



Analysis of Electric Heat Pumps in Solar Thermal District Heating Systems

Masters thesis

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Synopsis

There is a political ambition to gradually phase out fossil fuels in favour of an energy systems based on renewable energy sources and most actors of the energy sectors consider electric heat pumps a central element in this development. Currently, however, the implementation of heat pumps is developing slowly and largely loosing terrain to solar thermal operating under a more favourable legal and economic framework.

The purpose of this study is to analyse whether the current popularity of solar thermal could become a problem for the desired implementation of electric heat pumps in the district heating sector. The analysis takes its point of departure in a generic district heating plant dimensioned to simulate the type of plant typically investing in solar thermal or electric heat pumps. Using the energy system analysis software energyPRO simulations of different scenarios are carried out and the results form the basis of an economic calculation estimating the net present value of an investment with a time horizon of 15 years.

As a first part of the analysis the feasibility of investing in solar thermal and electric heat pumps individually is calculated concluding a higher feasibility for a solar thermal solution. Following this, the feasibility of a solar thermal district heating plant to investing in a heat pump is calculated. The robustness of these results are tested in a series of sensitivity analyses, including varying electricity and gas prices, varying heat sources for the heat pump and changes to existing tax, tariff and subsidy structures. The study concludes that the economic feasibility of investing in a heat pump is severely reduced by the investment in solar thermal. However, the sensitivity analysis shows some potential especially if the heat pump is exempted from the PSO tariff.

PREFACE

This master thesis is prepared by Mie Lebeck and Kristian Brun Madsen on the 4th semester of the master program in Sustainable Energy Planning and Management at Aalborg University in the period from the 1st of February to the 2nd of June 2016.

The purpose of the master thesis is to explore any possible conflict between solar thermal and large electric heat pumps in Danish district heating systems. Hereby, the master thesis is especially targeting decision-makers at a political level but also interest organisations related to the energy sector and district heating companies are considered a target group.

ACKNOWLEDGEMENTS

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- Knud Erik Nielsen, head of sales at Arcon-Sunmark.
- Jørgen Risom, special advisor at The Heat Pump Mobile Task Force.
- Kasper Nagel, project analyst at The Danish District Heating Association.
- Energinet.dk, for ongoing help and guidance.
- Kristina Brun Madsen, for proofreading.
- Anders N. Andersen, supervisor.

READING GUIDE

REFERENCING

The project is referenced using the Harvard method, meaning that all references are given with a name and a date as for example (Energinet.dk, 2015). This format also applies in the case of interviews as for example (Risom, 2016). Where more than one source exist with the same name and date these are marked with a letter as for example (The Danish Energy Agency, 2015 A). In the case of legal sources, these are referenced by their official name as for example (LBK no 1307 of 24/11/2014).

NUMBER FORMAT

This project will present numbers after the traditional grammar rules of the English language, where a dot denotes decimals and a comma denotes thousands, as follows:

2,500 – two thousand five hundred

2.500 – two and a half

APPENDICES

Appendix A – Solar thermal data

Appendix B – Sæby District Heating

Appendix C – Arcon-Sunmark

Appendix D – Heat Pump Mobile Task Force

Appendix E – Economy data

Appendix F – Heat profile

Appendix G – Production and operation costs, Basic scenario

Appendix H – Production and operation costs, Solar thermal scenario

Appendix I – Production and operation costs, Heat pump scenario

Appendix J – Production and operation costs, Combined scenario

Appendix K – Method improvement calculation

Appendix L – energyPRO model, Standard analysis

Appendix M – energyPRO model, Method improvement

Appendix N – energyPRO model, Sensitivity analysis – Electricity prices

Appendix O – energyPRO model, Sensitivity analysis – Gas prices

Appendix P – energyPRO model, Sensitivity analysis – Seawater

Appendix Q – energyPRO model, Sensitivity analysis – Industrial waste heat

Appendix R – energyPRO model, Sensitivity analysis – Taxes, tariffs and subsidies

The appendices as well as a digital version of the project can be found on the enclosed CD.

NOMENCLATURE

Name	Definition	Unit
η_{HP}	Heat pump efficiency (COP)	
η_L	Lorenz efficiency	
η_s	Heat pump system efficiency	
c	Heat capacity of water	kJ/kg*K
C_{loss}	DH pipe heat loss coefficient	kW/K
D_{DH}	Heat delivered to consumers	kW
L_{DH}	Loss in district heating grid	kW
\dot{m}	Flow	kg/s
T_{AvSup}	Average supply temperature	°C
T_{AvRet}	Average return temperature	°C
T_{sap}	Temperature, supply at plant	°C
T_{rap}	Temperature, return at plant	°C
T_{sac}	Temperature, supply at consumer	°C
T_{rac}	Temperature, return at consumer	°C
T_{soil}	Soil temperature	°C
T_H	Logarithmic mean high absolute temperature	K
T_L	Logarithmic mean low absolute temperature	K
T_{in}	Absolute inlet temperature from HP evaporator or condenser	K
T_{out}	Absolute outlet temperature from HP evaporator or condenser	K

ABBREVIATIONS

CHP – combined heat and power
 NPV – net present value
 SPT – simple payback time
 DH – district heating
 HP – heat pump
 COP – coefficient of performance

TRANSLATIONS

Some names of specific legislation, schemes, taxes etc. have been found difficult to translate. To avoid confusion the following table offers translations for these.

Original name	Translation
Grundbeløb 1 and 2	1st and 2nd basic subsidy
Nettoafregning	Net settlement
Energispareaftalen	The Energy Savings Scheme
Varmepumperejseholdet	The Heat Pump Mobile Task Force
Elpatronordningen	Scheme on reduced taxes for district heating

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1 THE ROLE OF ELECTRIC HEAT PUMPS IN THE FUTURE ENERGY SYSTEM

Over the recent decades, the environmental as well as social impacts of conventional energy systems have gained increasing focus both politically and from the public. As a result, international and national goals have been set for a gradual transition of the energy system towards renewable sources. In the 2020 climate and energy package, the European Union set forth three key targets: a 20% cut in greenhouse gas emissions compared to 1990 levels, a 20% improvement of energy efficiency, and that 20% of the energy consumed within the EU be produced from renewable sources (European Commission, 2016 A). In the more recent 2030 energy strategy these targets have been raised to a 40% cut in greenhouse gas emissions, 27% energy from renewable sources and 27% energy savings compared to “business as usual”; however the energy savings are only indicative (European Commission, 2016 B). As some EU member states are thought better suited for this transition than others, the concrete targets of the individual state varies. There has been criticism of the EU’s climate goals from several parts. It has been argued that the goals are too easily attainable, as the targets will be met with the current development and therefore have no real effect (The Danish Ecological Council, 2014). Another argument is that the target of a 40% greenhouse gas reduction is insufficient to secure a maximum of 2°C global warming increase (Videnskab.dk, 2014). The 40% greenhouse gas reduction applies within the EU, meaning that CO₂ quotas bought outside of Europe will constrain the total greenhouse gas reduction, and thus interfere with the overall goal. Christian Ege from The Danish Ecological Council comments: “the cheapest energy is the energy that we don’t consume” referring to the non-binding targets of 27% reduction of energy savings as being unambitious (The Danish Ecological Council, 2014). As a result of the EU 2020 climate and energy package in Denmark, the goal for 2020 is to have 30% of the consumed energy produced from renewable sources. With the energy agreement from 2012, the Danish government set forth more far-reaching goals. According to this agreement, by 2020 half of the electricity consumption should be covered by wind; by 2030 coal should be phased out from Danish power plants; by 2035 the electricity and heat supply should be covered by renewable sources; and by 2050 the entire energy supply including industry and transport should be covered by renewable sources (Social Democrats, The Danish Social-Liberal Party, The Socialist People's Party, The Liberal Party of Denmark, Danish People's Party, Red-Green Alliance and Conservative People's Party, 2012) (The Danish Government, 2011).

1.1 THE RENEWABLE ENERGY TRANSITION IN DENMARK

Investments in new production units carried out today last for several decades, meaning that it is important to make the right investment now, if the 2035 goal of a fossil fuel free district heating sector is to be obtained. In Denmark, the primary focus of the renewable transition has been wind power and by 2015 production from wind covered 42.1% of the total Danish electricity consumption (Energinet.dk, 2016 A). Like many other renewable energy sources, however, wind is characterised by its intermittent nature. This means that, unlike in traditional fossil-based energy systems, it is not possible to adjust energy production according to the demand. In 2015 for Jutland and Funen, this resulted in a production from wind that exceeded the total consumption for 1460 hours of the year, equivalent to 16.7% of the time (Energinet.dk, 2016 A). As there is no easy way of storing electricity for later use, the solution has generally been to exchange electricity with our neighbouring

countries. Some do, however, question both the flexibility and feasibility of a future electricity system largely built on import and export (Lund, Renewable Energy Systems, 2014). An alternative approach is to utilise the excess electricity in the heating sector through conversion technologies such as electric boilers or, more efficiently, electric heat pumps. Unlike electricity, heat can easily be stored, which means that the energy would not go to waste even if there were no immediate heat demand; it could be stored to substitute future heat production. Such a solution would not only help balance the electricity system but would also offer potentially cheaper heat as the tendency shows still lower electricity prices and, as a consequence hereof, still less production from the many installed CHP-units (The Danish Energy Agency, 2016 A).

In some future energy system scenarios, the utilisation of electricity in the heating sector is part of a larger plan for a “smart energy system” connecting both the electricity, heating, cooling, gas and transport sectors through the conversion of one form of energy to another (Connolly, et al., 2013). In other scenarios energy conversion technologies such as heat pumps are simply seen as a minor part of a solution primarily focusing on the exchange of electricity across borders.

However, the consumption of wind power is not the only objective of large electric heat pumps. As the production on CHP-units is reduced, these become less attractive as base load in the future energy system. The usage of biomass boilers is questionable as the use of biomass could lead to a dependency on fuel import and as biomass is not considered a CO₂ neutral source by all. A district heating sector based on a diversity of renewable sources such as heat pumps, solar thermal and industrial waste heat is both efficient and good at balancing the energy system, and thus the usage of biomass in the district heating sector can be limited. The transport sector is difficult to convert to e.g. electricity, and therefore biofuels is a more suitable solution for the transport sector (Energinet.dk, 2015 A). All considered it generally appears, that heat pumps are a desired technology for the future energy system from the point of view of most actors in the energy sector.

1.2 DANISH DISTRICT HEATING SCENARIOS

Changing governments have set forth different concrete strategies and scenarios for meeting the future energy targets. For the current government no official plan or scenario exists for this area. Some less official scenario reports do, however, exist for a fossil free heat and electricity sector in 2035. In their report *Energy scenarios for 2020, 2035 and 2050* from 2014, The Danish Energy Agency analysed four different scenarios for a renewable heat and electricity supply by 2035 and an entirely renewable energy sector by 2050. All the analysed scenarios include an expansion of the district heating system as well as heat savings. Furthermore, both solar thermal and electric heat pumps are expected to play a certain part in all scenarios in 2035 and even more so in 2050 with scenarios focussing on electrification of the energy system allowing for a greater use of heat pumps than scenarios focussing on biofuels.

In the report, both solar thermal and electric heat pumps are expected to be implemented primarily in decentral district heating plants. Hence, by 2050 the report predicts a share of production from solar thermal on decentral district heating plants of 13% and a share of production from heat pumps of 20-62% (The Danish Energy Agency, 2014 A). This tendency is even clearer in another report from The Danish Energy Agency, *The role of district heating in future energy supply*, also from 2014. Here heat production from solar thermal and elec-

tric heat pumps or boilers is expected to make up around 12.3% and 14.2% respectively of the total production of district heating by 2035 but as much as 33.3% (3.1 TWh) and 50.0% (4.6 TWh) respectively of the district heating produced on small district heating plants¹ (The Danish Energy Agency, 2014 B). Since in the analysis, small district heating plants are responsible for 24% of all district heating production, this concerns a large share of Danish district heating plants that are expected to invest in either solar thermal, electric heat pumps or boilers or a combination of these (The Danish Energy Agency, 2014 B).

Another point that can be drawn from the report is that a significant difference can be seen between the proposed business-economic scenario and the socioeconomic one with the business-economic clearly favouring the penetration of solar thermal over electric heat pumps and boilers and vice versa. This suggests that the existing taxes and subsidies as well as other planning framework are at present favouring solar thermal over heat pumps in district heating production even though this is not, according to the analysis, the most socio-economically favourable technology (The Danish Energy Agency, 2014 B).

Companies and organisations outside of official national jurisdiction have made scenarios for the composition of the future energy system, too. The tendency is that most of these also predict an increased use of both solar thermal and electric heat pumps, though generally not to the same extent as seen in the analyses by The Danish Energy Agency. In their report, *Scenarios for Danish electricity and district heating 2020 to 2035*, The Danish Energy Association set forth two more or less opposing scenarios, one focusing on expansion of renewable energy technologies and one focusing on the utilisation of fluctuating energy. The expansion scenario suggests an increase in solar thermal production of about 8.3% (3 TWh) but completely disregards large heat pumps for the district heating sector. The utilisation scenario predicts a slightly smaller share of solar thermal in district heating of about 5.5% (2 TWh) but a significant increase in heat pump share to about 27.8 (10 TWh) without further specifying where this production should be located (The Danish Energy Association, 2013). In *Energy Vision 2050*, The Danish Society of Engineers (IDA) predicts a solar thermal district heating share of about 6-7% (2.5 TWh) and a heat pump share of about 18.4% (7 TWh) already by 2035, and these numbers hardly change by 2050. As opposed to The Danish Energy Agency scenarios, the IDA scenario assumes that the majority of the heat pump capacity should be located in the central district heating areas with solar thermal making up 25.0% of the decentral and 5.0% of the central district heating production (Mathiesen, et al., 2015). This means that a potential conflict between solar thermal and heat pump production could be avoided. Finally, in their report *Energy concept 2030* from 2015, the Danish TSO Energinet.dk predicts a 14.5% (4.5 TWh) district heating production from solar thermal and geothermal and only 4.5% (1.4 TWh) produced from heat pumps, with the remaining share divided equally between biomass and industrial waste heat. This prioritisation is quite opposite to the others, as the focus is on large solar thermal capacities rather than heat pumps. The report does, however, specifically recommend the combination of CHP, solar thermal and heat pumps as a supply solution that is very robust towards varying electricity prices (Energinet.dk, 2015 A). Hence, the report still partly assumes a certain compatibility of the solar thermal and heat pump technologies within a single district heating plant. The Danish District Heating Association is working on a district heating strategy for 2030 to be presented in October 2016, but by the deadline of this thesis, no official strategy exist. Inquiries with the Danish District Heating Association do, however, support most of the scenarios

¹ In the report "*The role of district heating in future energy supply*" The Danish Energy Agency defines small district heating systems as systems with an annual heating demand below 1 PJ and with no production from waste incineration.

proposed by other organisations with both solar thermal and electric heat pumps playing a role especially in decentral district heating systems (Nagel, The Danish District Heating Association, 2016). The share of solar thermal and heat pumps in district heating by 2035 as presented in the different scenarios is presented in Figure 1.

