperature distribution as a function of storage depth needed for the storage to be able to deliver heat to the district heating system. This is true since the forward temperature of the district heating system is 80°C and therefore heat cannot be extracted from the storage before the top layer, from where heat is extracted, reaches this temperature.

3.2.4 Energy Gradient

Due to the non uniform temperature distribution in the storage, the amount of energy needed to heat each interval of the storage, from the minimum storage temperature to the depth-dependent temperature plotted in Figure 8, will vary with the depth of the storage. Due to the storage heat loss, the temperature in the bottom layers of the storage will be lower than the district heating return temperature. The varying amount of energy will be found using intervals for both the specific heat and density, as these parameters change with temperature. Also, the storage is divided into 14 volume portions of the size of $\frac{1}{14}$ of the total volume. The function governing the amount of energy needed to heat each volume portion from the return temperature to the depth-dependent temperature will then be Equation 22,

$$E_{interval}(z) = V \times (T(z) \times C_P(z) \times \rho(z) - T_{min} \times C_{P,min} \times \rho_{min}), \tag{22}$$

where the temperature of the storage water is $T(z)$, which varies with the depth. The specific heat and density of the inlet water varies with this temperature as well. The minimum temperature, which will be the temperature of the storage water before it has been heated, but after the storage heat loss, will be constant at the minimum temperature of the gradient and therefore the temperature dependent parameter. Density and specific heat will be constant for this return temperature as well.

Using Equation 22, the amount of energy needed to heat the storage water is found, so that the temperature of the top layer of the storage is 80°C. The following layer in accordance with the temperature gradient will be 76.53°C, and so on for each interval. The total amount of energy needed to produce this temperature gradient will be 1801.1 MWh and is found by summing all the intervals in Equation 22. This amount of energy is significant because heat cannot be extracted from the storage if the temperature of the storage water is not the forward flow temperature of the district heating system. Therefore, this amount of energy needed to produce the required temperature gradient is essentially the minimum amount of energy needed in the storage, before heat can be extracted directly from it. It should be said that the maximum energy content of the storage is now larger, due to the minimum temperature in the storage being lower than the return temperature, because of the heat loss in the storage. Using Equation 22 and applying the total volume of the tank and the extreme temperatures, the maximum energy that can be stored is 3174 MWh, therefore, the energy available for supply in case of a full storage is 1373 MWh.

The energy needed to determine the temperature gradient, and thereby heat the top 1-meter layer to a temperature of the forward flow temperature, 80°C, is plotted versus the temperature in the storage in Figure 9.

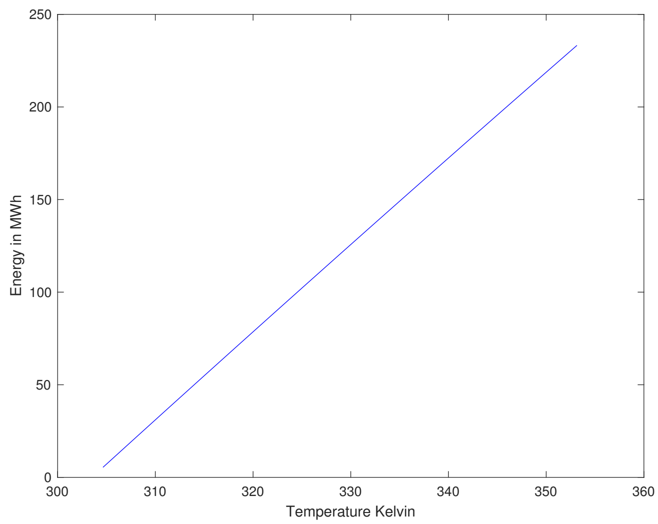


Figure 9: The energy needed to heat each layer of the storage to a temperature in accordance with the temperature profile, where the extreme temperatures are 80°C and 31.5°C.

The sum of the individual energy contents in each layer is then the minimum heat needed, for the storage to be able to deliver to the district heating system, given that the storage layers are 14 equal volumes, each of a height of 1 meter.

3.2.5 Efficiency as a Function of the Water Temperature

The storage efficiency is found from Equation 23,

$$\eta_{interval} = \frac{E_{interval}(z) - E_{heatloss}(z)}{E_{interval}(z)}, \tag{23}$$

where $E_{interval}(z)$ is the energy needed to heat a storage layer to the temperature described by the temperature gradient above. This energy is a function of the depth of the storage, z, as the energy is a function of the temperature gradient. Similarly, $E_{heatloss}(z)$ is the heat loss from each layer of the storage, which is also temperature dependent. The heat loss through each layer is found from Equation 24,

$$E_{heatloss} = U \times (T(z) - T_{ambient}) \times A_{wall}, \tag{24}$$

where $T(z)$ is the depth-dependent temperature of each layer, U is the overall heat transfer coefficient and A_{wall} is the surface area of each storage-depth-interval.

The storage efficiency of the walls is now plotted versus the temperature and illustrated in Figure 10.

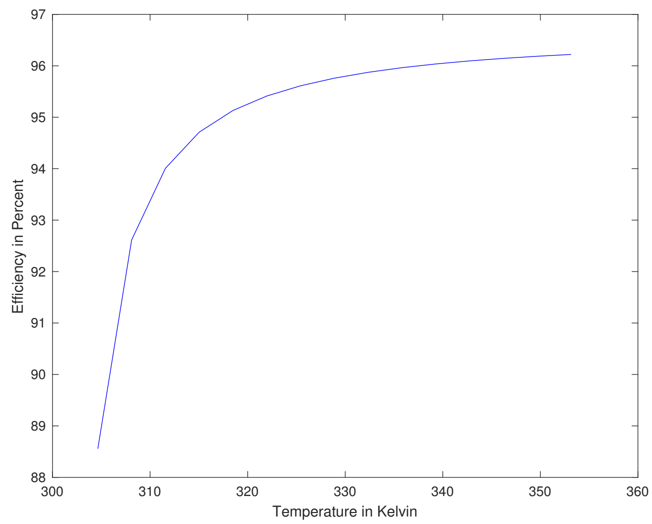


Figure 10: Storage efficiency as a function of temperature in each storage layer. The maximum and minimum temperatures are 80°C and 31.5°C, respectively.

The wall efficiency, as can be seen from Figure 10, depends on the temperature in the individual wall layers. The efficiency of the storage is highest at the top layers of the storage, with the highest temperature, as the heat losses in these layers are smaller relative to their energy content. That is, even though the heat loss in the top layers are larger than in the lower layers due to the larger temperature differences between the water and the ambient soil, the energy content of these upper layers is much greater than in the lower layers due to the larger temperature difference between the water temperature of that layer, relative to the minimum storage temperature of the storage, found using the temperature gradient. Therefore, the efficiency decreases with the depth of the storage, as the energy content decreases more rapidly with the decreasing temperature than the heat loss does.

The efficiency at the top of the storage is found using the heat loss and the energy content of the top layer. The heat loss of the top layer is found using Equation 24, though with a surface area of the length times the width of the storage. The heat loss through the walls of the top layer is subtracted from this amount, as to only take into consideration the loss through the top surface area. Using this approach yields a heat loss from the top area of 113.37 MWh, if the top layer of the storage is maintained at 80°C for an entire year. Such a heat loss, relative to the energy contents, gives an efficiency of 55.13 %. This efficiency is lower than the average efficiency due to the much larger surface area of the entire top of the storage relative to the 1-meter high wall intervals. This larger surface area yields a larger heat loss relative to the energy content of the top layer, and therefore a smaller efficiency. The average efficiency of the entire storage, using the method mentioned above, is 87.02 % at the minimum energy content.