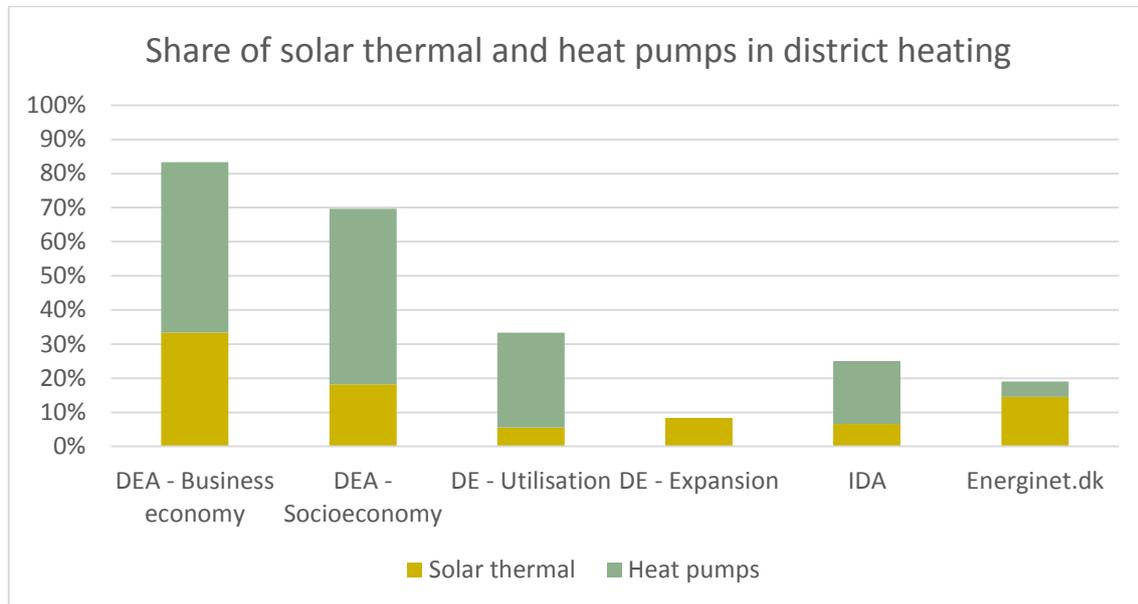


Figure 1: Solar thermal and electric heat pump production shares in district heating scenarios for 2035. It is important to be aware that the different shares are calculated based on considerably different total expected demands for district heating. The scenarios for the Danish Energy Agency (DEA) are both for smaller district heating systems with no waste incineration. These, hence, represent a smaller actual energy amount than the other scenarios. The DEA scenarios do not specify the technology but only the fuel (electricity) and electric boilers are, hence, also represented in the graph. The DE - Utilisation scenario does not differentiate between heat pumps and geothermal and the specific heat pump share is, hence, not known. Besides solar thermal and heat pumps the six scenarios primarily focus on biomass and biogas but also sources such as waste, industrial waste heat and geothermal are mentioned. (Energinet.dk, 2015 A) (Mathiesen, et al., 2015) (The Danish Energy Association, 2013) (The Danish Energy Agency, 2014 B).

It is important to note that the presented scenarios do not necessarily aim to set forth one optimal solution or prediction for the composition of the future energy system. They can, however, lay the basis for a discussion of the consequences of different foci in the planning of the energy system. For example, the expansion scenario from The Danish Energy Association represents a somewhat extreme case aiming to “show the effects of a continuous acceleration of the expansion of renewable energies without the consumption side keeping up” (The Danish Energy Association, 2013 – translated by the author). The general picture drawn from Figure 1 is, thus, that all of the leading energy system actors represented in this review expect both solar thermal and electric heat pumps to play a role in the future energy system, though the expected proportional significance of each of these technologies varies between the different scenarios. Most notably, The Danish Energy Agency proposes that solar thermal and electric heat pumps be the most dominant technologies in all small district heating plants by 2035.

Looking at actual development tendencies, however, the two technologies are not equally gaining ground in the Danish district heating sector. By the beginning of 2016, a total of 52 solar thermal plants have been established in connection to district heating, mainly in smaller district heating systems, and plans are made for more projects (Solvarmedata,

2016). Moreover, prospects for both very large solar thermal plants above 100.000 m³ and production shares above 40% are looking promising (Silkeborg Forsyning, 2015) (Dronninglund Fjernvarme, 2014). Quite the reverse, electric heat pumps appear to be struggling on the market. By March 2015, 15 large electric heat pumps had been installed in connection to district heating with a total effect of 20.3 MW_{th} (PlanEnergi, 2015). Figure 2 shows the development in solar thermal and large electric heat pumps 2009-2015 as well as a linear forecast of the development until 2035.

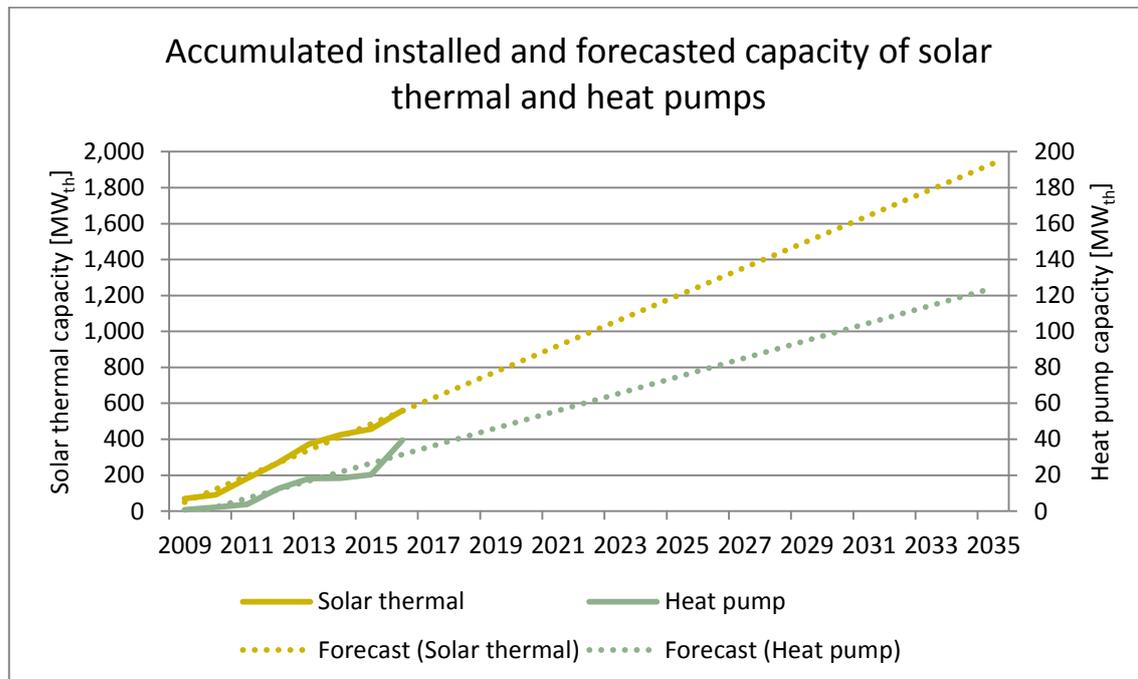


Figure 2: Accumulated installed and forecasted heat capacities for solar thermal and electric heat pumps. Notice that the axes for installed capacities of the two technologies differ by a factor ten. Besides already established projects, the figure includes known solar thermal and heat pump projects planned for 2016. (Solvarmedata, 2016) (Silkeborg Forsyning, 2015) (PlanEnergi, 2015) (Wittrup, 2015). For calculations see Appendix A – Solar thermal data.

Even though in the presented scenarios, heat pumps are generally expected to play a bigger role than solar thermal in the future energy system, currently heat pumps only make up about 7% of the total installed solar thermal capacity. Assuming an annual operation time of 7000 hours, heat pumps currently make up about 6% of the 2035 level as proposed by The Danish Energy Agency in their report, “*The role of district heating in future energy supply*”. Looking at the projection for the development until 2035, about 19% of the proposed installed heat pump production of 4.6 TWh_{th} can be expected to be met. With an assumed production of 700 MWh_{th} per installed MW_{th} solar thermal, production from solar thermal currently makes up about 13% of the 2035 level as proposed by The Danish Energy Agency and with the projected development 43% of the 3.1 TWh_{th} is expected to be met. Hence, both solar thermal and heat pumps are struggling to meet the levels proposed by The Danish Energy Agency. The prospects for heat pumps are, however, most critical.

1.3 FUTURE CHALLENGES

Several conditions are expected to limit the interest in heat pump projects. First and foremost, the economic and legal framework for using electric heat pumps is complex and does

not always favour the use of the most attractive heat sources. This has historically led to failed projects as the feasibility of investing in a heat pump is not always simple to estimate beforehand (The Danish Energy Agency, 2009). Moreover, the feasibility of a heat pump project is highly dependent on proximity of an attractive heat source. As such a heat source is not always available and as several challenges can occur linked to the use of certain types of heat sources, this can also negatively affect the feasibility of a heat pump project (Clausen, From, Hofmeister, Paaske, & Flørning, 2014 A). Finally, the production pattern of a heat pump is relevant. As the initial investment in a heat pump is relatively costly, the feasibility of a heat pump project is generally highly dependent on the heat pump operating as much as possible. In most cases, a heat pump is expected to operate as a base load unit, running 6000-8000 hours of the year (Clausen, Kim S.; From, Niels; Hofmeister, Morten; Paaske, Bjarke Lava; Flørning, John, 2014 B). This could conflict with other production units operating base loads especially in periods of low heat demand.

None of the scenario reports referred to in Figure 1 concretely states how the different technologies are expected to complement each other. Hence it is not specified if solar thermal and electric heat pumps are expected to work side by side within the same district heating systems. In the scenarios set forth by The Danish Energy Agency, the sheer size of the shares of solar thermal and heat pump production (though electric boilers are also part of this) almost inevitably appear to assume the presence of both technologies in the same district heating systems. With the current rapid growth in solar thermal district heating it may, in any event, be relevant or necessary to combine the two technologies in some cases in order to meet the stated targets. This calls attention to the compatibility of the two technologies. If solar thermal and electric heat pumps are difficult to integrate within the same district heating system, the current expansion of solar thermal could potentially become a barrier for the desired implementation of electric heat pumps. This study takes its point of departure in this potential conflict.

2 RESEARCH QUESTION

This study aims to test the compatibility of solar thermal and electric heat pumps in district heating systems. This is done with the purpose of determining whether the current popularity of solar thermal could become a barrier for the penetration of large electric heat pumps. The analysis takes its point of departure in the following research question:

Is the current development in solar thermal district heating hindering the implementation of large electric heat pumps in the Danish district heating sector, and what external factors are influencing this?

The first objective of the study is, hence, to determine whether a conflict actually exists between the two technologies in a district heating system. By testing different external conditions, it is hopefully possible to determine which factors are influencing this subject and, hence, which changes in these factors could possibly allow for a better coproduction from solar thermal and electric heat pumps in a district heating system.

2.1 DELIMITATIONS

The study takes its point of departure in the aforementioned stated interest in electric heat pumps in the future district heating system. A fundamental assumption of the study is, hence, that large electric heat pumps are a desired technology for the future energy system and society as a whole. Based on this assumption the study focuses on the rationality of the district heating companies and the motivation of these to invest in solar thermal and heat pumps. This means that the study is constructed as a business economic analysis focusing on business economic factors such as technical potentials and economy. Socioeconomic factors such as the environment and possible social implications of different technologies are, thus, not considered in the study.

The study tests how external factors affect the economic feasibility for solar thermal district heating plants of investing in electric heat pumps. This includes factors such as fuel prices and taxes, tariffs and subsidies. For simplification reasons, however, the study applies a fairly simple understanding of district heating systems where only existing and tested technical solutions for solar thermal and electric heat pumps are applied. This means that the study does not thoroughly analyse different systemic constellations of solar thermal and heat pumps and does not test different options for using solar thermal as a heat source for the heat pump.

2.2 PROJECT STRUCTURE

The project is structured around a simulation of the operation of a generic district heating system imitating a typical system suitable for solar thermal and district heating with the stepwise addition of solar thermal and electric heat pumps. Subsequently, a series of method improvements and sensitivity analyses test the robustness of the findings and identify any focus points for future improvement to the existing framework. The study goes through four separate steps:

CONTEXT

The first step describes the general context of the study, i.e. the involved technologies and

their economic framework. First, the technical specifications of solar thermal and electric heat pumps are accounted for along with their production patterns and potentials for district heating both separately and combined. After that, the economic framework of the study is presented including costs and revenues linked to investments, maintenance and production and other economic factors such as taxes, tariffs and subsidies affecting the operation of a district heating plant.

STANDARD ANALYSIS

The second step prepares and carries out the standard analysis of the study. First and foremost, this includes designing and dimensioning the generic district heating plant forming the basis of the study. This being achieved, the energy system analysis software, energyPRO, is employed to simulate the annual operation of the system including different capacities of solar thermal and electric heat pump individually and combined. The economic potentials of different scenarios are then calculated as the net present value over the time horizon of the investment. This analysis results in an initial conclusion on the feasibility of combining solar thermal and heat pumps in district heating which is then expanded and tested in the following steps.

METHOD IMPROVEMENT

The third step tests the validity of the results from the standard analysis by applying a more complex, improved method. In this step, the sufficiency of the simple heat pump simulation offered in energyPRO is questioned and a more advanced heat pump based on varying supply temperatures is simulated. With the use of the more advanced heat pump, the combined scenario of the standard analysis is repeated.

SENSITIVITY ANALYSIS

The fourth step tests the robustness of the results of the study through a series of sensitivity analyses testing factors possibly affecting these. The sensitivity analyses test four different external factors: electricity prices, gas prices, heat sources for the heat pump and taxes, tariffs and subsidies. Based on this step it is possible to determine what conditions have the greatest effect on the results of the study.

All four steps considered, the study includes a series of scenarios that are tested, processed and then either kept or rejected for the further study depending on the results. In an attempt to minimise any confusion, the following diagram, Figure 3, illustrates the structure and four steps of the study as well as the different scenarios tested.

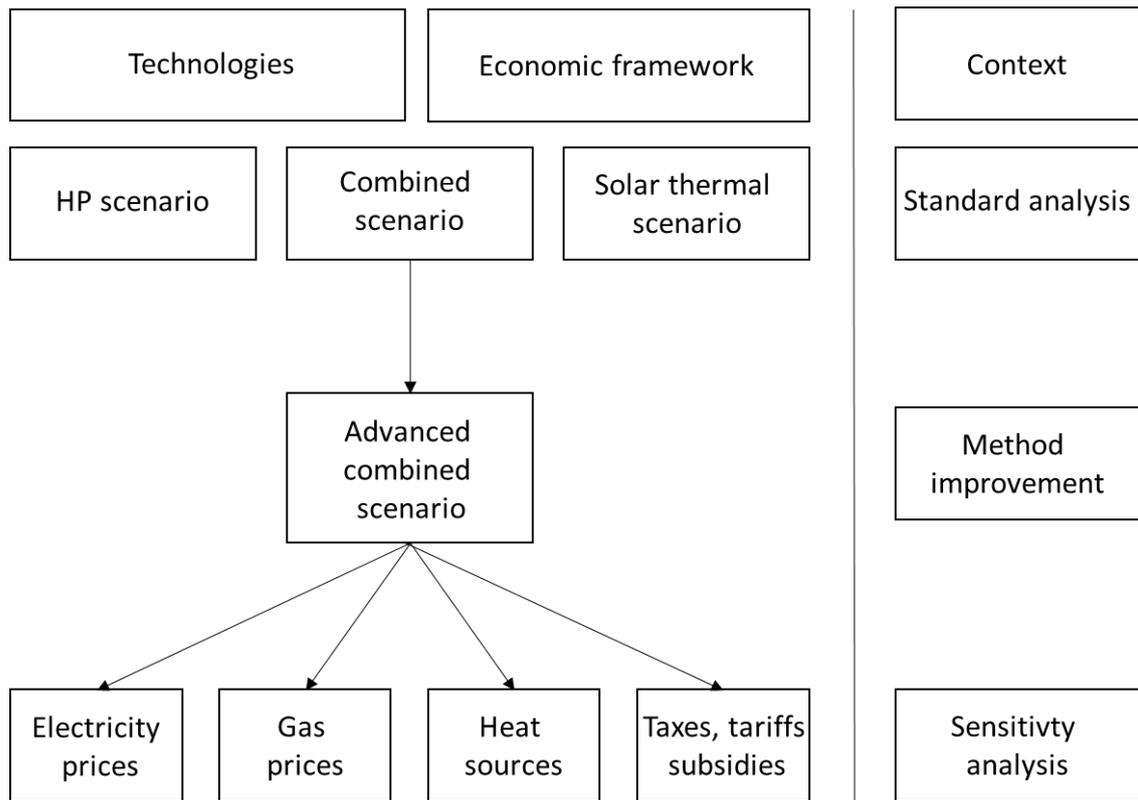


Figure 3: On the right, the four steps of the study are shown, on the left their corresponding analyses.

3 METHODOLOGY

The study is built on three methodological pillars; the basic qualitative understanding of the context of solar thermal and electric heat pumps in Danish district heating, the technical analysis of the interplay between different technologies in a district heating system, and the economic analysis of the investment potentials of different scenarios. In combination, these three approaches offer a holistic understanding of the potentials for solar thermal and electric heat pumps in a district heating system. The following chapter describes the concrete methods used in the study, i.e. qualitative interviews, the energy system modelling software energyPRO and economic principles for business economic calculations.

3.1 INTERVIEWS

A series of experts in different areas of district heating have contributed to this study; some through actual interviews and visits to relevant locations, some through continuous help and guidance in different parts of the project.

The following interviews have been conducted:

- A visit to Sæby District Heating Plant and interview with operation manager, Pouli S. Rugholt.
- A visit to Arcon-Sunmark and interview with head of sales, Knud Erik Nielsen.
- A telephone interview with Jørgen Risom, special advisor at The Heat Pump Mobile Task Force.

The interview with Pouli S. Rugholt has contributed with general knowledge on the economy and operation tasks of a district heating plant as well as an understanding of the considerations when investing in new technology. More specifically for the focus of the study, the interview offered an understanding of the pros and cons of solar thermal and heat pumps from a district heating company perspective.

The interview with Knud Erik Nielsen has contributed with concrete knowledge on solar collectors and the specifications and production patterns of these. Moreover, the interview contributed to an understanding of the potentials for utilising solar thermal in different district heating contexts and offered an insight into the future perspectives of the technology.

The interview with Jørgen Risom has contributed with a general understanding of the purpose and work of The Heat Pump Mobile Task Force. This includes the specific procedures as well as prospects for the future of the Task Force. Most importantly, the interview offered a broad insight into both economic and practical potentials and challenges for electric heat pumps in district heating now and in the future.

Besides these, the project group has been in continuous contact with Kasper Nagel from The Danish District Heating Association. Kasper has helped answer a number of questions, especially regarding taxes and tariffs and furthermore helped to a better understanding of the district heating sector and the ambitions and targets of The Danish District Heating Association.

It has been a primary interest of the project group to talk to a district heating plant already employing both solar thermal and electric heat pump. As such plants are very few and proved to be very busy this has, unfortunately not been possible.

The notes from the three interviews can be found in Appendix B-D.

3.2 COMPUTER TOOLS

There exist several different computer tools capable of simulating an energy system. Each of these different computer tools has various focuses and functions, and is therefore suitable for different tasks. The focus both varies in scope, from single plant level to large national and transnational energy systems, and in technologies, from conventional fossil-based systems to entirely renewable ones. Generally speaking, these tools can be divided into simulation tools and scenario tools. Simulation tools are used to simulate an energy system based on supplying certain energy demands, often with a time period of one year. Often simulation tools optimise a certain energy system in accordance with its operation and do not consider alternative scenarios or additional investments. Scenario tools generally extend a simulation of one year into a long-term scenario. Oftentimes scenario tools seek to optimise new investments in a given energy system. (Connolly, Lund, Mathiesen, & Leahy, 2009) There exist several mathematic models for calculating an energy system, such as Mixed Integer Linear Programming (MILP) and energy balance models. MILP is a commonly used model and is usually a complex and time-consuming one. Typically, in a MILP model, the costs of the energy system are minimised or the profit is maximised. The variables in the model can be given a penalty or reward to lead to desired behaviour. Energy balance models are typically lighter models than MILP models, with the ability to modify the energy system manually, thus obtaining an energy system with desired result through trial and error. (Østergaard, Reviewing EnergyPLAN simulations and performance indicator applications in EnergyPLAN simulations, 2015)

In this study the focus is on single plant level as well as simulation of a given energy system. The object is to identify the best economical operation for a district heating plant by testing different sizes and capacities of solar thermal and heat pumps. This is most easily accomplished with a light computer tool simulating one-year of operation with the ability to easily change the parameters of the energy system in question. Subsequently, the results of the simulated energy system can be used to create different scenarios of the energy system and thus investigate different investment potentials for solar thermal and heat pumps. According to the comparison of different energy system models in "*A review of computer tools for analysing the integration of renewable energy into various energy systems*", energyPRO is an obvious computer tool for this study.

3.2.1 ENERGYPRO

energyPRO is an energy balance model that keeps track of supply and demand of e.g. heat and electricity. energyPRO is capable of simulating and optimising the operation of an energy system as well as providing a techno-economic analysis. Setting up an energy system in energyPRO requires a number of different inputs describing the characteristics of the energy system in question. These inputs are described in the following section.

There are nine different production units available including both dispatchable energy units such as CHP-units, boilers and heat pumps and intermittent renewable energy units such as wind parks, photovoltaic and solar thermal. The production unit characteristics are expressed with a power curve. A power curve typically consists of an input (consumption) and output (production). Input would be fuel, for instance natural gas, biogas or coal. The output typically consists of a production such as heat and/or electricity. A power curve can be ex-

pressed with one or more values e.g. minimum and maximum production. The power curve can also be a function of exterior conditions and thus enables e.g. a varying Coefficient of Performance (COP) depending on the ambient temperature. The production units can be allowed to store production in storage, for instance thermal storage, to increase the flexibility and efficiency of the energy system. To ensure balance in the energy system, the thermal storage is empty both at the start of the simulation period as well as in the end. (EMD International A/S, 2014)

In order to determine production patterns, time series are applied. A time series describes e.g. weather conditions, fuel prices, demands, flows or other input data. The priority of the production units is defined in the operation strategy. If a production unit is given high priority, it will be given first priority whereas a production unit with low priority will be given last priority. A production unit's priority can also be determined by the production costs for heat. Some production units depend on the electricity price whereas others depend on e.g. natural gas price. (EMD International A/S, 2014)

3.2.2 CALCULATION METHOD

In energyPRO the calculation of production is done by dividing the simulation period into fixed time steps; in this study one hour time steps are used. The production is then selected according to the most economically beneficial periods and not in chronological order, see Table 1. Thus the new production always has to be chosen in accordance with already scheduled production to avoid conflicts with system boundaries e.g. thermal storage capacities. To limit the amount of start-ups, the load of the production units is derating, however this can be limited in case partial load is not permitted or if a minimum load on the production units is specified. If it is possible to increase production on an active unit, in accordance with the aforementioned, this is preferred over starting a new unit. It is possible to specify start-up costs for production units to ensure fewer start-ups. With start-up costs, two already scheduled production periods can be merged if the priority increases sufficiently due to the removal of start-up costs. To ensure that production units do not start-up just to fill the storage, the start is delayed until the storage is empty if the priority remains the same in the following time step, thus allowing for a continuously production on the production unit. (EMD International A/S, 2014)

Hour	555	556	557	558	559	560
Unit 1	200	150	100	10	30	50
Unit 2	20	50	100	130	200	200
Unit 3	40	40	40	40	40	40

Table 1: Principle diagram of energyPRO for a selection of production units. Each number represents the production costs for the different production units in the individual hour. The first production to be chosen is on Unit 1 in hour 558 as this is the cheapest production price. The second chosen production is on Unit 2 in hour 555, followed by Unit 1 in hour 559. Then the production on Unit 3 is chosen if not in conflict with e.g. the production already planned on Unit 2 in hour 555. This principle applies until the demand is covered for all hours of the year.

3.2.3 PROS

energyPRO uses technical and economical prerequisites for the production units to optimise the heat production. As energyPRO contains a large variety of different energy technologies, it can optimise the operation of an energy system according to e.g. storage capacity and/or

electricity prices. With a heat storage attached to the energy system, it is possible to plan production in accordance with the cheapest production units. It is, thus, possible to optimise the production costs, as excess production on cheap units can be stored and replace future production on more expensive units. energyPRO also optimises according to the varying electricity spot prices which is essential for operating units consuming or producing electricity, such as CHP plants and heat pumps.

3.2.4 CONS

As energyPRO is only an energy balance model, other important parameters in a district heating system, such as e.g. temperatures, flows and losses, are not included. These parameters are also important when simulating an energy system, as a certain temperature is needed in the district heating grid to ensure the consumers the proper supply temperature. The supply temperature is dependent on the flow in the grid as well as the loss to the surroundings, see *Chapter 7 Method improvement* for details.

3.3 ECONOMIC METHOD

Having simulated the annual operation of different district heating technologies in energyPRO the actual investment potential of these technologies can be calculated. The following chapter describes the basic principles of economic terms such as net present value, simple payback time, and scrap value as well as their concrete application in this study.

NET PRESENT VALUE

The net present value sums up all payments, including both initial investment costs and annual costs and revenues over a certain period of time. In the case of investments linked to district heating, the annual costs could be for fuel, operation and maintenance, taxes or, in the case of a socio-economic calculation, externalities such as health or pollution costs. The revenues would primarily be from sale of heat and electricity but also from subsidies etc. (Lund & Østergaard, 2010).

The principle behind the calculation of net present value is shown in Figure 4.

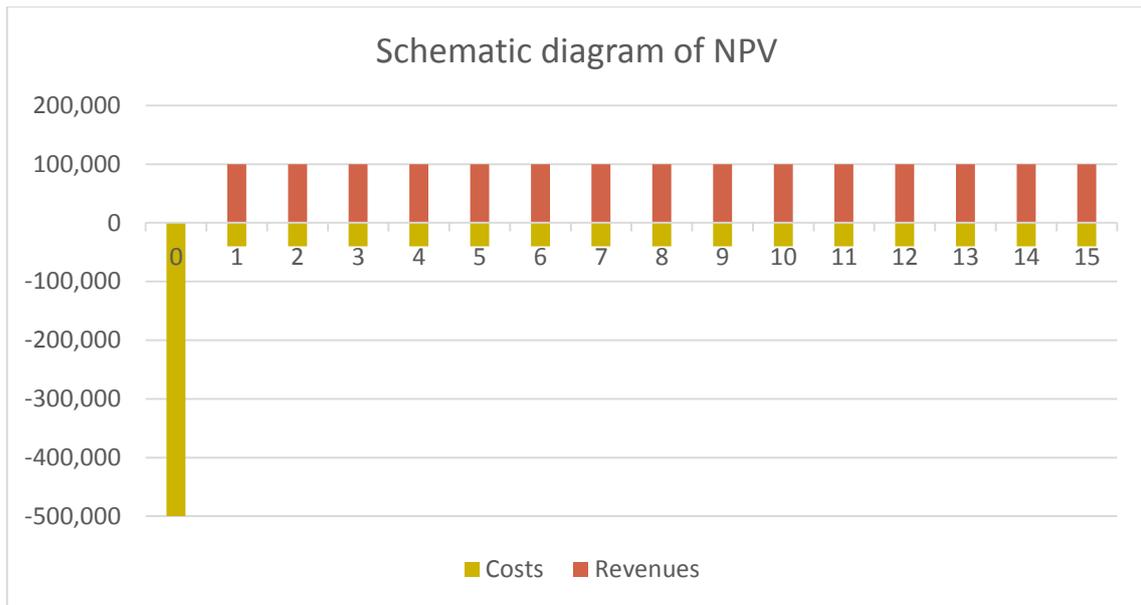


Figure 4: Schematic diagram of the principle behind the net present value calculation. The discount rate is not included in the diagram.

Figure 4 illustrates the costs and revenues of a hypothetical investment over its time horizon. In the beginning of the time horizon, the initial investment is made. After this, every succeeding year has revenues and costs. By incorporating a discount rate in the calculation, a present value is attributed to both costs and revenues that fall at a later stage of the time horizon.

The net present value can be expressed through the following formula:

$$\text{Net present value (NPV)} = \sum_{t=0}^T \frac{R_t - C_t}{(1 + r)^t}$$

T: Time horizon of investment

r: Discount rate

t: Specific year for money flow

R_t: Revenues in the specific year, *t*

C_t: Costs in the specific year, *t*

From the point of view of economic theory, every project with a positive net present value within the time horizon of the investment will be an attractive investment. In reality, however, district heating company will expectedly need a positive net present value of a certain size in order to be willing to invest. This is supported by the fact that net present value calculations over a series of years will always represent some uncertainties, as many basic conditions are difficult to predict for the future.

SIMPLE PAYBACK TIME

The simple payback time is the time (most often number of years) it takes for the accumulated annual net payments (revenues minus costs) to match the initial investment. Hence, the simple payback time can be expressed:

$$\text{Simple payback time (SPT)} = \frac{\text{Investment}}{\text{Annual net payments}}$$

The simple payback time offers a quick evaluation of the potentials of an investment, which is particularly relevant for private companies that often have a requirement for very short payback times for investments. Where net present value is sometimes used to decide between different sizes of a potential investment, the simple payback time is often decisive for whether or not a company will be willing to invest at all. The simple payback time does not, however, consider interest nor discount rate just as the net payments beyond the payback time are not included. The result is therefore severely simplified (Lund & Østergaard, 2010). There is no rule of thumb for a maximum simple payback time for a district heating company when making investments. It would generally be higher than the 2-3 years that are often a maximum for private companies. Existing cases are inconclusive with maximum simple payback times varying significantly from project to project. However, the tendency appears to be that district heating companies are willing to accept considerably longer simple payback times for projects involving technologies that are considered stable and tested such as solar thermal than for projects involving technologies of a more uncertain economic framework such as heat pumps. The available literature suggests simple payback times of around 12 years for solar thermal projects and around 6-8 years for heat pump projects (Rugholt, 2016) (Koch, 2015). This is, however, only guiding, as the simple payback time would always be based on the specific case.

INFLATION

Inflation describes a general and on-going rise in the price of goods and services. The term opposite to inflation, deflation, describes a general fall in the price of goods and services. Even though a certain inflation is generally desirable, extreme situations of both inflation and deflation can be harmful to the economy. The European Central Bank has an ambition to keep the inflation rate close to but below 2% (The European Central Bank, 2016). In Denmark, inflation has been relatively stable since 1990 with an average annual inflation of 2.0% (Statistics Denmark, 1990-2015). In this project, an inflation of 2% has been applied.

DISCOUNT RATE

The discount rate is an expression for the value of a payment now compared to its value in the future. A payment of one million DKK now would be more desirable than a payment of one million DKK in a year. By use of the discount rate, the factor of time is considered in the calculation. The discount rate is not to be understood as an easily defined and calculable quantity, as it is not only based on the economic conditions and risks linked to a certain investment but also on the personal preferences of the investor in question. A high discount rate attributes less value to future payments than a low one. This means that a high discount rate will favour some types of projects over others. Renewable energy projects that often have high initial investment costs and very low annual operation costs will benefit from a low discount rate when compared to most non-renewable projects that often have high annual costs for fuels throughout the lifetime of the investment.

In Denmark, the official discount rate set by The Ministry of Finance for socio-economic projects is 4% for time horizons up to 35 years. For socio-economic projects of longer time horizons, the discount rate is lowered (The Ministry of Finance, 2013). For business economic projects, the discount rate would often be higher than this, depending on the liquidity and specific interests of the investing company in question. As district heating companies are operated non-profit and from socio-economic interests and as the municipality can offer security for the loan in the case of new district heating investments the discount rate for

district heating companies would expectedly be relatively low (The Danish District Heating Association, 2013). The organisation Kommunekredit is authorised to offer loans to Danish municipalities, regions and institutions and companies with 100% municipal guarantee. In 2016, these loans were offered with 1.99-2.48% interest rates for investments of 20-25 years (Kommunekredit, 2016). As, however, the interest rate is only one of the factors included in the discount rate in this project a nominal discount rate of 6% has been selected. As this does not take into consideration the inflation that needs to be subtracted, a real discount rate of 4% has been applied.