To conclude, the maximum amount of energy that can be stored is 3174 MWh of which 1373 MWh are available for distribution. In the model two storage facilities are implemented, the one already installed at *Fynsværket* and the one dimensioned here, giving a total storage capacity of 2746 MWh.

3.3 The Optimisation Model

The purpose of this optimisation model is to optimise the amount of heat produced, the amount of heat sent to the heat storage and the amount of heat withdrawn from the heat storage. MATLAB has been used to make the model and it can be found in Appendix H. In this model the storage solution has been simplified by neglecting the heat loss. As the district heating companies are obligated to operate financially under the self-sustained principle, they cannot earn a profit and therefore the goal of this optimisation model is to minimise the price of district heating by minimising the costs. The heat price would be equal to the expenses of the production company. The following model will only optimise the short term expenses. In order to understand the model, the variables and constants from Table 1, must be understood.

Nomenclature	Explanation	Unit
Q_{HP}	Heat produced by the heat pumps that is delivered directly to the consumer	MWh
Q_{STin}	Heat produced by the heat pumps that is put into storage	MWh
Q_{STout}	Heat withdrawn from the storage and delivered to the consumer	MWh
MC_{HP}	Marginal cost of heat pump	$DKK/MW/hour$
MC_{ST}	Marginal cost of storage	DKK/MWh
PoE	The price of electricity in the given hour in 2014	DKK/MWh
$AvgPoE$	The average price of electricity in 2014	DKK/MWh
COP	The coefficient of performance of the heat pump	-
Q_{Demand}	The consumption of heat in the given hour in 2010	MWh
ST_{Max}	The maximum capacity of the storage unit	MWh
$EnergyInStorage$	The current amount of energy in the storage unit in the given hour	MWh
$InstalledHP$	The maximum capacity of the heat pumps installed	MWh

Table 1: The various variables and constraints used in the model.

The marginal cost of heat pumps has been found in the *Technology Data for Energy Plants* which is a data catalogue made by *The Danish Energy Agency*[6] and *Energinet.dk.*[18] For this optimisation, the projected 2030 data has been used. The marginal cost of heat pumps is found to be 3650 €/MW/year which is equal to 3.10 DDK/MW/hour.

The marginal cost of storage is also found in the *Technology Data for Energy Plants.* It is 0.7 % of the investment cost per year. The investment costs are 35 €/m^3 for the first 50,000 m^{3}and 20 €/m^3 for everything above 50,000 m^3.

[6] In Danish: Energistyrelsen

With a storage size of 65,000 m^3 this results in an investment cost of 14.9 million DDK and a marginal cost of 0.56 DDK/MWh.

The price of electricity has been downloaded from the market data at *Energinet.dk*. [22] For this model the electricity prices of 2014 in DK1 have been used. The COP used in the model has been calculated in section 3.1.1 and is found to be 3.65. In this model the COP is assumed to be constant.

For the heat demand, the heat production of FV07 in 2010 has been used. [23] Data from 2010 has been used because it was the only data available. This is a source of error since the model would be more accurate with newer data. The maximum storage capacity is calculated in section 3.2.4 and found to be 2745.8 MWh and yhe heat pump capacity installed is set equal to the maximum value of the chosen demand.

The model created for optimising the heat price is:

Minimise the object function,

$$\begin{aligned} HeatPrice = &\left(\frac{PoE}{COP} + MC_{HP}\right) \times Q_{HP} + \left(\frac{PoE}{COP} + MC_{HP} - \left(AvgPoE - PoE\right)\right) \times Q_{STin} \\ &+ \left(MC_{ST} + \left(AvgPoE - PoE\right)\right) \times Q_{STout}. \end{aligned} \tag{25}$$

Subject to the constraints,

$$Q_{HP} + Q_{STout} = Q_{Demand}$$

$$Q_{HP} \leq Q_{Demand} + ST_{Max} - EnergyInStorage$$

$$Q_{HP} \geq Q_{Demand} - EnergyInStorage$$

$$Q_{STin} \leq STMax - EnergyInStorage$$

$$Q_{STout} \leq EnergyInStorage$$

$$Q_{HP} + Q_{STin} \leq InstalledHP$$

$$0 \leq Q_{HP} \leq 571$$

$$0 \leq Q_{STin} \leq 310$$

$$0 \leq Q_{STout} \leq 310$$

In the following section the object function, Equation 25, will be explained. The optimisation of the object function is done 8760 times – one time for each hour of the year. The variables of the function are Q_{HP}, Q_{STin} and Q_{STout}.

Most of the constants have the same value for all of the hours but for the electricity price and the heat demand, actual values from 2014 and 2010 respectively, are being used. The first term,

$$\left(\frac{PoE}{COP} + MC_{HP}\right) \times Q_{HP}, \tag{26}$$

is the sum of the cost of the electricity that is used to produce the heat and the marginal cost of the heat pumps. The second term of the object function,

$$\left(\frac{PoE}{COP} + MC_{HP} - \left(AvgPoE - PoE\right)\right) \times Q_{STin}, \tag{27}$$

is just like the previous term the sum of the cost of the electricity that is used to produce the heat that goes to storage and the marginal cost of the heat pumps. Different from the first term is the constant $-(AvgPoE - PoE)$, which compares the current price of electricity with the average price of electricity. It ensures that if the current price of electricity is lower than the average price of electricity some amount of extra heat will be produced and stored in the storage tank. It also ensures that no extra heat is produced if the current price of electricity is higher than the average price of electricity. The third term of the object function,

$$\left(MC_{ST} + \left(AvgPoE - PoE\right)\right) \times Q_{STout}, \tag{28}$$

consists of two parts. The first part is the marginal cost of storage. The second part compares the current price of electricity with the average price of electricity. It ensures that heat from the storage is not used if it is cheaper than average to produce heat directly. It also ensures that heat from the storage is used if it is more expensive than the average cost to produce heat. If the current price of electricity is higher than the average price of electricity the second part is an expression of how much money is saved when taking heat from the storage, compared to the cost of producing the heat with the average electricity price. If the current price of electricity is lower than the average price of electricity the second part is an expression of how much money is lost when taking heat from the storage, compared to the cost of producing the heat with the current electricity price. Therefore, when the current electricity price is less than the average, heat is not drawn from the storage but sourced to it instead.