TIME HORIZON

When calculating the socioeconomic feasibility of energy projects the standard is to set the time horizon equal to the technical lifetime of the investment (The Danish Energy Agency, 2016 B). However, when carrying out a business-economic calculation the time horizon is generally lowered to ensure a faster profit and for this project a time horizon of 15 years have been applied. When comparing two scenarios, as in this study, the same time horizon needs to be applied in order for the results to be comparable. This might be a challenge in situations with different technical lifetimes. One approach is to perform life extending investment for the plant with the shortest lifetime. However, in this study, the approach is to ascribe a so-called scrap value (The Danish Energy Agency, 2005).

SCRAP VALUE

The scrap-value assigns value to any remains of an investment at the end of the calculation period. This could be e.g. the value of an old sofa (either for new ownership use or for its scrap parts) when this is replaced with a new one. In the case of energy projects, the scrap value can be difficult to estimate as the technological development means that plants can become outdated before the end of their estimated lifetime. In this project, the scrap value is calculated as a linear write-off of the initial investment including the discount rate meaning that the scrap value makes up the share of the investment costs that fall after the end of the investment period if the investment is divided equally over the lifetime of the technology in question. As solar thermal and electric heat pumps are expected to have a technical lifetime of 30 and 20 years, respectively, the scrap value for solar thermal is calculated as the last 15 years and the scrap value for the heat pump as the last five years of the initial investment.

4 TECHNOLOGIES

Before testing the economic feasibility of implementing solar thermal and electric heat pumps in the district heating system it is necessary to be familiar with the technical specification of these technologies. The following chapter describes the technology of solar thermal and electric heat pumps, the production patterns and overall potentials and challenges for these in district heating systems.

4.1 SOLAR THERMAL

Solar collectors allow for the utilisation of solar radiation for heating purposes either in individual households, in district heating, or in some cases for industrial purposes. Solar collectors can be constructed both as flat plate collectors and as evacuated tube collectors. As flat plate collectors are easily the most common in Danish district heating, these will be the focus of the following analysis (Solvarmedata, 2016) (Rugholt, 2016). On a basic level, flat plate solar collectors are constructed as an insulated box with a black background and pipes filled with fluids. The front of the box is made of either glass or plastic and is transparent. The black background is heated by the sun's rays and the heat is transported by the fluid to a heat exchanger from where it can be used for different purposes. Because of reflections and heat loss, only about 25-50% of the solar radiation can be utilised. The efficiency of the solar collector is further affected by the angle on the sun, ambient temperatures and possible shadows just as the efficiency at different temperatures varies between different models (Lauritsen, 2015). Figure 5 shows the principle sketch of the theoretical efficiency of two types of solar collectors.

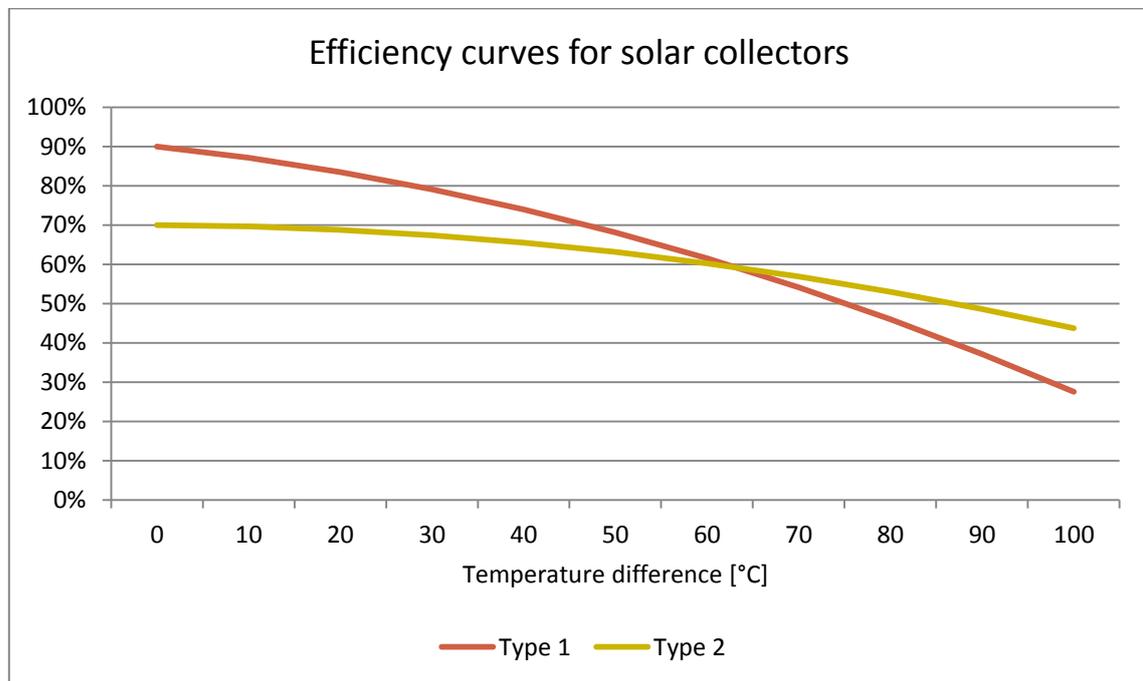


Figure 5: Efficiency curves for two theoretical types of solar collectors for different temperature differences between the ambient temperature and the fluid temperature.

The figure shows how the efficiency is generally lowered with lower ambient temperatures or higher desired output temperatures. This can be a reason for considering lowering the supply temperature of your district heating system when investing in solar thermal. Some

solar collectors produce more efficiently with a high temperature difference between the desired output temperature and the ambient temperature than others. This can mean that some types of solar collectors are better suited for production in cooler or warmer environments. However, it can also mean that an overall higher efficiency could be reached by employing a combination of the two types in one production plant. In the case illustrated in Figure 5, the type 1 solar panel would be preferred in the beginning of a row of solar panels to preheat the water as this has the best efficiency for low temperature differences. As the water is gradually heated, the type 2 solar panel could be preferred in the end of the row as this has a higher efficiency when operating under high temperature differences.

Traditionally, many solar thermal plants have been running with a constant flow, leading to varying supply temperatures depending on the specific weather conditions of a given day. Today, however, most plants are operated with adjustable flows that allow for a constant supply temperature and a more consistent production (PlanEnergi, 2013) (Clausen, Kim S.; From, Niels; Hofmeister, Morten; Paaske, Bjarke Lava; Flørning, John, 2014 B).

As district heating supply temperatures have historically been higher than now and the obtainable output temperatures of solar thermal plants lower, the technology has not always been considered suitable for district heating purposes (Urbanek, et al., 2014) (Paar, et al., 2013). However, with modern technology, it is possible to deliver heat at temperatures compatible with most district heating systems and often the delivered heat has to be kept below 100°C to accommodate the requirements for the heat storage (Clausen, Kim S.; From, Niels; Hofmeister, Morten; Paaske, Bjarke Lava; Flørning, John, 2014 B).

Solar thermal is often installed with some kind of heat storage capacity. This can be basic steel tanks capable of storing equivalent to a few days' heat demand or seasonal storages such as pit heat storages or borehole storages capable of storing heat over several months (Sørensen, Paaske, Jacobsen, & Hofmeister, 2013). As a rule of thumb, solar thermal plants with no heat storage facilities should be dimensioned to be able to cover the heat demand of a warm summer day equivalent to about 5% of the annual heat demand. In a system with storage capacity equivalent to a couple of days or weeks, solar thermal plant can be dimensioned to cover 10-30% of the annual demand. If a seasonal storage is applied, the share of solar thermal in the total annual heat supply can be as high as 60-75% (Lauritsen, 2015).

In early 2016, a total of 52 solar thermal plants were connected to Danish district heating systems. These made up a total capacity of 292 MW_{th} equivalent to about 0.5% of the total district heating production (The Danish Energy Agency, 2015 A). For the majority of Danish district heating companies currently utilising solar thermal energy, this fraction makes up about 20% of the total heat production. Fractions as low as 7% (Sæby District Heating) and as high as 50% (Dronninglund District Heating) do, however, exist (Solvarmedata, 2016).

4.2 HEAT PUMPS

As stated in the introduction, electric heat pumps can benefit the national energy system in several ways and add value to electricity that would otherwise have to be exported at low or even negative prices. Moreover, electric heat pumps have the opportunity to benefit the individual district heating plant. First of all the use of heat pumps allows for an improved efficiency of the overall system, since it is possible to make use of low-temperature heat sources already within the system and/or alternative heat sources outside the system, such as industrial waste heat. By introducing a new fuel, electricity, into the production, the economic risk of heat production is spread out, adding to the “robustness” of the system in case

of fluctuations in fuel prices. Finally, when producing heat on an electric heat pump, cooling is produced as a by-product. This means that the use of heat pumps in a district heating system facilitates the potential additional business area of district cooling (Clausen, Kim S.; From, Niels; Hofmeister, Morten; Paaske, Bjarke Lava; Flørning, John, 2014 B). The following describes the technical specifications of electric heat pumps including the potentials for coproduction with solar thermal.

TECHNICAL SPECIFICATIONS OF A HEAT PUMP

Heat pumps work by moving heat energy from a low-temperature heat source to a heat emitter at a higher temperature level. For this process, the heat pump uses an energy input that is, most often, smaller than the transported thermal energy. Two main types of heat pumps exist: compression heat pumps using electricity as a driving power and absorption heat pumps using heat as a driving power. Besides these hybrid heat pumps exist employing a combination of the two technologies. Depending on their technical specifications and the coolant used, these types of heat pumps have different pros and cons. According to The Danish District Heating Association in the case of renewable energy sources such as solar thermal, geothermal and industrial waste heat an absorption heat pump is normally preferred over an electrical one. In district heating plants based on production from CHP, however, electrical heat pumps can be preferred, as these two technologies supplement each other very well in regards to changes in electricity prices (Hougaard & Tang). As electric heat pumps are the focus of this study, absorption and hybrid heat pump technology will not be discussed further.

An electric heat pump moves heat by utilising the energy gains and energy losses linked to the phase change of different substances between liquid and gas form. A coolant circulates the system in a cycle that consists of four components; a compressor, a condenser, an expansion valve and an evaporator, see Figure 6 (Krebs, 2013).

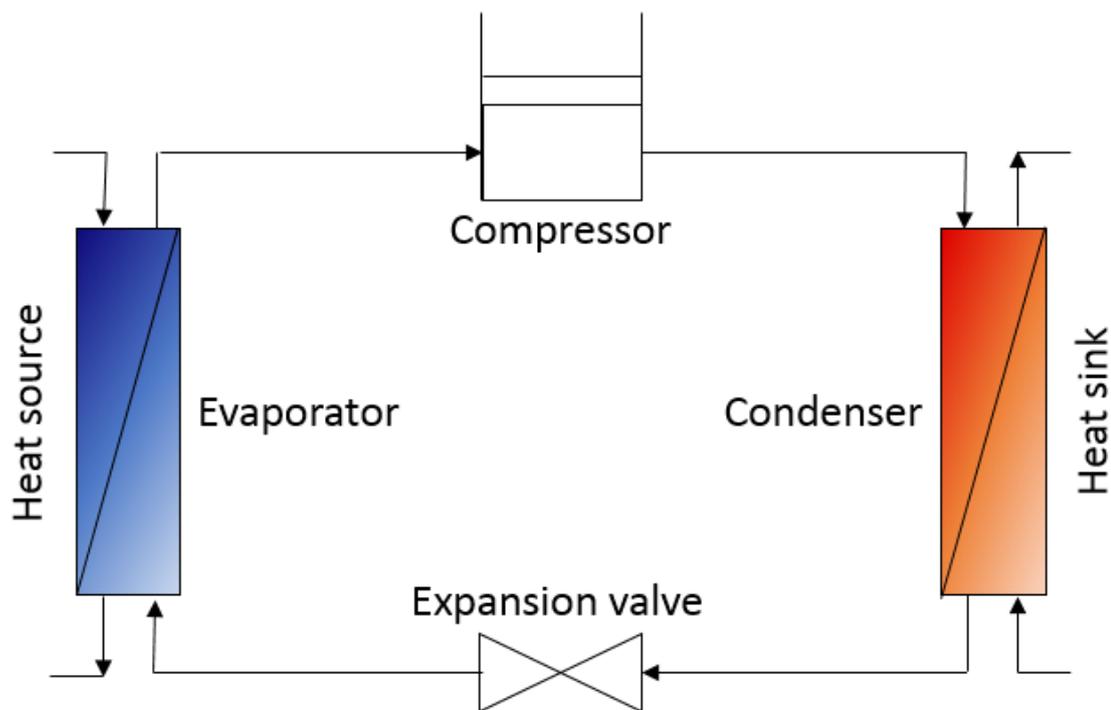


Figure 6: Schematic illustration of a heat pump.

When the coolant reaches the expansion valve, it is in fluid form and under high pressure. As the pressure is lowered in the expansion valve, the boiling point of the coolant is also lowered. In this state and under the given temperatures, the coolant will evaporate. This process, which takes place in the evaporator, requires a lot of energy that will be collected from the surroundings, in this case a specific heat source such e.g. flue gas, waste water, or ground water. After the evaporator, the coolant continues to the compressor, where the pressure and temperature is raised bringing the coolant to gas form. The coolant is led through the condenser, where lower temperatures in a heat exchanger make the gas condense and release energy in the form of heat into the heat sink. It is this heat that can be used for individual or district heating purposes. Completing the circle the coolant is led back to the expansion valve, where the pressure is once again lowered (Krebs, 2013).

COP

The efficiency of a heat pump is expressed by its COP. The COP describes the difference between the energy input to the heat pump and the heat delivered by it and can be expressed as follows:

$$COP(heat) = \frac{P(output)}{P(input)}$$

In the case of electric heat pumps, the COP depends on the temperature difference between the heat source and the heat output of the heat pump with higher temperature differences resulting in lower COP. Hence, the efficiency of an electric heat pump does critically depend on the circumstances under which it operates (Paaske, Pijenburg, & Tang, 2013).

TEMPERATURE

With maximum delivery temperatures often higher than 100°C, temperature levels are rarely a direct limitation to the use of a heat pump (Svedan Industri Køleanlæg A/S, 2015) (Reinholdt, 2015). However, as the COP is lowered when raising the temperature of the delivered heat keeping production temperatures relatively low is often prioritised, either by lowering the grid temperatures in the district heating system or by further heating the water in a boiler to reach the desired temperatures (Clausen, Kim S.; From, Niels; Hofmeister, Morten; Paaske, Bjarke Lava; Flørning, John, 2014 B) (Paaske, Pijenburg, & Tang, 2013).

HEAT SOURCES

As previously mentioned the availability of a suitable heat source is a prerequisite for the use of heat pumps. Generally speaking, heat sources can be internal or external. Internal sources could be flue gas, solar collectors, return water, a thermal store or similar heat sources linked to the primary production of district heating (Clausen, Kim S.; From, Niels; Hofmeister, Morten; Paaske, Bjarke Lava; Flørning, John, 2014 B). When using a production unit as a heat source the heat pump is dependent on the original production unit which reduces its flexibility (Clausen et al. 2014). External heat sources such as for example industrial waste heat, geothermal or waste water generally allow for improved flexibility but here other challenges occur. Table 2 shows a prioritised list of heat sources as stated by The Danish Energy Agency in their report "*Drejebog til store varmepumpeprojekter i fjernvarmesystemet*" (Catalogue for large heat pump projects in the district heating system). The list further includes the pros and cons specifically linked to the heat sources in question.

Heat source	Pros	Cons
Flue gas	Overall improvement of the operation economy and, hence, more operation hours of the source unit.	Requires co-production of the heat pumps and the source unit, significantly limiting the flexibility of the heat pump.
	Often relatively cheap and simple installation.	Flue gas condensation produces condensate the disposal of which carries some costs.
Industrial waste heat	Benefits both the DH company and the waste heat company.	Vulnerability linked to the potential closing-down of the waste heat company.
	Often higher temperature levels than in natural sources.	Potential conflict between long payback rates for district heating companies and short payback rates for private industries.
	Can help reduce existing nuisances linked to the disposal of waste heat.	Complex and time-consuming process Uncertainties linked to legal framework
Geothermal heat	Potentially high temperature heat source.	High risk investment partly due to high construction costs. Risk of precipitation of iron and limestone that must be dealt with.
Waste water	Though warmest in the summer waste water can be used all year round.	Vulnerability linked to the potential closing-down of the sewage treatment plant.
	Cheap source.	High requirements for exchangers, pumps, valves etc. due to rough environment.
	No need for test drillings.	Possible requirements for return temperatures from the sewage treatment plant. Unclear who owns the rights for using the energy content in waste water.
Ground water	Many aquifers in Denmark are suitable as a heat source for a heat pump.	The preliminary tests are rather comprehensive and expensive.
	Much data exists on the suitability of a specific aquifer as a heat source.	Availability is limited by zoning for drinking water.
	Ground water has a relatively stable temperature (8-10°C) all year round.	Different potential environmental concerns.
Lake and stream water	High water content in many lakes and streams means considerable energy potential.	Low temperatures during winter can limit the production significantly in these months.
		The authorities processing can be time-consuming.
		Challenges to keeping heat exchangers and other components clean.

Table 2: Heat sources for heat pumps in a prioritised order with the warmest source first being flue gas and the coldest source last being lake and stream water (Clausen, Kim S.; From, Niels; Hofmeister, Morten; Paaske, Bjarke Lava; Flørning, John, 2014 B).

Besides these, a series of other low-temperature sources exists such as air, seawater, and drinking water. While air, due to its low energy density, is often not a suitable heat source for large heat pumps, seawater can be a good source for district heating plants located in immediate proximity to the sea. However, due to low seasonal temperatures, seawater is, like lake and stream water, not always a suitable source. Drinking water has a steady temperature around 8-9°C but will risk being cooled to an undesirable level if used as a heat source for a heat pump (Clausen, From, Hofmeister, Paaske, & Flørning, 2014 A).

PRODUCTION PATTERN

Electric heat pumps have a long start-up time sometimes taking several hours to reach optimal operation. This limits the flexibility of the technology and can further make it difficult to calculate the operation expenditures of the heat pump in situations of stopping and starting. This in combination with the relatively high investment price and the often unlimited and low-cost character of the heat source argue for using the electric heat pump as a base load that allows for disconnection in situations with very high electricity or up-regulation prices. Under the existing framework, a heat pump can be expected to operate 6000-8000 hours of the year (Clausen, Kim S.; From, Niels; Hofmeister, Morten; Paaske, Bjarke Lava; Flørning, John, 2014 B). Being an easily integrable technology, however, the possible applications of electric heat pumps are many. Hence, it is also possible to place the heat pump decentralised in the grid and use the district heating water as a heat source. That way heat can be distributed at lower temperatures, reducing the heat losses in the grid. One practical problem to such a solution would be finding space for the heat pump within the grid. A further challenge is that in such a scenario the heat pump would be part of the distribution system and therefore would need to produce when the district heating demand is high which is often in periods with high electricity prices. Because of this, the solution is not very flexible (Tang, 2011). An alternative argued to both reduce grid losses and operation costs is to install “booster” heat pumps in the individual households allowing for low-temperature district heating to work as a heat source for heat pumps to produce domestic hot water of sufficient temperatures (Andersen & Østergaard, 2015). Furthermore, as previously mentioned, a heat pump does not always work as a “stand-alone” unit but can also be used to improve the efficiencies of other units. As an example, the heat pump can be used to increase the temperature difference between the top and the bottom layers of a heat storage just as the production of cold water can improve the efficiencies of CHPs or solar collectors (Paaske, Pijnenburg, & Tang, 2013).

EXPECTED IMPLEMENTATION

In their report “*Drejebog til store varmepumpeprojekter i fjernvarmesektoren*”, The Danish Energy Agency predicts that smaller district heating systems including small waste incineration areas will be the main target group for electric heat pumps in the future. Over the next decades, heat pumps are here expected to replace both natural gas-based CHP production and biomass-based boilers (Clausen, Kim S.; From, Niels; Hofmeister, Morten; Paaske, Bjarke Lava; Flørning, John, 2014 B). When looking directly at the economy, though, it is clear that heat pumps have a much higher potential in natural gas-based plants, including plants with installed solar thermal capacity, than in biomass-based ones where the economic prospects are less attractive. It is still possible to achieve a positive operation economy from a combination of a heat pump and a biomass boiler. If the heat pump is used for preheating the supply temperature, it is possible to obtain a high COP. The biomass boiler will then provide the

remaining temperature increase for the supply temperature. However, this is only desirable if the heat pump will replace an expensive unit, such as a natural gas-based CHP (Paaske B. L., 2015).

CHALLENGES FOR HEAT PUMPS

As described in the introduction, the implementation of large heat pumps in the Danish district heating sector is somewhat slow. The Heat Pump Mobile Task Force has gathered experiences from the Danish district heating companies, and some challenges exist when it comes to investments in large heat pumps. There are some hitches regarding knowledge of heat pumps, which hinders the implementation of large heat pumps. Mapping of relevant heat sources are essential for heat pumps, especially heat sources of great stability that can obtain a high COP. Another relevant issue is the framework conditions for heat pumps, as these pose a challenge for investments in large heat pumps. In particular for industrial waste heat there are challenges both in terms of potential but also in terms of a more consistent legislation (Ebbehøj, Debat og evaluering, 2015 B). Open field plants often have difficulties retrieving a useful heat source, as e.g. industrial waste heat oftentimes aren't available in these areas. Large heat pumps are only economical interesting for district heating plant if a COP of 3.5-4.0 can be obtained, thus eliminating low temperature heat sources such as ambient air (Risom, 2016).

At the time of March 2015, a total of 20.3 MW_{th} electric heat pumps divided between 15 installations were producing heat for district heating purposes (PlanEnergi, 2015). Seven of these use flue gas from other production units as a heat source while the remaining eight are divided between sources such as waste water, industrial waste heat, heat storages, drinking water and ground water.

4.3 SOLAR THERMAL AND ELECTRIC HEAT PUMPS IN DISTRICT HEATING

Several advantages are linked to the addition of a heat pump to a solar thermal district heating system. The solar collectors can benefit from lower temperatures by achieving higher solar yields and the system is less sensitive to high or fluctuating return temperatures as the heat pump can help regulate the return temperature level, in case that the heat pump uses the return water as a heat source. Moreover, when applying a heat storage, the heat pump allows for the energy from the solar collectors to be stored at lower temperatures leading to lower heat losses (Marx, Bauer, & Drueck, 2013). However, calculations from the Danish Energy Agency show generally poor economic prospect for utilising solar thermal as a direct heat source for a heat pump (The Danish Energy Agency, 2015).

Using solar thermal as a direct heat source is not the only way of implementing the two technologies into the same system. In one example, set forth by The Danish District Heating Association, the heat pump could be installed with the original production facilities along with a solar thermal plant and an additional accumulation tank that is colder than the original accumulation tank. During the day as heat prices are high solar panels can produce water of 40-60 °C for the cold tank. When the electricity prices go down the heat pump can start moving energy from the cold tank to the warm tank leaving the water in the cold tank at around 10-20°C which will raise the efficiencies when this water is applied in the solar panels. In such a system, the engine is producing electricity when this is expensive and the heat pump is consuming electricity when this is cheap (Tang, 2011). According to The Danish District Heating Association, such a solution with additional flue gas condensation and potentially also supply of district cooling allows for the most efficient heat production and a

high degree of flexibility and integration with the fluctuating electricity sector (Hougaard & Tang).

However, in order for a heat pump project to be economically feasible there generally needs to be “space” in the heat production of the plant, in the form of expensive production that can be replaced (The Danish Energy Agency, 2015). In the case of solar thermal district heating, the plant already has an almost free base load production; hence, the heat pump will often have a hard time achieving enough production hours during a year, as solar thermal is often expected to cover the entire heat demand in the summer months leaving close to no production for the heat pump.

5 ECONOMIC FACTORS

According to the Law on Heat Supply, Danish district heating companies are run non-profit and obliged to promote the most socio-economically feasible solution when investing in new technologies (LBK no 1307 of 24/11/2014). This explicit focus on socio-economy must, however, not end up compromising the business economy of the plant and district heating companies are, generally, not allowed to make investments that raise the heat prices for the consumers even if these investments are preferred from a socioeconomic perspective (Rugholt, 2016). With the overall aim to secure low heat prices for the consumers and ensure the future economy of the plant, business economic calculations are decisive for weighing different possible investments against each other. When calculating the feasibility of different investments for a district heating system, the different economic input such as investment and operation cost as well as taxes, tariffs and subsidies are, naturally, of critical importance. The following chapter accounts for the basic costs and revenues, taxes, tariffs and subsidies linked to the investment in and operation of a district heating plant. All fuel prices, taxes, tariffs and subsidies applied are from 2015.

5.1 COSTS AND REVENUES

The basic costs and revenues of this study are linked to the investment in and operation and maintenance of the different production units including sale of electricity and heat. The costs and revenues applied in the analysis can be found in Table 3. All investment costs (except for solar thermal) and costs for operation and maintenance are from the technology catalogue "*Technology Data for Energy Plants – Generation of Electricity and District Heating, Energy Storage and Energy Carrier Generation and Conservation*" from the Danish Energy Agency and the Danish TSO, Energinet.dk, hereafter denoted the Technology Catalogue.

5.1.1 REVENUES

SALE OF HEAT

As this study focuses on the potential costs or benefits when comparing district heating plants employing different technologies the sale of heat (and the revenues from this) will not vary from scenario to scenario and is, hence, not included in the study.

SALE OF ELECTRICITY

Unlike sale of heat the sale of electricity will potentially differ in the different scenarios and is therefore included in the study. As for fuel costs revenues from sale of electricity are given in accordance with the spot price for DK1 from 2015.

PAYMENT FOR UP-, DOWN- AND SPECIAL-REGULATION

The regulating power, traded on The Nordic Operational Information System (NOIS), helps sustain the balance and frequency of the European electricity system. On the regulating power market the actors (in this case the district heating company) can participate in one of two ways. The company can choose to put manual reserves at the disposal and is hereby obligated to submit bids for up and down regulation in a predefined period. The company will receive a payment for offering disposal capacity and an activation payment if activated. Alternatively, the company can choose not to offer any specific capacity and instead give in regulating power bids when this is attractive, and thus only receive the activation payment. The payment for up and down regulation is set by the merit order effect, thus all activated

bids receive the same price per MWh_e (Energinet.dk, 2015 A). Besides up and down regulation special regulation exists. In special regulation Energinet.dk can single out the regulating power bids without considering the normal price order. In the vast majority of cases special regulation is used when bottle necks occur in the system, e.g. in Germany. Unlike up and down regulation special regulation is settled as pay-as-bid (Parbo, 2015). District heating units that either produce electricity to or consume electricity from the grid are, in principle, relevant for up and down regulation. As heat pumps are generally operated as base load, however, these are often not relevant for this market (Clausen, Kim S.; From, Niels; Hofmeister, Morten; Paaske, Bjarke Lava; Flørning, John, 2014 B). As the demand for balancing is difficult to predict this market represents a significant uncertainty in the annual economy of a district heating plant. Because of this it can be argued that large investments should not be made based on the balancing market and up, down and special regulation has, hence, not been included in this study.

5.1.2 COSTS

INVESTMENT

As this study focuses on the potential for additional investments in solar thermal and/or heat pumps it is assumed that the remaining production units have already been invested in. Hence, the investment costs for the heat pump, the solar thermal plant, and the additional storage capacity are the only ones needed for this analysis. For the solar thermal plant and the additional storage capacity the majority of the investment costs are for the purchase of the actual equipment. In the case of the heat pump, however, only 55-60% of the investment costs are for the heat pump itself as the remaining share goes to the container, pipe connections, chimney anti-corrosion and other costs (Danish Energy Agency, 2012).

OPERATION AND MAINTENANCE

The operation and maintenance costs are calculated as fixed and variable costs, respectively. The fixed O&M costs (DKK/MW/year) are independent of the actual operation of the plant. These include operational staff, administration, insurance, property tax etc. The variable O&M costs (DKK/MWh) includes all costs dependent on the actual operation of the plant such as disposal of residuals, consumption of auxiliary materials (lubricants, water etc.) and unforeseen repairs and investments in spare parts. Fuel costs are not included in the O&M costs (Danish Energy Agency, 2012).

NATURAL GAS

The Danish Energy Regulatory Authority collects information containing the average monthly price based on the day-ahead spot price from Gaspoint Nordic. The spot price for natural gas for 2015 is applied in this study. The price for natural gas has been fluctuating since 2009 and is currently relatively low with an average price at 1.81 DKK/Nm³ in 2015 (The Danish Energy Regulatory Authority, 2016). Besides the cost for the natural gas, transmission and distribution tariffs as well as emergency supply (storage reservation) and energy savings tariffs are ascribed to the price, see *Section 5.2.2 Costs*.

ELECTRICITY

The spot price for DK1 (Western Denmark) from 2015 has been applied in the study. In recent years the spot price for electricity has been decreasing almost 57% from an average of about 395 DKK/MWh in 2010 to about 171 DKK/MWh in 2015 (The Danish Energy Agency, 2016 A). Figure 7 shows that the majority of electricity prices (83%) fall in the range from 50-250 DKK/MWh_e (Energinet.dk, 2016).

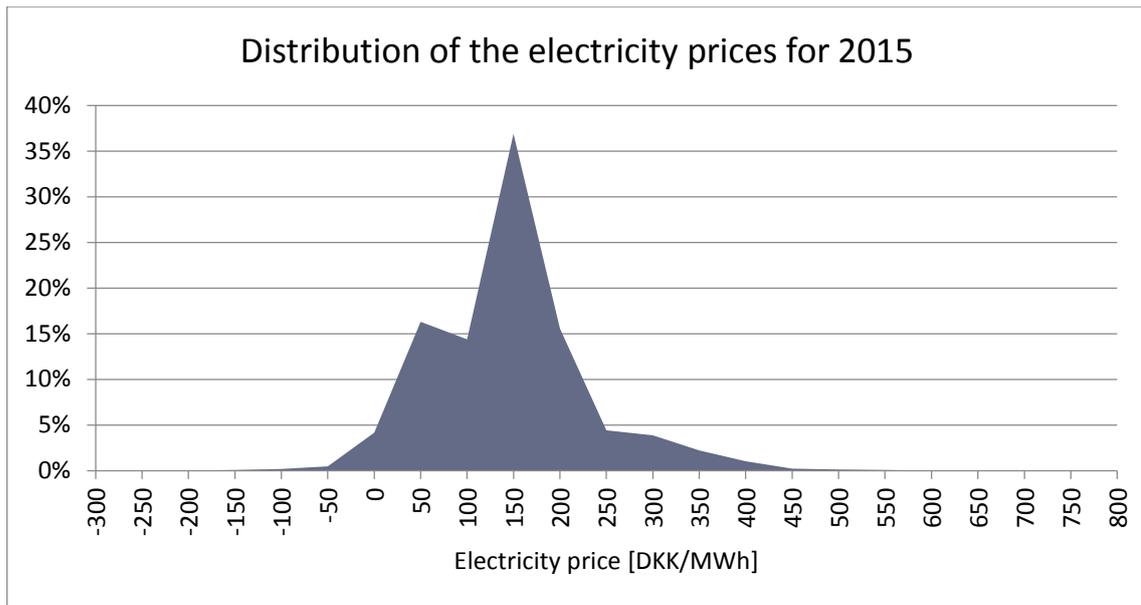


Figure 7: The distribution of the electricity prices for 2015. The average electricity price for 2015 is 171 DKK/MWh (Energinet.dk, 2016).

Table 3 shows the investments, operation and maintenance and fuels costs linked to heat production in the district heating plant in this study.