Next up is a walk-through of the constraints. In order to ensure that the demand for heat is always met, the following equality is made:

$$Q_{HP} + Q_{STout} = Q_{Demand}. \tag{29}$$

The equality ensures that the sum of the heat produced by the heat pumps that is delivered directly to the consumer and the heat withdrawn from the storage and delivered to the consumer are equal to the demand. In order to ensure that the heat pumps do not produce more heat than the system can handle the following constraint is made:

$$Q_{HP} \leq Q_{Demand} + ST_{Max} - EnergyInStorage. \tag{30}$$

Equation 30 ensures that the heat pumps do not produce more heat than the sum of the demand and the amount of storage capacity left in the storage tank. In order to ensure that the heat pumps and the storage can always supply enough heat, the following constraint is made:

$$Q_{HP} \geq Q_{Demand} - EnergyInStorage. \tag{31}$$

Equation 31 ensures that the production of the heat pumps is always bigger or equal to the difference between the demand and the energy in storage. In order to ensure that the amount of heat sent to the storage does not exceed the maximum storage capacity, the following constraint is made:

$$Q_{STin} \leq ST_{Max} - EnergyInStorage. \tag{32}$$

In order to ensure that the amount of heat withdrawn from the storage does not exceed the energy in the storage, the following constraint is made:

$$Q_{STout} \leq EnergyInStorage. \tag{33}$$

In order to ensure that the produced heat does not exceed the actual installed capacity, the following constraint is made:

$$Q_{HP} + Q_{STin} \leq InstalledHP. \tag{34}$$

The lower and upper boundaries of Q_{HP} are set to 0 and the maximum capacity of FV07 (571 MW) respectively:

$$0 \leq Q_{HP} \leq 571. \tag{35}$$

The lower boundary of Q_{STin} is set to 0 and the upper boundary is set to 310, calculated with a fluid velocity of 4 m/s and a pipe diameter of 70 cm using the methods of Appendix G:

$$0 \leq Q_{STin} \leq 310. \tag{36}$$

The lower boundary of Q_{STout} is set to 0 and the upper boundary is set to 310, calculated with a fluid velocity of 4 m/s and a pipe diameter of 70 cm using the methods of Appendix G:

$$0 \leq Q_{STout} \leq 310. \tag{37}$$

The energy in storage is initially set to zero. After each optimisation, the Q_{STin} is added to the previous value of energy in storage and the Q_{STout} is subtracted from the previous value of energy in storage:

$$EnergyInStorage(n+1) = EnergyInStorage(n) + Q_{STin} + Q_{STout}. \tag{38}$$

3.3.1 Optimisation Results

The result of the optimisation problem stated in Equation 25, is an average energy charge of 39.57 DDK/MWh throughout the entire year. When comparing this to the current energy charge of 313.20 DKK/MWh, it shows that the heat pump solution reviewed in this project, is much cheaper for the consumer.[24] It is important to understand that this is only the cost of production and storage, where the main expense is for electricity, which is cheaper than fossil fuels that would otherwise be used. This is the main reason why the price is low compared to the current price of heat.

In Figure 11, the results from the optimisation model are illustrated, for each hour throughout the year. The price varies mainly due to the price of electricity.

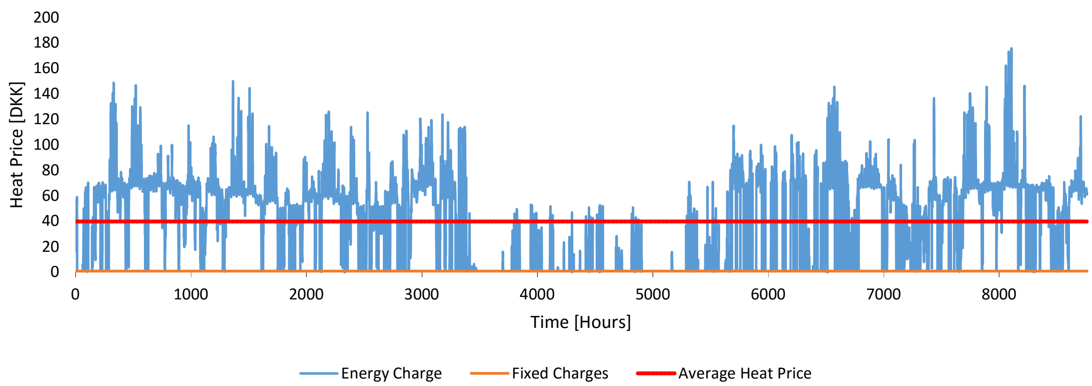
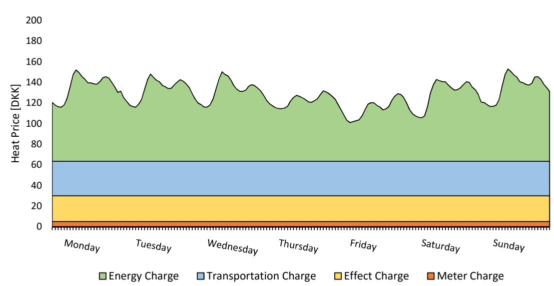
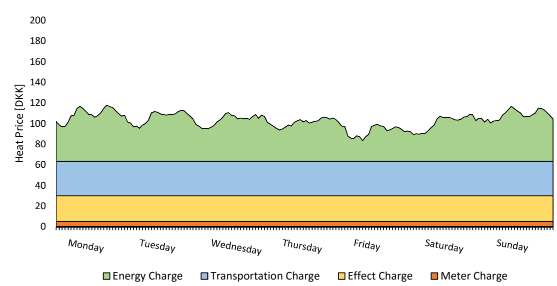


Figure 11: Illustration of the hourly district heating price. The fixed charges, the orange line, are so low on an hourly basis, that they do not have an effect on the total price. The red line illustrates the average district heating price.

An important thing to conclude from the optimisation model is that the storage unit lowers the heat price. When the optimisation problem is solved without a storage unit (upper boundaries of Q_{STin} and Q_{Stout} are set to 0) the heating price becomes 47.56 DDK/MWh. Both scenarios are illustrated in Figure 12.



(a) This figure is the same as Figure 3b and illustrates the average weekly district heating price if the only expense was the spot electricity price without heat storage.



(b) This figure illustrates the average weekly district heating price when a heat storage is used to regulate the heat production from heat pumps.

Figure 12: Comparison of the district heating price with and without heat storage.

The most significant difference when comparing Figure 12a and Figure 12b, besides the lower average when the heat storage is utilised, is the fluctuation in the energy charge. The use of a heat storage lowers these fluctuations and evens out the heat price as the ratio of supply from the heat pumps and the storage facilities is optimised with respect to their respective marginal costs and the price of electricity.

3.4 Future Implementation

Making the district heating price vary with time in the future could create an incentive to design the heating sector in somewhat the same way as the electricity sector, where each actor in the market trades energy on *Nord Pool*, the Nordic market of electricity. By doing so, the production technology with the highest price at a given demand would dictate the consumer price for that given hour. In Figure 13 the heat prices for the three largest sustainable suppliers in *Fjernvarme Fyn*'s supply area are listed together with the energy charge for the heat pump solution from this project.[25]

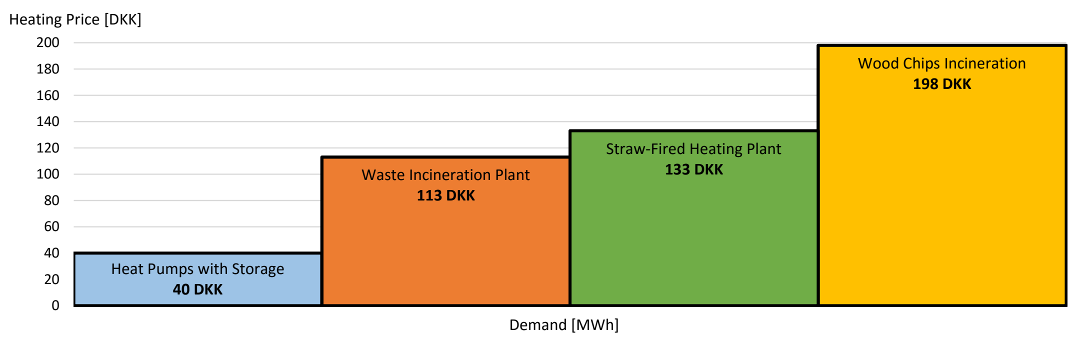


Figure 13: Illustration of the different sustainable production technologies in *Fjernvarme Fyn*'s supply area and their respective prices. The supply amount is assumed to be the same for each technology.

For each hour, there will be a given demand, and for each demand there will be a maximum heat price set by the production technology matching that exact demand in that exact hour. Say, for example, that the demand would require the entire production capacity from both the heat pumps and the waste incineration plant and half the capacity from the straw-fired heating plant. Then the price for the latter, 133 DKK/MWh, will determine the market price. This will be the price paid by every consumer in the supply area for that hour. By constructing the market like so, the general idea is, that in a perfect market, the competition alone would create incentive to produce district heating at the lowest possible cost, minimising the general price for the consumer.

4 Pipe Flow Analysis

This section will analyse the pressure and heat loss on a pipe-section of *Fjernvarme Fyn*'s district heating system. The pipe analysed will be a LOGSTOR 168-168/500 TwinPipe, as used in *Fjernvarme Fyn*'s district heating transmission system. A schematic of the pipe can be seen in Figure 14 and the dimensions are presented in Table 2.

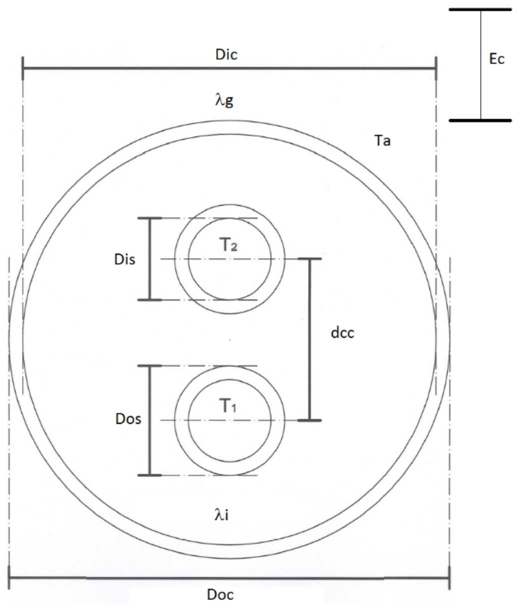


Figure 14: Schematic of a Twin-pipe district heating transmission pipe [26].

Description	Nomenclature	Value
Outer diameter, steel pipe	D_{os}	0.1683 m
Inner diameter, steel pipe	D_{is}	0.1643 m
Steel pipe thickness	th_s	0.004 m
Outer casing, outer diameter	D_{oc}	0.5 m
Outer casing, inner diameter	D_{ic}	0.4944 m
Casing thickness	th_c	0.0056 m
Distance between steel pipes	d_{cc}	0.019 m
Earth cover	E_c	0.6 m
Thermal conductivity of the ground	λ_g	$1.6\frac{W}{m\times K}$
Thermal conductivity of the insulation	λ_i	$0.027\frac{W}{m\times K}$
Supply temperature	T_1	$353.15K$
Return temperature	T_2	$313.15K$

Table 2: Overview of twin-pipe dimensions and corresponding nomenclature.[27]

4.1 Pressure Loss

The pressure loss within a pipe is an important factor when dimensioning the district heating system. Given the length of the pipe, the internal pressure loss of the pipe must be adjusted by using pumps so that the working fluid of the transmission-pipes reaches the branch pipes for further distribution, at the correct pressure.

First, the cross sectional area of the steel pipe must be found:

$$A_{cs} = \left(\frac{D_{is}}{2}\right)^2 \times \pi. \tag{39}$$

Now, for a specific flow rate, Q, the fluid velocity in the pipe can be calculated from

$$V_f = \frac{Q}{A_{cs}}. \tag{40}$$

The flow rate is found from the mass flow rate and the density of the fluid at a specific temperature. The mass flow rate is found given a specific amount of heat required to be transported, and from the return and supply temperatures specified.

Now, choosing an arbitrary amount of heat that needs to be transported,P_t, as 80,000 W, the mass flow rate can be found using the following equation:

$$\dot{m} = \frac{P_t}{Cp_{T_1} \times T_1 - Cp_{T_2} \times T_2} = 0.4779\frac{kg}{s}, \tag{41}$$

where Cp_{T_1} and Cp_{T_2} are $4.198\frac{kJ}{kg\times K}$ and $4.179\frac{kJ}{kg\times K}$, respectively. The volume flow rate can then be found from

$$\dot{V} = \frac{\dot{m}}{\rho_{avg}} = 0.000487\frac{m^3}{s}, \tag{42}$$

where $\rho_{avg} = 982.15\frac{kg}{m^3}$. Now, having both the volume flow rate and the cross sectional area of the pipe, the fluid velocity is calculated from Equation 40 to be $0.024\frac{m}{s}$. To calculate the pressure loss in the pipe correctly a friction factor must be found. The Cole-Brook equation describes the friction factor

$$\frac{1}{\sqrt{\lambda}} = -2 \times log\left(\frac{k}{3.7 \times D_{is}} + \frac{2.51}{Re \times\sqrt{\lambda}}\right), \tag{43}$$

where λ is the friction factor, k is the relative roughness of the pipe and Re is Reynolds number, which can be found from

$$Re = \frac{D_{is} \times V_f}{\nu_{avg}} = 7683.6, \tag{44}$$

where ν_{avg} is the average kinematic viscosity for water in the temperature range $313.15K$ to $353.15K$, which is $0.511 \times 10^{-6}\frac{m^2}{s}$. Equation 44 is now inserted into Equation 43 and the friction factor is found to be 0.00805. The total pressure loss in the supply and return pipe can now be found from

$$\frac{P_{loss}}{m} = 2 \times \left(\frac{\lambda \times \rho_{avg} \times V_f^2}{2 \times D_{is}} \right) = 0.029 \frac{Pa}{m}. \tag{45}$$

4.2 Heat Loss

For the heat flow analysis, the Wallentén analysis method is used [28], see Figure 14 for a schematic of the pipe.[29] Before further analysis can be undertaken, some parameters need to be defined[7].

Description	Definition	Value
Outer radius of the steel pipe	$r_i = \frac{D_{os}}{2}$	$0.08414m$
Inner radius of the entire pipe	$r_c = \frac{D_{ic}}{2}$	$0.244m$
Distance from the centre of the pipe to the surface of the earth cover	$H = E_c + \frac{D_{oc}}{2}$	$0.85m$
Distance from the far end of one of the steel pipes to the centre of the entire pipe	$D = \frac{d_{cc}}{2} + r_i$	$0.09364m$
Ambient ground temperature	T_a	$282.15K$
Average transmission temperature	$T_{avg} = \frac{T_1 + T_2}{2}$	$333.15K$
Average temperature difference between the supply and return pipe	$T_{avgd} = \frac{T_1 - T_2}{2}$	$20K$

Table 3: Heat loss parameters

To find the heat loss two characteristic thermal resistances, symmetric and asymmetric, h_s^{-1} and h_a^{-1} respectively, are needed:

$$h_s^{-1} = 2 \times \frac{\lambda_i}{\lambda_g} \times ln\left(\frac{2H}{r_c}\right) + ln\left(\frac{r_c^2}{2Dr_i}\right) + \sigma \times ln\left(\frac{r_c^4}{r_c^4 - D^4}\right), \tag{46}$$

$$h_a^{-1} = ln\left(\frac{2D}{r_i}\right) + \sigma \times ln\left(\frac{r_c^2 + D^2}{r_c^2 - D^2}\right), \tag{47}$$

where the dimensionless parameter $\sigma = \frac{\lambda_i - \lambda_g}{\lambda_i + \lambda_g}$ describes the relationship between the different thermal conductivities.