Costs and revenues	Cost	Unit
Investment¹		
- Solar thermal (fixed) ²	1,650,000	DKK
- Solar thermal (variable) ²	1,600	DKK/m ²
- Steel tanks	1,560	DKK/m ³
- Seasonal storage	260	DKK/m ³
- Heat pumps	5,260,000	DKK/MW _{th}
Operation and Maintenance¹		
- Gas engine	71.17	DKK/MW _{h_e}
- Gas boiler	28,625.44	DKK/MW _{th}
- Electric boiler (variable)	3.87	DKK/MW _{h_{th}}
- Electric boiler (fixed)	8,510.27	DKK/MW _{th}
- Solar collector	4.41	DKK/MW _{h_{th}}
- Heat pump	56,864.04	DKK/MW _{th}
Fuel		
- Natural gas ³	Varying monthly prices	DKK/Nm ³
- Electricity ⁴	Varying hourly prices	DKK/MW _{h_e}

Table 3: Cost and revenues applied in this study. The procurement of the investment costs for solar thermal is explained in Section 6.3 Solar thermal scenario. ¹ (Danish Energy Agency, 2012), ² (Solvarmedata, 2016), ³ (The Danish Energy Regulatory Authority, 2016) and ⁴ (Energinet.dk, 2016).

5.2 TAXES, TARIFFS AND SUBSIDIES

Besides the basic costs and revenues of a district heating plant a series of taxes, tariffs and subsidies exist critically influencing the feasibility of different investments. In the following these are explained and discussed. The taxes, tariffs and subsidies applied in the study are shown in Table 5.

THE EU EMISSIONS TRADING SYSTEM (ETS)

The EU Emissions Trading System aims to limit the emission of different greenhouse gases in European industrial processes. When used in regards to energy production the system is often referred to as the CO₂ quota system as CO₂ is the only greenhouse gas included in the emissions trading system that is linked to the production of energy. The system works through the “cap and trade” principle, meaning that a “cap” is set to determine the maximum amount of certain greenhouse gases that can be emitted within the system. The cap is reduced over time. The quotas within the cap are given or sold to companies that following can trade these (European Commission, 2016). According to annex 1 of the Emission Trading System Directive the ETS encompasses electricity and heat producing units of more than 20 MW input effect. As the generic district heating plant modelled in this study will not have an input of more than 20 MW fuel the plant will not be encompassed by the EU ETS (The Danish Energy Agency, n.d.).

5.2.1 REVENUES

1ST BASIC SUBSIDY

The first basic subsidy is a production-independent subsidy for decentral CHPs with the purpose of promoting energy efficient coproduction of electricity and heat. The plants are subsidised according to their installed capacities and in order to receive the maximum first basic subsidy the district heating plant has to be operational and available for balancing production the majority of the hours of the year. Furthermore the first subsidy varies from year to year partly depending on the spot price meaning that a low spot price induces a higher subsidy and vice versa. Only plants established before the 1st of April 2004 are entitled to the first basic subsidy and, with few exemptions, the subsidy expires at the end of 2018 (LBK no 1329 of 25/11/2013) (The Danish Energy Regulatory Authority, 2015). Given that the first basic subsidy will soon expire it can be discussed whether it should be included in this analysis. As, however, the first basic subsidy is crucial for the economic sustainability of existing district heating plants it is by many expected that this will be replaced by a similar subsidy in order to ensure the survival of these (Rugholt, 2016). Taking this into account the first basic subsidy will be included in the analysis. Originally the first basic subsidy was based on the individual production numbers from 2001-2003 and awarded to correlate so that high annual production resulted in a high first basic subsidy. However, as only produced electricity fed to the grid counted plants that produced directly for industrial purposes, heat pumps, electric boilers etc. were generally awarded smaller basic subsidies than the ones that did not have this kind of direct consumption (Albertsen, Energinet.dk, 2016).

In this project, based on statistics of awarded first basic subsidies according to MW_e installed capacities, the first basic subsidy is set to be around 3 million DKK/year or 250,000 DKK/month (Albertsen, Energinet.dk, 2016). In practice, for each month, the initially awarded first basic subsidy is adjusted according to the spot price by employing the so-called “Index factor”. The index factor is partly based on the “index for regulation of the basic subsidy” (*I_r*) which was, in the years 2005-2009, set every year taking into account the net price index and the coal price index through the following formula:

$$I_r = \frac{0.7 \cdot I_{net} + 0.3 \cdot I_{coal}}{102.1}$$

After 2009 the *I_r* has been fixed at its 2009 value: 1.223. Having established the *I_r* the index factor can be calculated through the method illustrated in Table 4.

Spot price, Sp, øre/kWh	Index factor
$Sp < 11 * Ir$	$1,4 * Ir$
$11 * Ir < Sp < 34 * Ir$	$1,4 * Ir - 0,06087 * (Sp - 11 * Ir)$
$34 * Ir < Sp$	0

Table 4: Regulated index function (BEK no 760 of 24/06/2013).

As Table 4 shows, with the 2015 Ir of 1.223 the monthly index factor will be a maximum of 1.71 for spot prices below 13.45 øre/kWh and a minimum of 0 for spot prices higher than 41.58 øre/kWh. Between these two extremes the index factor will vary (BEK no 760 of 24/06/2013). When calculating the actual monthly first basic subsidy the monthly share of the total first basic subsidy, in this case 250,000 DKK, is multiplied by the index factor of the month in question. For years with high spot prices this calculations method means that the actual paid first basic subsidy will be lower than the one originally awarded while years of low spot prices will cause higher payouts.

2ND BASIC SUBSIDY

Like the 1st basic subsidy the 2nd basic subsidy is production-independent and designed to ensure balancing capacity within the electricity system. The subsidy is given to CHP plants with a production capacity of 25 MW_e or less that use natural gas or biogas as a fuel. The 2nd basic subsidy is only given to plants put into service before the 1st of July 2002. A total of 344 district heating plants receive the 2nd basic subsidy and the subsidy expires at the end of 2019 (The Danish Energy Regulatory Authority, 2015). According to statistics within the capacity category 3-5 MW_e an average annual 2nd basic subsidy of 625,011 DKK/year equivalent to 52,084 DKK/month has been awarded (Albertsen, Energinet.dk, 2016). In this study the monthly value of 52,084 DKK has been applied.

THE ENERGY SAVINGS SCHEME

The Energy Saving Scheme is an agreement from 2012 between the Climate, Energy and Building Minister and the net and distribution companies in electricity, natural gas, district heating and oil. The scheme obliges Danish energy companies to implement annual energy saving of a certain size. In the case of a district heating company, these could be in the form of initiatives specifically reducing the heat demand at the consumer or investments in technologies substituting fossil based heat production with renewable (The Minister of Climate, Energy and Buildings, The Danish Energy Association, HMN Natural Gas, DONG Gas Distribution, Natural Gas Fyn Distribution, The Danish District Heat Association, The Association for Danish CHPs and Energy and Oil Forum, 2012). Until 2015, the Energy Saving Scheme included solar thermal in the way that the first year of solar thermal production would be counted as energy savings. Solar thermal is, however, not included in the current scheme (Risom, 2016). In the case of heat pumps using industrial waste heat these can only be counted as energy savings for the industrial company and only if they are owned and operated by this (Risom, 2016). Even though there have previously been revenues linked to the investment in solar thermal in the form of energy savings that would otherwise have to be found elsewhere, these are not applicable anymore and not included in the study.

5.2.2 COSTS

TARIFFS FOR NATURAL GAS

- *Transmission tariff:* The transmission tariff covers the expenses of the capacity and volume payment for the transmission system and is handled by Energinet.dk (Energinet.dk, 2013).

- *Distribution tariff*: The distribution tariff is payed to the local distribution system operator and covers the expenses for operating the distribution grid (HMN Naturgas, 2016).
- *Emergency supply tariff*: The purpose of the emergency supply tariff is to ensure the security of supply of natural gas by reserving capacity in the gas storage (Energinet.dk, 2013). This tariff is collected and handled by Energinet.dk.
- *Energy savings tariff*: In order to promote energy savings towards customers the energy savings tariff is payed (HMN Naturgas, 2016).
- *Energy saving tariff*: The energy saving tariff ensures the promotion of energy savings of the consumers. The tariff is administered by the local distribution company.

TARIFFS FOR ELECTRICITY

- *Net tariff*: The net tariff covers the expenses of expanding and maintaining the Danish electricity grid and is paid to Energinet.dk (Energinet.dk, 2016 B).
- *Distribution tariff*: Equivalent to the net tariff the distribution tariff covers the costs linked to the transportation of electricity to the consumers. This tariff is, however, paid to the local distribution system operator (Nagel, Fremme af fleksibelt forbrug ved hjælp af tariffer, 2015).
- *System tariff*: The system tariff covers the expenses of maintaining reserve capacity, operating the electricity system etc. and is paid to Energinet.dk (Energinet.dk, 2016 B).
- *Production tariff*: The production tariff is paid every time electricity produced at the district heating plant is fed into the electricity grid. This is paid to Energinet.dk (Energinet.dk, 2016 B).
- *PSO tariff*: The Public Service Obligation (PSO) tariff was introduced in 1998 as a source for funding for renewable energy projects, decentral CHP production, research etc. The PSO tariff is paid by the consumers to Energinet.dk as part of their electricity bill (Energinet.dk, 2015 C). District heating companies have to pay PSO when they use electricity also when this is for heat production purposes. When the electricity used is not taken from the grid but produced directly by e.g. a gas engine a reduced PSO tariff is can be paid in cases where the producer produces electricity with the primary purpose of covering own electricity demand. As this is generally not the case for decentral combined heat and power plants the reduced PSO is not relevant in this study (Energinet.dk, 2016). According to the "*scheme on reduced taxes for district heating*" (elpatronordningen) electric boilers owned by the district heating company have certain benefits, one of which is that they do not have to pay PSO (Nagel, The Danish District Heating Association, 2016) (LOV no 722 of 25/06/2010).

TAXES

- *Energy taxes*: The purpose of the energy tax is to promote a certain line of development by giving certain fuels an advantage over others. As a result of the oil crises of 1973-74 and 1979-80 the energy taxes were, following these years, used to reduce the consumption of fossil fuels, especially oil, and promote energy savings as well as the use of renewable energy sources. From the 1990s onwards the purpose of the energy taxes has primarily been to reduce the environmental impacts of energy con-

sumption and the energy taxes, hence, reflect the environmental costs for society linked to the use of different energy forms (Den store danske, 2012).

- *Reimbursement of energy taxes:* As energy taxes are only placed on the share of the fuel that is used for heat production a certain reimbursement of energy taxes is possible in the case of cogeneration of heat and electricity (Ea Energianalyse, 2011). The individual district heating plant can choose between two different methods, the V-formula and the E-formula, for distributing the tax (LBK no 312 of 01/04/2011).

The share of the fuel consumption which is dutiable calculated with the V-formula is:

$$\text{Tax share} = \frac{\left(\frac{\text{Heat production}}{1.2}\right)}{\text{Fuel consumption}}$$

Using the V-formula the reimbursement cannot exceed 35% of the fuel consumption for electricity. Using the E-formula the share of the fuel consumption which is dutiable is calculated as:

$$\text{Tax share} = 1 - \left(\frac{\left(\frac{\text{Electricity production}}{0.67}\right)}{\text{Fuel consumption}}\right)$$

The share of the fuel consumption which is dutiable can be compared to the heat efficiency of the CHP unit, see Figure 8. Typically, plants with a high electric efficiency will choose the E-formula while plants with a low electric efficiency will choose the V-formula. The engine in this project has a heat efficiency of 48% which favours the E-formula and is therefore chosen as the applied formula.

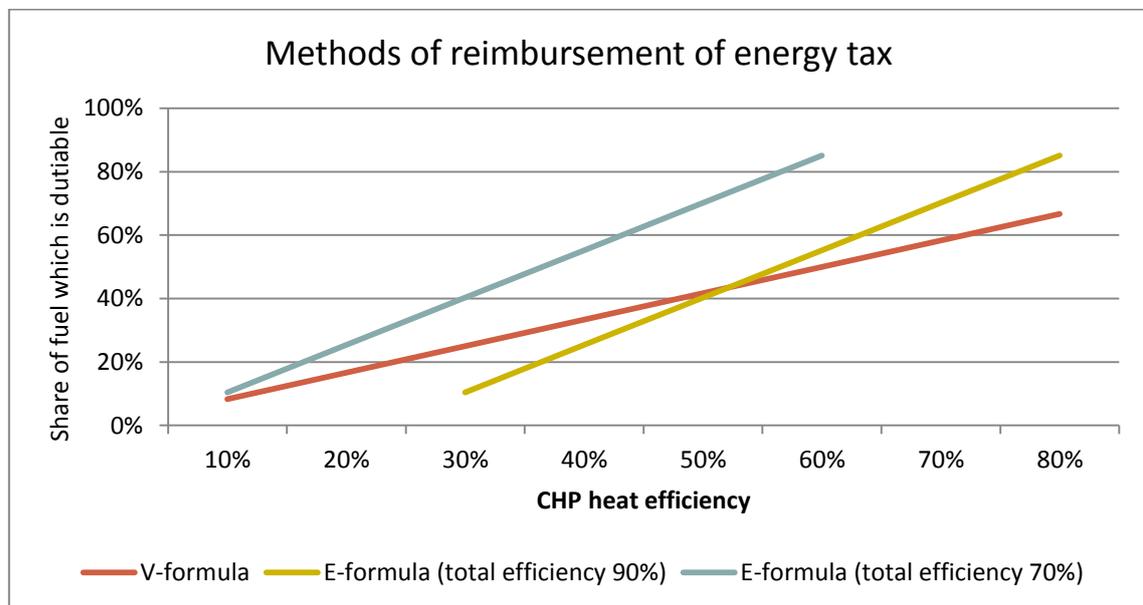


Figure 8: With a total CHP efficiency of 70% the E-formula is always less desirable than the V-formula. For a total CHP efficiency of 90% the E-formula is preferred until a heat efficiency of approximately 50%.

- *Electricity tax:* The electricity tax is part of the energy taxes but specifically targeted electricity used for heating purposes. As this tax is often a significant barrier for the use of electricity for heating purposes the “*scheme on reduced taxes for district heating*” has allowed certain tax reductions one of which is that boilers that are owned by the heating plant pay a reduced electricity tax (LOV no 722 of 25/06/2010). For heat pumps two methods exist for the calculation of the electricity (energy) tax, the thermal and the electric method. The thermal method is calculated as a certain tax per heat output, in 2015 equivalent to 212 DKK/MWh_{th}. When using this method there is no PSO tariff. The electric method is calculated as a higher tax per electric input, in 2015 380 DKK/MWh_e, plus the PSO tariff (Nagel, The Danish District Heating Association, 2016). Using the taxes and tariffs of 2015 this means that for COPs of 3.0 and above the electric calculation method is more attractive than the thermal one. As the heat pump of this project has a COP of 3.0 the electric method is used for calculating the electricity tax.
- *Taxes on emissions:* Four different types of emissions are subject to taxation, CO₂, NO_x, SO₂ and CH₄. As taxes on SO₂ is specifically linked to the use of coal or waste that are not part of this analysis only CO₂, NO_x and CH₄ taxes will be included in the energyPRO model (The Danish District Heating Association, 2014).
- *Reimbursement of CO₂ tax:* It is possible to get reimbursement of the CO₂ tax for fuels used for electricity production. This is, however, only possible for plants that are part of the CO₂ quota system. As the district heating plant of this study is not part of the CO₂ quota system there is no reimbursement of CO₂ tax (PwC, 2016).
- *Reimbursement of NO_x tax:* It is possible for district heating plants to get reimbursement of the tax on NO_x if e.g. they are able to show that the annual NO_x emissions are lower than the limit values. In the generic district heating plant of this study, however, there is no reimbursement of NO_x tax (PwC, 2015).

Table 5 shows the taxes, tariffs and subsidies linked to heat production in the district heating plant of this study.

Taxes, tariffs and subsidies	Cost	Unit
Subsidies¹		
- 1 st basic subsidy	2,997,179	DKK/year
- 2 nd basic subsidy	625,011	DKK/year
Natural gas tariffs²		
- Transmission tariff ³	Varying quarterly price	DKK/Nm ³
- Distribution tariff	0.150	DKK/Nm ³
- Emergency supply tariff	0.002	DKK/Nm ³
- Energy savings tariff	0.054	DKK/Nm ³
Electricity tariffs⁴		
- Net tariff	42.000	DKK/MWh _e
- Distributions tariff ⁵	90.000	DKK/MWh _e
- System tariff	29.000	DKK/MWh _e
- Production tariff	3.000	DKK/MWh _e
- PSO tariff	Varying quarterly price	DKK/MWh _e
Energy tax⁶		
- Gas engine	2.158	DKK/Nm ³
- Gas boiler	2.158	DKK/Nm ³
- Reimbursement - Gas engine	-2.158	DKK/Nm ³
- Electric boiler	212.000	DKK/MWh _{th}

- Heat pump	380.000	DKK/MWh _e
CO₂ tax⁶		
- Gas engine	0.384	DKK/Nm ³
- Gas boiler	0.384	DKK/Nm ³
NO_x tax⁶		
- Gas engine	0.146	DKK/Nm ³
- Gas boiler	0.042	DKK/Nm ³
CH₄ tax⁶		
- Gas engine	0.066	DKK/Nm ³

Table 5: Taxes and subsidies applied in this study. ¹ (Albertsen, Grundbeløb, 2016 B), ² (HMN GasNet, 2015), ³ (HMN Naturgas, n.d.), ⁴ (Energinet.dk, 2015 A), ⁵ (Nord Energi Net, 2016) and ⁶ (The Danish District Heating Association, 2014).

This study takes its point of departure in a generic district heating plant modelled to resemble a typical plant suitable for investments in solar thermal and potentially also heat pumps. In this chapter such a generic district heating plant is dimensioned and a year of operation is simulated making up the Basic scenario of this study. Following this, three scenarios will be tested; a Solar thermal scenario, a Heat pump scenario and a Combined scenario consisting of both solar thermal and heat pumps. For economic calculations on the different scenarios see *Appendix E – Economy data*.

6.1 DESIGNING A GENERIC DISTRICT HEATING PLANT

The following presents the different parameters making up the generic plant. These are the time horizon, demand, heat profile, weather data, fuels and the different production units.

TIME HORIZON

The scenarios of this study are modelled to simulate one year of production with the intent to show how the annual production is influenced by the inclusion of solar thermal and electric heat pumps, respectively. Based on the economic output from energyPRO investment calculations with a 15-year time horizon are carried out to estimate the long-term feasibility of the scenarios.

DEMAND

The generic plant should simulate one that would, in reality, be relevant for investments in both solar thermal and electric heat pumps. According to a report on the use of large heat pumps made for The Danish Energy Agency, large heat pumps are expected to play a role in smaller district heating areas, with an annual production less than 1 PJ, including ones with waste incineration and only in systems that are not based on biomass boilers (The Danish Energy Agency, 2014 A). According to the Benchmarking statistics of The Danish District Heating Association the district heating plants meeting these requirements, have an average annual production of around 53,000 MWh_{th}.

Looking specifically at plants that have already invested in solar thermal, however, some tendencies can be seen. Of the plants listed on Solvarmedata.dk 39 plants give data that reveal their total annual heat production. The annual production amongst these varies between about 7,000 MWh_{th} and 100,000 MWh_{th} with an average of around 29,000 MWh_{th} (Solvarmedata, 2016). The tendency is, hence, that mostly relatively small district heating plants have until now invested in solar thermal. It is possible that this tendency is changing as larger plants such as e.g. Silkeborg Forsyning (with an annual production of around 350.000 MWh_{th}) are currently planning to install solar thermal (Silkeborg Forsyning, 2015).

As this study assumes that plants are to invest in both solar thermal and heat pumps it is important that the simulated generic plant is representative of plants fit for both technologies. Using this logic the annual heat demand of the generic plant is set to be 29,000 MWh_{th}. It is possible that the heat demand could change within the 15 year time horizon of the investments analysed in this study. There is a political focus on energy savings and many energy system scenario reports predict significant reductions in the heating demand by 2035 and 2050 (Social Democrats, The Danish Social-Liberal Party, The Socialist People's Party, The Liberal Party of Denmark, Danish People's Party, Red-Green Alliance and Conservative People's Party, 2012) (Energinet.dk, 2015 A) (The Danish Energy Agency, 2014 B). At the

same time several reports predict an ongoing expansion of the district heating system towards 2035 and it is, hence, difficult to estimate the precise development in the heating demand of the individual plant (Energinet.dk, 2015 A) (Mathiesen, et al., 2015). As the future development in heat demand at the individual plant level is difficult to predict, a fixed heat demand of 29,000 MWh_{th} is assumed for all years of this study.

HEAT PROFILE

The heat profile is divided into three demands: space heating, domestic hot water and grid loss, see Figure 9. The fractions of space heating and domestic hot water are based on the average share of hot water for Danish households (The Danish Building Research Institute, 2009). Space heating makes up the largest share with 52% of the total heat demand, whereas domestic hot water makes up 23%. The remaining 25% of the total heat demand is constituted by grid loss. As opposed to the space heating demand and domestic hot water, the grid loss is, in this study, distributed evenly over the year. The demand for domestic hot water is, set to vary throughout every 24 hours to account for hourly fluctuations in demand. This means that the domestic hot water demand will peak in the morning hours and again in the early evening every day.

GRID LOSSES

An average annual grid loss is estimated based on the Benchmarking statistics of 2015 from The Danish District Heating Association. For district heating plants with an annual heat production in the range between 20,000 and 40,000 MWh_{th} the grid loss makes up 25% of the demand (The Danish District Heating Association, 2015). It is, hence, estimated that an annual grid loss of 25% is realistic for the generic plant of this study. In reality the grid loss would see some annual variations. Depending on the depth of the pipes grid losses would increase as the ambient temperature decreases in the colder months. Contrarily the distribution system sees an increase in grid losses during the summer months as the flow is reduced in the pipes (Østergaard & Andersen, Booster heat pumps and central heat pumps in district heating, 2016). These fluctuations are not included in the standard analysis of this study but are further discussed in *Chapter 7 Method improvement*.

HEATING SEASON

The heating season is set to run between the 1st of September and the 31st of May. The hourly distribution of space heating is based on degree days. The number of degree days is calculated as 17°C minus the daily mean temperature (The Danish Meteorological Institute, 2013). This means that when the daily mean temperature is below 17°C there is a need for space heating. Consequently, the space heating demand is the same within 24-hours, as hourly variation would be too rapid when considering the heat accumulated in the building mass (Østergaard & Andersen, Booster heat pumps and central heat pumps in district heating, 2016). Outside the heating season the only heat demand is for domestic hot water.

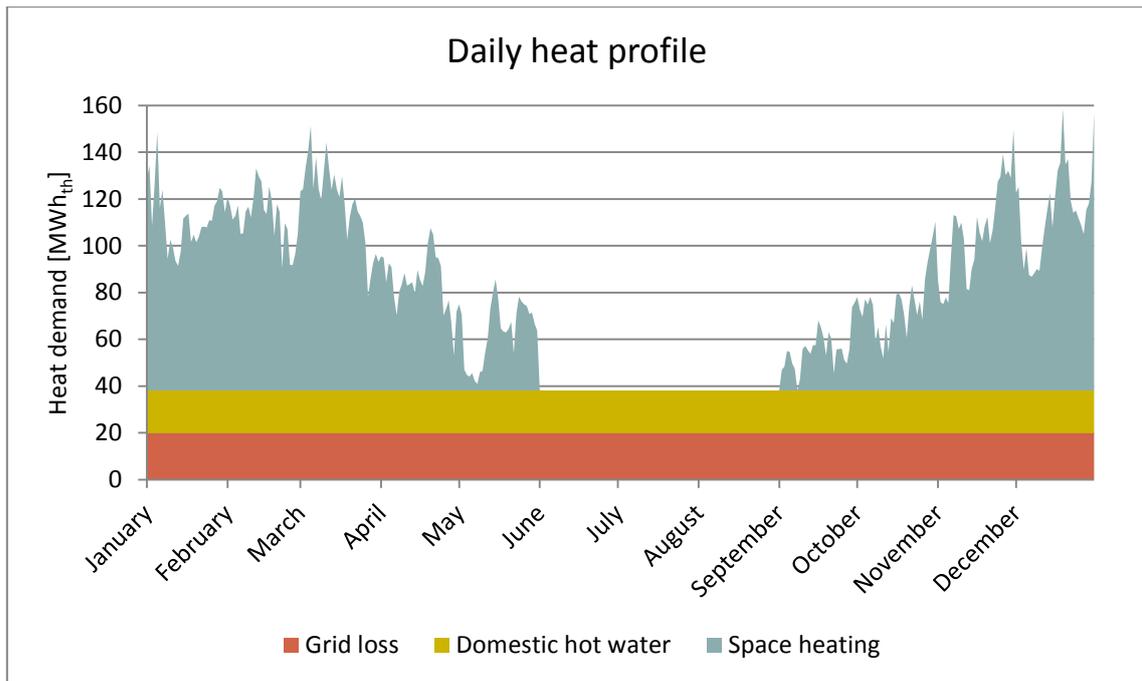


Figure 9: The heat profile with daily values. The heating season starts in September with the space heating demand and ends in May when the space heating demands stops. From June up to and including August the heat demand is constituted by grid loss and domestic only. For calculations of the heat profile see Appendix F – Heat profile.

WEATHER DATA

The input climate data used in the energyPRO model is the so-called, Design Reference Year (DRY), published by The Danish Meteorological Institute. The purpose of DRY is to offer a dataset of representative climate data to be used in the energy and construction sector. The DRY is constructed as a reference year based on climate data from the years 2001-2010. Instead of using one continuous annual measurement monthly data has been put together in order to construct a combined representative year. Each month has been selected as this represents a *typical* month with a certain variance but no extreme values. The data used is for ambient temperature as well as both direct and diffuse solar radiation. The DRY data used is in all three cases from zone two as this zone covers a large share of central and southern Jutland that is some of the most common locations for solar thermal projects (The Danish Meteorological Institute, 2013).

HEATING VALUES

The heating value for natural gas is set to be 11.0 kWh/Nm³ in accordance with the socio-economic calculation assumptions set forth by The Danish Energy Agency (The Danish Energy Agency, 2014 A).

6.1.1 PRODUCTION UNITS

For production units all capacities, efficiencies, availabilities, minimum/maximum load etc. are based on the Technology Catalogue unless otherwise mentioned.

NATURAL GAS ENGINE - CHP

According to the Collective Heat supply Projects Act §11 subsection 2, when dimensioning CHP units for district heating plants the engine should be dimensioned so that the heat production capacity can cover the demand 90% of the year (BEK no 1124 of 23/09/2015). In

this project, this is equivalent to 5.3 MW_{th}. As the c_b coefficient is set to be 0.9 the electric capacity is 4.8 MW_e. The total efficiency of the CHP is set to be 92%. In the operation strategy the CHP is allowed to run on partial load but only as low as 50% of the maximum capacity. In this mode the efficiency is assumed to still be 92% though it might be lower in reality. As the CHP is expected to be unavailable for maintenance purposes 5% of the year the first 18 days of July are reserved as non-availability period. Minimum operation hours is set to 2 hours and the start-up and shut-down time is set to be 10 minutes, respectively. The CHP is allowed to produce to the thermal storage.

NATURAL GAS BOILER

The natural gas boiler is dimensioned to be able to cover the maximum hourly demand on an annual basis. Considering this the boiler is given a capacity of 8 MW_{th}. The efficiency of the boiler is set at 101%. As the boiler is out of service for maintenance 1-2% of the time four days in August are reserved as non-availability period. The natural gas boiler is not allowed to produce to the thermal storage.

ELECTRIC BOILER

The electric boiler is dimensioned to a capacity of 4 MW_{th}. It is allowed partial load but only down to a minimum load of 15%. As the boiler is out of service for maintenance 1-2% of the time four days in June are reserved as non-availability period. The electric boiler is allowed to produce to the thermal storage.

THERMAL STORE

The thermal storage is dimensioned to be able to cover the heat demand throughout a weekend in the summer period, equivalent to about 100 MWh_{th}. The bottom temperature is set to be 40°C while the top temperature varies between 80°C in the heating season and 70°C outside the heating season in accordance with the tendency seen in the benchmarking statistics of The Danish District Heating Association (The Danish District Heating Association, 2015). Applying these temperatures a total volume of 2,400 m³ is needed.

Figure 10 shows a schematic representation of the generic plant.

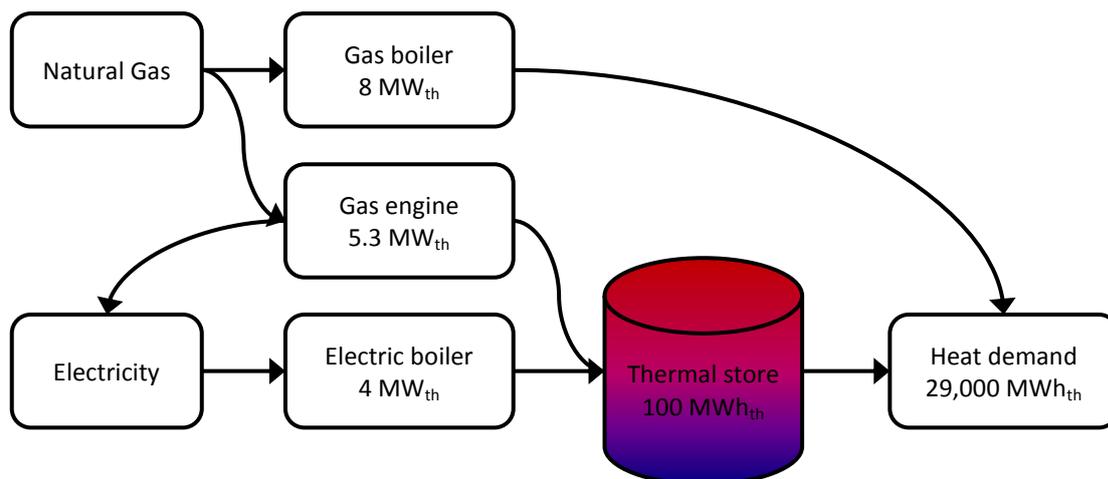


Figure 10: Diagram of the generic district heating system. The heat demand is covered by the gas boiler, gas engine and electric boiler in combination. The gas engine and electric boiler can produce to the thermal store while the gas boiler can only produce for direct consumption.

6.1.2 OPERATION STRATEGY

Having dimensioned the different production units, these have to be prioritised according to their heat production costs. This is done automatically in energyPRO but can also be done manually by adding up all costs from fuels, taxes, tariffs and operation and maintenance and dividing these by the efficiency of the unit in question. In the case of the CHP unit revenues from sale of electricity have to be added to the equation.

$$\text{Heat production cost} = \frac{\text{fuel} + \text{taxes} + \text{tariffs} + \text{O\&M}}{\text{efficiency}} - \text{electricity price} \cdot c_b$$

Fuel: natural gas or electricity [DKK/MWh]

Taxes: energy-, CO₂-, NO_x- and CH₄ tax [DKK/MWh]

Tariffs: net-, system-, PSO-, production- and distribution tariffs [DKK/MWh]

O&M: variable O&M [DKK/MWh]

Efficiency: efficiency of the production unit [%]

Electricity price: Only relevant for the gas engine [DKK/MWh]

c_b: ratio between electricity and heat production in gas engine [0.9]

When the heat production price has been calculated for all production units, these can be displayed side by side in a production hierarchy demonstrating what production units are more attractive at different electricity price levels, see Figure 11.