With expressions for h_s^{-1} and h_a^{-1} the symmetric and asymmetric heat loss, q_s and q_a respectively, can be found as

$$q_s = \left(T_{avg} - T_a\right) \times 2\pi \times \lambda_i \times h_s, \tag{48}$$

$$q_a = T_{avgd} \times 2\pi \times \lambda_i \times h_a, \tag{49}$$

where q_s is the collective heat transfer from the two fluid pipes to the surrounding insulation and the ground and

[7] The Wallentéen model assumes an infinitesimally small thickness of the steel pipe and takes the outer radius of the steel pipe as the inner radius of said pipe, it also ignores the thickness of the outer casing.

q_a is the heat transfer from the supply pipe to the return pipe. Now the heat loss from the supply and return pipe, as well as the total heat loss is found:

$$Q_f = q_s + q_a = 12.885 \frac{W}{m}. \tag{50}$$

$$Q_r = q_s - q_a = -0.314 \frac{W}{m}. \tag{51}$$

$$Q_{total} = Q_f + Q_r = 12.571 \frac{W}{m}. \tag{52}$$

The result for Q_r signifies that the supply pipe actually transfers heat to the return pipe due to the large temperature difference and thus a part of the heat loss from the supply pipe is recovered, making the total heat loss smaller than the forward heat loss.

5 Perspectives of Further Study

This project is concerned with the Danish CHP-plant *Fynsværket*, taking its point of departure in the Danish governmental goal of having a completely renewable heat and electricity sector by 2035. It aims to replace all non-renewable district heating produced at FV07 with heat pumps and a thermal storage. If the Danish 2035 governmental goals are met, using renewable electricity to produce heat with heat pumps, it will automatically yield a renewable heat production. However, there are other ways of replacing all the non-renewable district heating produced at FV07. Given more resources, other solutions would have been evaluated and compared to the heat pump and storage scenario presented in this project. As an example, other heat production technologies could include biomass or biogas for combined heat and power production. This would provide the completely renewable system with a more adjustable heat production compared to heat pump production, where the fluctuating electricity production from wind turbines dictates the district heating production. Other storage solutions, besides the thermal storage containing water as the storage medium, would have been analysed given more time. As an example, a thermal storage using large blocks of rock or smaller pebble rocks as the storage medium would have been interesting to consider as a storage solution. Both financial and efficiency related aspects as well as heat extraction rates of these alternative storage solutions would have been of particular interest.

The renewable heat pump production analysed in the project is only renewable if the electricity used in the heat pumps is produced by renewable electricity production facilities. The effect of having a fluctuating heat price in terms of heat consumption and consumer behaviour in general, would have been an interesting addition to the project. Having a fluctuating heat price enables the consumers to benefit from and consume accordingly to such a price. This would require their heat consumption to be recorded hourly using remote heat meter readings. The possibility of installing such remote meters in Danish consumers' homes and in the Danish industry, as well as benefits from doing so, would be interesting to investigate.

The optimisation model minimises the price of district heating that the consumer has to pay when having completely renewable district heating delivered from the solution in this project, in terms of the electricity price and the marginal costs of the heat pump and the storage. Given more time, an optimisation model containing additional parameters such as pump work and heat loss, etc, would have been constructed. This model could then optimise the flow temperature in the district heating system minimising the total cost of meeting the demand. The pipe analysis in the project is made as a per-unit-length notation. Having additional resources, the software *Termis* would have been used to analyse, dimension and optimise a large pipe network in accordance with the criteria of being able to supply the consumers with heat produced by the solution presented.

The scope of the project is limited to *Fjernvarme Fyn*'s sypply area as seen in Figure 2. Given additional resources, a wider scope would have been adapted to investigate the possibility of making the entire Danish district heating sector renewable, by using heat pumps and storage facilities. Other possibilities could include investigating the feasibility of using solar panels for heating in *Area 4*, where district heating at the moment is non-feasible in terms of socio-economics. Furthermore, the benefits of decentralised heat pumps in *Area 4* could have been considered.

6 Conclusion

In this project the challenges of removing all non-renewable heat production from *Fjernvarme Fyn*'s district heating network have been evaluated, both technically and financially. The motivation for the project's topics is the Danish governmental goal of having a completely renewable heat and electricity sector by 2035. The non-renewable heat production is replaced with heat pumps and thermal storage. The heat pumps produce heat from renewable electricity, thus producing completely renewable heat. For the procedure of using heat pumps and storage to work, fundamental legislative and consumer-orientated aspects of the energy system will have to be adapted.

Heat pumps were chosen as the renewable heat producing technology. An analysis of the technology was carried out, and inherent challenges when implementing them in the current district heating system are accounted for. The implementation feasibility and the most important evaluation parameter, the COP of the heat pump, varies with the circumstances in which the heat pump is implemented. The maximum COP achievable given the specified temperatures is 3.65. Due to very low maintenance requirements and a very long lifetime a heat pump is an extremely reliable production technology.

A large water tank is chosen to be the storage solution. Therefore, a storage temperature gradient, storage heat loss and both a maximum and minimum energy content analysis were carried out. The maximum energy content of the storage is 3174 MWh. The thermal efficiency when having a full storage for an entire year is 84.15 %. The analysis also shows a minimum energy content of the storage, for the district heating system to be able to extract heat from it, of 1801.1 MWh. Therefore, the maximum heat that can be extracted from the storage is 1372.9 MWh. The average thermal efficiency of the storage at the minimum energy content is 87.02 %.

The minimum energy charge after replacing all non-renewable heat production is determined by constructing an optimisation model. The average heat price is found to be 39.57 DKK/MWh when the entire system is implemented. If the system was to run without a storage facility the average price would be 47.56 DDK/MWh, so the storage facility lowers the overall heat price.

A pipe analysis finding pressure and heat losses in per-unit-notation of twin pipes, such as the ones used in certain parts of *Fynsværkets* transmission system, is carried out. The analysis yields a total pressure loss in both the supply and return pipe of 0.029 $\frac{Pa}{m}$. The heat loss in the forward pipe is 12.885 $\frac{W}{m}$. The return heat loss will be -0.314 $\frac{W}{m}$. Therefore, the total heat loss will be 12.571 $\frac{W}{m}$ as the negative return pipe heat loss signifies a heat transfer to the return pipe.

The conclusions above, all indicate that using large industrial heat pumps and heat storage facilities to replace all non-renewable heat production in *Fjernvarme Fyn*'s district heating network, is a viable solution, both technologically and financially. However, it requires a comprehensive alteration within the energy sector to implement such a completely renewable solution. The remaining unknown is whether or not the Danish society is capable of grasping such a paradigm-shift.

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Appendices

A Group Process

The 6-phase model is composed of six isolated stages. The model is a work model that attempts to ensure, that a subject is thoroughly examined and that the problems are solved optimally.

Problem Analysis: During the first phase, the Problem Analysis, challenges regarding the government's 2035 goals for a renewable district heating system was analysed and discussed. Tasks and various subtasks were established so that the overall idea of the project and how to solve the problems was more clear. This was done by brainstorming what kind of the problems and challenges we were going to work with in detail. During this phase, a time schedule found in Appendix E was also created.

Idea Phase: After considering all problems and challenges, we could move on to the next phase, the Idea Phase. Here, we evaluated the problems and challenges, and brainstormed on how to solve these problems. The brainstorms can be seen in Appendix F.

Planning Phase: In the next phase, the Planning Phase, we discussed how we wanted to work with the individual tasks and concluded that we were to choose between two options. The first option was to split the tasks up between us so that each group member single-handedly had responsibility of their respective tasks. By doing so, the other group member's understanding of a certain topic would depend completely on that one person's written product, which might lead to misinterpretations and misunderstandings within the report. This could be avoided if the group worked on the topics in plenum. We chose a middle way between the two options, which was that groups of 2 and three group members worked on individual subtask in order to supplement each other's knowledge, while at the same time keeping every group member busy, and therefore getting sufficient amounts of work done, in less time than working everything through in plenum. We choose to begin every topic by harmonising our understandings and expectations in plenum, where after we divided the tasks between us regarding research for data, theory discussion and so on. This middle way of working in plenum, and working individually ensured both a large amount of work being done in little time, while ensuring an organized product in terms of every member having an idea, of what the other members where doing, at all times.

Problem-solving Phase: The fourth phase, the Problem-solving phase, was the most time consuming phase since it was here the report itself had to be worked out. The sub tasks were treated as described above and in accordance with the time schedule. Due to our well-organized work schedule, this phase was carried out without complications, mainly because we at all times had an idea of how far in the process we were and where we were headed in terms of how we wanted the product to shape up. As mentioned in our Group contract, we agreed to meet at least one day a week, but often more, to focus on the project and to assure that we kept up with our time schedule. During the rest of the week, we worked on our respective assignments and made sure to keep in touch with the rest of the group. To do this we established a Dropbox folder, in which we had a system to store every single part of written material. This was done both to ensure a back-up of our work but also so that every group member at all times was kept up to date with what was going on during the entire process.

Conclusion Phase: In this phase we summed up our results and discussed how we could have done things differently and what results we might have come up with then. We defined the most important results with regards to the model and the simulations and tried to validate them as much as possible.

Product Phase: In this last phase we produced most of the written material. We made sure everything was written to address the target group outlined in the project outline and formulated in a proper manner. The end of the product phase was marked by a period of proofreading all the written material and making sure the layout was set-up according to general guidelines as well as making sure all the references were correct.

B Methods

The data used has been analysed with a mixture of qualitative and quantitative methods. The quality of the given data had to be assessed and additional data had to be acquired where necessary. The following subject-specific methods is used in the elaboration of the report:

Heat transport and storage: Used to analyse the storage solution along with a district heating pipe in the Danish transmission system. This includes finding both heat loses in the storage and the pipes and pressure loses in the pipes as well.

Energy and cost optimization: Knowledge and course specific methods acquired from this course, have been used to construct a mathematical model. The model minimizes the cost of delivering the demanded district heating in the district of *Fjernvarme Fyn*.

Legislation: Knowledge regarding district heating legislation acquired last semester has been used to evaluate the challenges when replacing coal-fired heat production, using heat pumps only.

C Problem Formulation

Background

Today CHP-plants produce both electricity and heat, using primarily fossil fuels. The Danish government has a goal of having a completely renewable electricity and heat sector in 2035. Therefore, the heat and electricity produced at Danish CHP-plants, will have to be replaced with renewable production technologies.

In the second semester project[31], it was determined that it is not feasible to continue CHP production in the future. Therefore, a different heat production technology is needed in the future.

The combination of the 2035 goal and the economic aspect makes the study in this report important, when pursuing a high security of supply in the Danish heat sector.

To limit the scope of this project, *Fynsværket* will be the point of departure when replacing the non-renewable production. The renewable technology, replacing the current heat production at *Fynsværket*, will be heat-pumps using electricity produced by wind turbines. Given the fluctuating nature of wind turbines, heat storage will also be considered to allocate the heat produced by heat pumps to periods where it is needed.

Objectives

The objective of the project is to test the feasibility of replacing current heat production of a CHP-plant, with heat produced by heat pumps using wind turbine electricity. This will be done by conducting a model, determining the amount of electricity and the heat pumps needed to replace the heat produced at *Fynsværket*, with the efficiency of the heat pumps as the deciding parameter.

The heat pump efficiency will primarily be investigated using the course *Heat Transport and storage*. Knowing the efficiency, the amount of wind turbine electricity needed for heat-pumps to replace the non-renewable heat production from *Fynsværket*, can be found. Furthermore, the heat flow from the heat pumps, through storage facilities to the consumer will be investigated in terms of heat losses.

To investigate an optimal renewable solution, using only wind turbine electricity and heat pumps, linear optimization from the course *Cost and Energy Optimisation* will be used.

D Supervisor Contract

Project group no. 1
Supervisor: Ashok Kumar Singh

1. The students construct the project. The supervisor will on basis of an introduction by the students, have a dialogue about problem analysis, choice of method, solutions, laboratory tests and report writing. It is possible, with consent from the supervisor, for the supervisor to review any produced documents and comment on those.

2. Time and setting for each group meeting is agreed upon on a weekly basis. Eventually as a final agenda point at each meeting. If not needed, a meeting can be cancelled.

3. If any documents are to be sent to the supervisor for review or as an orientation, the supervisor needs to receive these two days before the next meeting.

4. Besides the agreed meetings the supervisor and group may contact each other on email. If the students need to contact other faculty teachers or workshops and companies, they do it on their own.

5. If any cooperation issues appear within the group, personal as well as professional, it is expected of the group to resolve these by themselves. If this is not possible (highly unlikely) the supervisor can act as a negotiator.

6. If agreed upon the supervision contract can be changed during the semester.

E Time Table & Supervisor Meeting Summaries

Meeting 1, March 1 2016

- Discussing problem formulation.
- Setting up future supervisor meetings.

Until next meeting:

- Form out a supervisor contract.

Meeting 2, March 8 2016

- Supervisor contract.

Until next meeting:

- Gather data:
  - Heat and Electricity production at Fynsværket (Karl).
  - Electricity prices from Nordpool (Allan).
  - Heat prices today (Allan/Karl).
  - Data on heat pumps (COP, Marginal Costs) (Karl).
  - Research possible storage solutions (Jonathan).
- Specify the constraints for the optimisation (Rasmus).

Meeting 3, March 15 2016

- Present gathered data etc.
- For the coming meetings Ashok would like an agenda on beforehand of what we have been doing since last, specifying who has done what and which problems we have solved (attempted to solve).

Until next meeting:

- Begin optimisation model and storage analysis on water tank.
- Consider legal issues and price determination on district heating.

Meeting 4, March 29 2016

- Present the work we have done since last meeting.
  - Working on optimisation model.
  - Working on price determination in district heating.

Until next meeting:

- Begin heat pump COP analysis and heat flow analysis (If possible at this point, use *Termis*).
- Finish optimisation model and legal and economic aspects.

Meeting 5, April 12 2016

- Working on heat flow analysis and storage analysis.

Until next meeting:

- Finalise heat flow analysis and storage analysis.

Meeting 6, April 26 2016

- Storage analysis is done.

Until next meeting:

- Economic & legislative analysis, heat pump analysis, optimisation and heat flow analysis is done.
- Finalise writing process.

Meeting 7, May 10 2016

- Heat pump and heat flow analysis is done.

Until next meeting:

- Finish optimisation results, conclusion and appendix.
- Deadline for draft to Ashok (May 12).
- Proof reading.

Meeting 8, May 17 2016

- Final comments for the report.
- Project due date: 19, May 2016

F Brainstorms

Project Topic

- Heat production in the future
  - Currently mostly CHP and gas
  - In the future completely renewable
- Wind power
- Biogas
- Heat pumps
- Large wind production in the winter - more electricity
  - Large heat consumption in the winter
  - Heat pumps use electricity to produce heat

Perspectives of Further Studies

- Alternative district heating sources (Biomass, Biogas and coproduction of heat and electricity).
- Solar heating for the outskirts of Denmark.
- More wind capacity for the district heating system.
- Heat consumption with a fluctuating heat price.
- Alternative heat storage solutions and location of storage (Termis).
- Surplus heat from large production companies used as district heating.
- Remotely read heat meter.
- Optimisation between, pump work and supply temperature in perspective with heat loss (Termis).

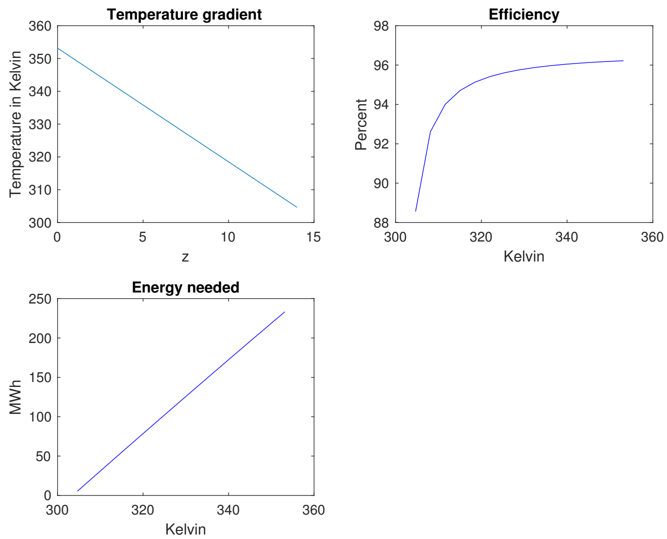
G Storage Analysis MATLAB-Model

```
Ts1=353.15;
Ts2=313.15;
Tearth=291.15;


q_cube=0.705;
k_water=0.58;
H=14;
z=[0:1:14];
Tz=[((2*Ts2*k_water*z(1:15)-2*Ts1*k_water*z(1:15)-H*q_cube*z(1:15)+2*H*Ts1*k_water)/(2*H*k_water))];
disp(Tz')
subplot(2,2,1)
plot(z,Tz)
title('Temperature gradient')
xlabel('z')
ylabel('Temperature in Kelvin')
hold on


U=0.045;
qwall=U*(Tz(1:15)-Tearth);
Atotal=14340;
Qlosstotal=(qwall(1:15)*Atotal)./1000000;
Qlossmwh=Qlosstotal(1:15)*8760;

Cp90=4208;
Cp40=4179;
Interval=2.07;
Cp=[Cp90:-2.0714:Cp40];
rho40=992.3;
rho=[971.8:1.7000:995.6];
Volume=65000;
Tmin=40+273.15;
% nedenstående er energien i hvert lag
Etotal=(Volume.*(Cp(1).*rho(1).*Tz(1)-Cp40.*rho40*Tz(15)))./(3600*1000000);
% denne effektivitete er forkert
A_wall1=31.11*2 % dette er et wall "stykke"
```

```
A_wall2=149.235*2
A_wall=A_wall1+A_wall2
A_bottomandtop=4643
qwalls=U*(Tz(1:15)-Tearth);
qtop=U*(Tz(1)-Tearth);
qbottom=U*(Tz(15)-Tearth);
Qlosstotal_walls=((qwalls(1:15).*A_wall)./1000000)*8760; % in MWH
Qlosstotal_top=((qtop*A_bottomandtop)./1000000)*8760;
Qlosstotal_bottom=((qbottom*A_bottomandtop)./1000000)*8760;


Qlosstotal=Qlosstotal_walls+Qlosstotal_top+Qlosstotal_bottom;
Qlossmwh2=Qlosstotal(1:15)*8760;
Vtoplayer=4643;
Etotal2=(Vtoplayer.*(Cp90.*rho(1:15).*Tz(1:15)-Cp40.*rho40*Tz(15)))./(3600*1000000);

Efficiency_walls=((Etotal2(1:15)-Qlosstotal_walls(1:15))./Etotal2(1:15)).*100;
Efficiency_top=((Etotal2(1)-(Qlosstotal_top-Qlosstotal_walls(1)))./Etotal2(1))*100;
Efficiency_bottom=0

Efficiency_avgwall=(sum(Efficiency_walls)+Efficiency_top)/17;

subplot(2,2,2)
plot([Tz],Efficiency_walls,'b')
title('Efficiency')
xlabel('Kelvin')
ylabel('Percent')

Emax=[(Vtoplayer.*(Cp(1).*rho(1).*Tz(1)-Cp40.*rho40*Tz(15)))./(3600*1000000)]'


Eneedlayer=[(Vtoplayer.*(Cp(1:15).*rho(1:15).*Tz(1:15)-Cp40.*rho40*Tz(15)))./(3600*1000000)]'
Egraidenttotal=sum(Eneedlayer)% i mwh
subplot(2,2,3)
plot([Tz],Eneedlayer,'b')
title('Energy needed')
xlabel('Kelvin')
ylabel('MWh')
E_HP=310*10^6; % in WH
```

```
Hours_storage=Egraidenttotal*10^6/E_HP;
%Finding the flowrate
% from here, we can found the mass-flow needed, to fill the storage in 3
% hours, using the full heat-pump capacity for all those 3 hours. The
% capacity of the heat pump will then be 571 MW, if the pump can deliver
% 571 MWH of energy, by producing its maximum capacity of 571Mw for one
% hour
%therefore,
P_transport=E_HP;
% we can use the equation: P_transport=mdot*(Cp(1:14)*Tx(1:14)-Cp40*Ts2)
% so that we get:
mdot=P_transport./((Cp(14)*Tz(1))-(Cp40*Tz(15))); % her skal vi IKKE bruge
%variende temperaturer og Ts, da mass flow rate ved en temperatur-forskel
%på 0 grader (det sidste lag) bliver massflow-rate uendelig stor.
% where P_transport is in WATTS
% this is then the required mass flow rate that is needed, when the storage
% is to be heated from 40 degrees (uniform temperature) to produce the
% temperature gradient above
Q_flowrate=mdot./rho(1:15);
% by dividing through with the density, we can get the average volume flow
% rate:
Q_flowrateavg=sum(Q_flowrate)/14;
% if the required maximum velocity is 4 m/s, we can now find the required
% diameter of the pipe needed
V_need=4; % in m/s
% now the area can be found as
A_rea=Q_flowrateavg/V_need;
% and as the area of a circular pipe is 1/4*Diameter^2*pi, we get that the
% required diameter of the pipe is
Diameter=sqrt((A_rea*4)/pi)

  353.1500
  349.6851
  346.2202
  342.7553
  339.2904
  335.8255
  332.3606
```

```
  328.8957
  325.4308
  321.9659
  318.5010
  315.0361
  311.5712
  308.1063
  304.6414


A_wall1=62.2200   A_wall2 =298.4700   A_wall =360.6900

A_bottomandtop =4643   Efficiency_bottom =0   Emax =233.2527

Eneedlayer =

  233.2527
  217.2952
  201.2887
  185.2333
  169.1289
  152.9758
  136.7740
  120.5236
  104.2248
   87.8775
   71.4820
   55.0382
   38.5463
   22.0064
    5.4186


Egraidenttotal =1.8011e+03    Diameter =0.7268
```


Temperature gradient
Temperature in Kelvin
z
Efficiency
Percent
Kelvin
Energy needed
MWh
Kelvin

H Optimisation Model MATLAB

Semesterprojekt - Minimering af varmeprisen

Contents

- Data
- Optimization

Data

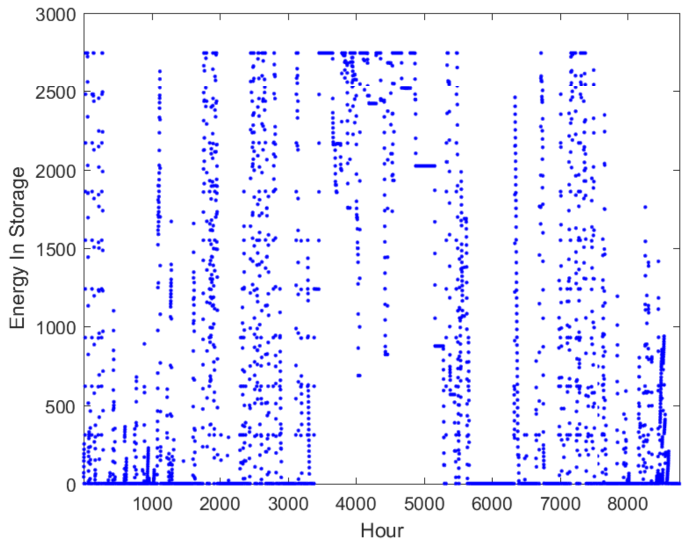
```
%Electricity prices in DK1 in 2014.
Elpris = xlsread('ProductionDATA', 'Q7:Q8766');
%Heat production of Fynsværket - non-negative.
Q_Demand = xlsread('ProductionDATA', 'I7:I8766');
Gns_Elpris  = sum(Elpris)/8760; %Average electricity price in 2014.
COP = 3.65; %Effectivity of the heat pump.
%The amount of heat pumps wich needs to be installed in MW.
Installed_Heatpumps = max(Q_Demand);
%Investment cost of heat pumps in DDK.
Investment_Heatpumps = 580000*7.45*Installed_Heatpumps;
MC_HP = 3650*7.45/8760; %Marginal cost of heat pump in DDK/MW/hour.
Storage_Size = 65000; %Size of storage in m^3.
%Investment cost of storage in DDK.
Investment_Storage = 34*50000*7.45+20*(Storage_Size-50000)*7.45;
%Marginal cost of storage in DDK/MWh.
MC_ST = Investment_Storage*0.007/1.5498e+05;
EnergyInStorage = 0; %Initial energy in storage in MWh.
Sum_Varmepris = 0; %Initial price of heat production in DDK.
Q_ud = 0; %Initial amount of energy out of storage.
Storage_Max = 2745.8; %Max capacity of storage in MWh.
VarmeprisVektor = zeros(1,8760);
```

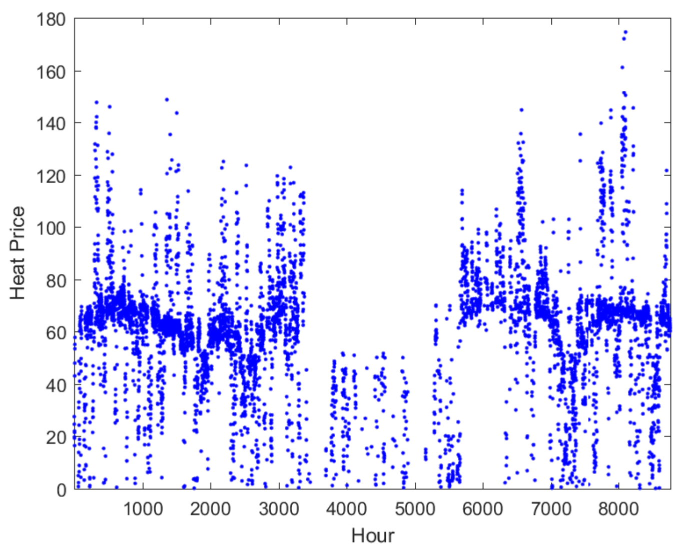
Optimization

```
for n = 1:8760
    f = [(Elpris(n)/COP)+MC_HP (Elpris(n)/COP)-(Gns_Elpris-Elpris(n))+...
        MC_HP (Gns_Elpris-Elpris(n))+MC_ST];

    A = [1 0 0
```

```
     -1 0 0
     0 1 0
     0 0 1
     1 1 0];

b = [Q_Demand(n)+Storage_Max-EnergyInStorage
     EnergyInStorage-Q_Demand(n)
     Storage_Max-EnergyInStorage
     EnergyInStorage
     Installed_Heatpumps];

Aeq = [1 0 1];

beq = [Q_Demand(n)];

lb = [0 0 0];

ub = [Installed_Heatpumps 310 310];

[x] = linprog(f,A,b,Aeq,beq,lb,ub);

EnergyInStorage = EnergyInStorage+x(2)-x(3);

Varmepris = (((Elpris(n)/COP)+MC_HP)*x(1)+((Elpris(n)/COP)...
  -(Gns_Elpris-Elpris(n))+MC_HP)*x(2)+(Gns_Elpris-Elpris(n)+MC_ST)...
  *x(3))/Q_Demand(n);

plot(n,EnergyInStorage,'b.')
xlabel('Hour')
ylabel('Energy In Storage')
axis([1 8760 0 3000])
hold on

plot(n,Varmepris,'b.')
xlabel('Hour')
ylabel('Heat Price')
axis([1 8760 -200 200])
hold on
```

```
    Q_ud = Q_ud+x(3);
    if Varmepris>1000;
       Varmepris=0;
    end

    Varmepris;

    if Varmepris>0
        Sum_Varmepris = Sum_Varmepris+Varmepris;
        Gns_Varmepris = Sum_Varmepris/n;
    end
    VarmeprisVektor(n) = Varmepris;
end
Q_ud
VarmeprisVektor;
Gns_Varmepris

filename = 'VarmeprisVektor.xlsx';
xlswrite(filename,VarmeprisVektor,1,'A1')



Gns_Varmepris =

   39.5716
```


Energy In Storage
3000
2500
2000
1500
1000
500
0
1000
2000
3000
4000
5000
6000
7000
8000
Hour


Heat Price
180
160
140
120
100
80
60
40
20
0
1000
2000
3000
4000
5000
6000
7000
8000
Hour