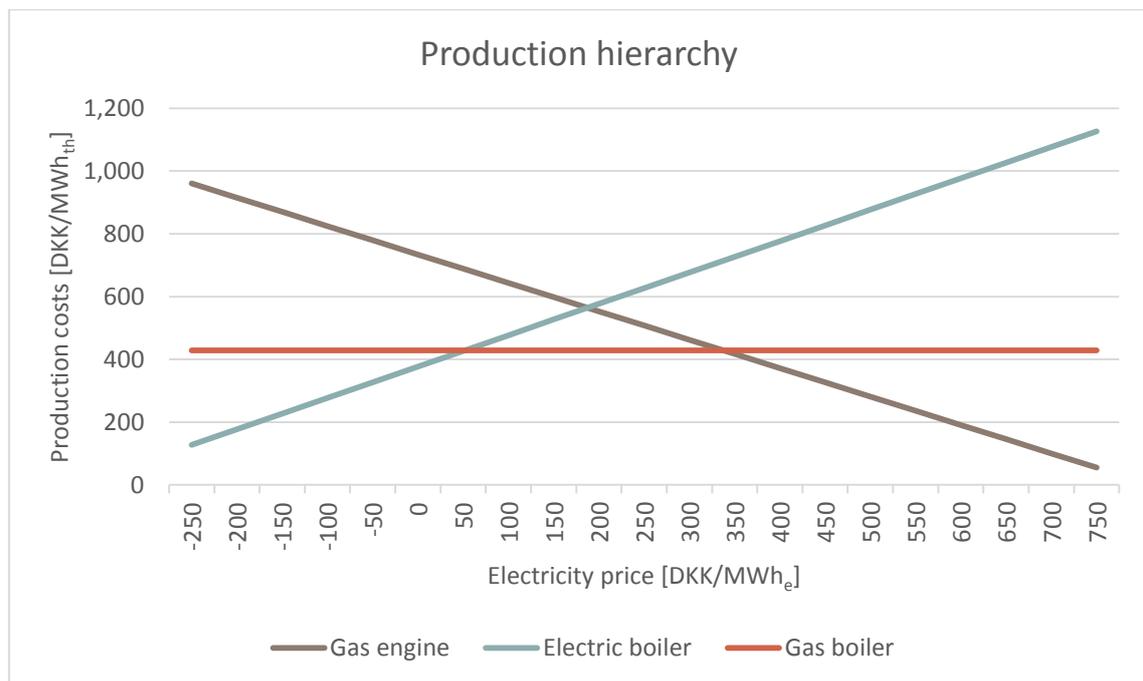


Figure 11: The production hierarchy of this study is not fixed but varies slightly from month to month with varying natural gas prices and PSO tariffs. The displayed production hierarchy is from January 2015. The production hierarchy does not include fixed operation and maintenance as this is given per installed capacity and independently of the actual production. This represents an uncertainty for production units that are only attributed a fixed operation and maintenance cost.

As Figure 11 shows the heat production price decreases for the gas engine as the electricity price increases. Opposite, for the electric boiler the heat production price increases as the electricity price increases. Finally, the production price of the gas boiler remains stable un-

affected by the electricity price. The electric boiler is the cheapest unit until the electricity price reaches approximately 50 DKK/MWh_e. With an electricity price of 50-340 DKK/MWh_e the gas boiler is the cheapest unit, and above 340 DKK/MWh_e the gas engine is the cheapest unit.

6.2 BASIC SCENARIO

When running the Basic scenario, the generic plant with the abovementioned characteristics, in energyPRO the following production pattern can be seen:

Basic scenario	Heat production [MWh _{th} /year]	Heat production [%/year]
Gas engine	2,943.3	10.1%
Electric boiler	1,816.3	6.3%
Gas boiler	24,270.5	83.7%
Storage loss	-30.2	-0.1%

Table 6: Annual operation characteristics of the generic plant for the Basic scenario. For operation details see Appendix G – Production and operation costs, Basic scenario.

As seen in Table 6 the gas boiler is accountable for the majority of the produced heat. This is due to the fact that, the majority of the time, the electricity price is between 50 and 340 DKK/MWh_e. Due to different capacities of the production units the production share is not directly comparable with the annual distribution of electricity prices. Taking electricity prices into account the gas boiler is the cheapest unit 90.7% of the year, the electric boiler operates as the cheapest unit 4.9% of the year and in the remaining 4.4% of the time the gas engine is the cheapest unit.

Figure 12 shows the duration curve of the heat demand as well as the annual heat production in the basic scenario.

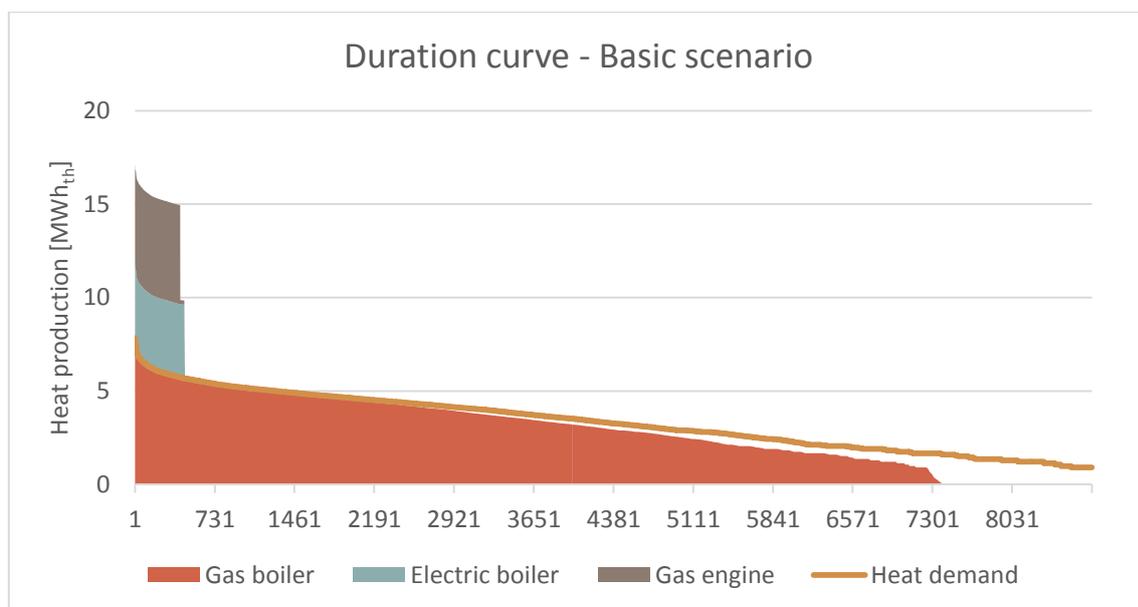


Figure 121: Duration curve of heat demand and annual heat production in the Basic scenario.

It is evident that the gas boiler is responsible for by far the largest production share and the most production hours. However, unlike the electric boiler and the engine the gas boiler does not utilise its full capacity in the vast majority of production hours. The flexibility of the gas boiler allows for a production that complies with the demand many hours of the year reducing the need for the thermal store.

When looking at the economy of the plant it is clear that a relatively large share of the annual costs and revenues are from taxes and subsidies. Of the annual costs of around 13.3 million DKK about 52.3% (7.1 million DKK) are made up of taxes and tariffs with energy taxes as the most significant contributor. The remaining annual costs are mainly for fuels (43.3%, 5.7 million DKK) while operation and maintenance only make up a smaller share of about 2.3% (0.3 million DKK). Of the annual revenues of around 6.0 million DKK subsidies in the form of the 1st and 2nd basic subsidy make up about 84.2% (5.0 million DKK) while sale of electricity accounts for the remaining 1.0 million DKK.

When comparing the annual costs and revenues a total deficit of about 7.3 million DKK remains. In reality this deficit would expectedly be even higher as it does not consider wages, rent and other costs that are left out as they do not vary between the scenarios. If the 7.3 million DKK were to be covered by the sale of heat the heat price would be 336 DKK/MWh_{th} excl. VAT. This is in the low end when comparing with district heating prices of August 2015 with an average price of 446 DKK/MWh_{th} excl. VAT (The Danish Energy Regulatory Authority, 2015). For comparison of the annual operation economy of the four tested scenarios see Table 11.

Having dimensioned the basic generic district heating plant and run the Basic scenario, the possible costs or revenues of investing in additional production units can be explored. The following sections uses economic and production data to calculate the optimum use of solar thermal and electric heat pumps, respectively, in the generic plant.

6.3 SOLAR THERMAL SCENARIO

Before determining the size of the solar collector area some basic data on solar thermal have to be applied. The specifications of the solar collectors are set to match the Arcon-Sunmark HEATboost solar collector (Arcon-Sunmark). As Arcon-Sunmark is the dominant supplier of solar collectors in Danish district heating these values are estimated to be suitable for this study.

In the statistic of established solar thermal plants for district heating the inclination of the solar collectors vary between 30° and 45° with no apparent correlation with the location of the individual plant (Solvarmedata, 2016). As the majority of Danish cases have an inclination of 38° the same value is used in this study. The solar thermal plant is set to deliver heat at 70°C which also indicates a general supply temperature of the district heating system of 70°C. Finally, the lifetime of the solar thermal plant is set to be 30 years in accordance with the technology catalogue (The Danish Energy Agency, 2012 A).

INVESTMENT COSTS

The solar thermal plant is dimensioned in order to ensure the highest possible profit when considering the investment as well as the annual operation costs over the investment period as a net present value calculation plus a scrap value for the remainder of the plant's lifetime. The investment in solar thermal can be calculated as a price per m² collector area (The Danish Energy Agency, 2012 A). As, however, it is expected that some start-up expenses

would not vary significantly depending on the size of the plant an attempt for a more correct investment calculation has been made. Figure 13 shows a scatter plot of the investment costs per m² of existing solar thermal plants of relevant size to the scope of this study.

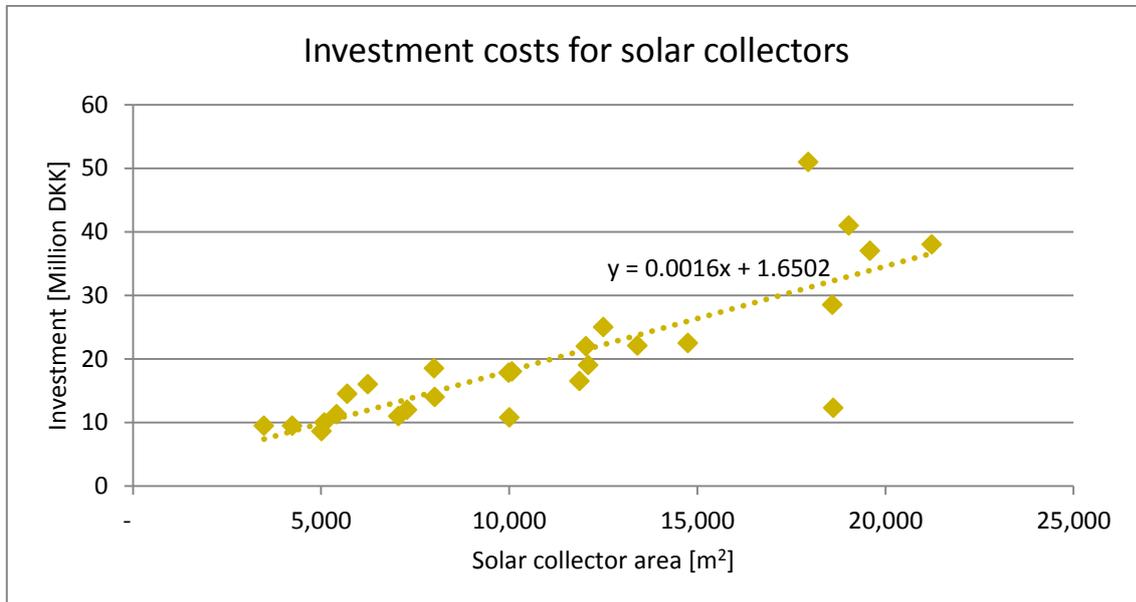


Figure 13: The investment cost per m² of established Danish solar thermal projects (Solvarmedata, 2016).

As it can be seen from the trend line the investment costs can be calculated as an initial investment of about 1.65 million DKK and an investment per m² of 1,600 DKK.

DIMENSIONING THE SOLAR THERMAL PLANT

The annual revenues of a solar thermal plant are calculated as annual savings in operation costs when compared to the basic scenario. In order to determine the optimum size of the solar thermal plant the simple payback time as well as the net present value are calculated for different sizes of solar thermal plants ranging from 1,000-35,000 m². Besides investment costs and annual savings the calculation of net present value contains a scrap value of the remaining 15 years of the solar thermal plant's lifetime. As the potential for utilising solar thermal is highly dependent on the storage capacity the calculation is made both for the existing storage capacity and for an increasing storage capacity, both as steel tanks and seasonal storage. For steel tanks a size of 0.3 m³ per m² solar collector area has been applied and for seasonal storage a size of 1.25 m³ per m² solar collector area has been applied (The Danish Energy Agency, 2012 A). When additional storage capacity is added to the system a scrap value for the remaining 15 years of the storage is included in the net present value calculations. The results are shown in Figure 14.

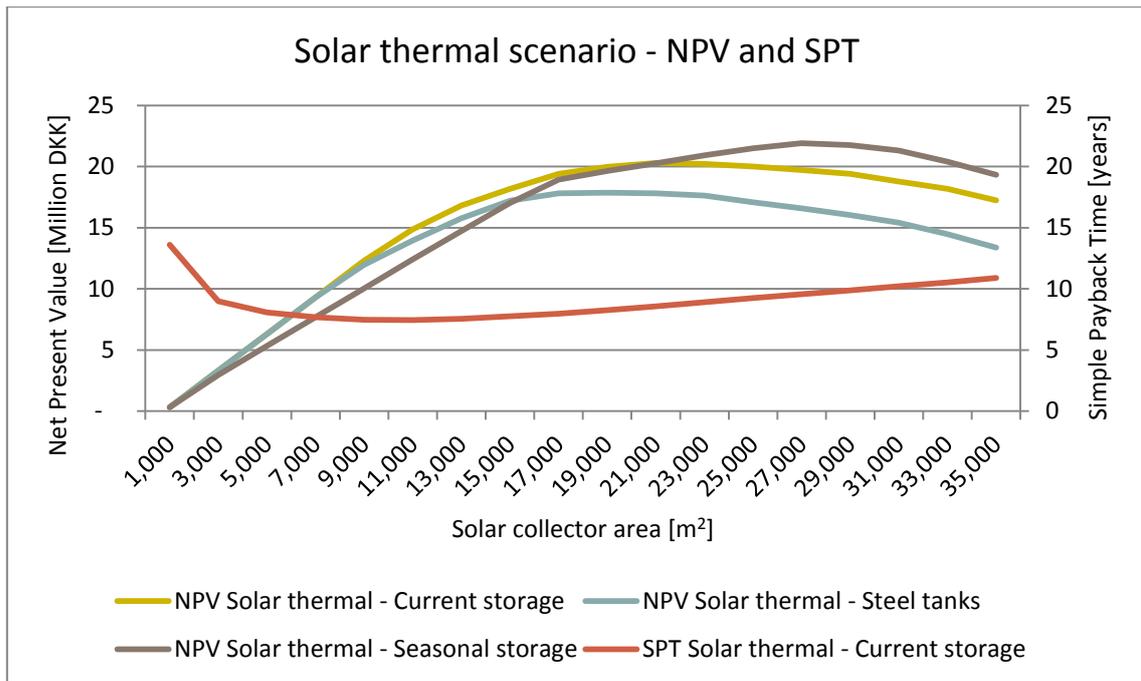


Figure 14: Net present value and simple payback time calculated for different sizes of solar thermal plants. The net present value calculations for the two scenarios of additional storage capacity include both the additional investment costs for storage and the additional revenues for better utilisation of the solar collectors as well as a scrap value.

As Figure 14 shows, the simple payback time is relatively stable in the range from 5,000 to 19,000 m² with a minimum of 7.4 years at 11,000 m². The simple payback time is, however, relatively short also for solar collector coverage above 19,000 m².

The net present value of steel tanks is equal to the current storage with a solar collector area until 7,000 m². Above that size, the net present value of steel tanks is worse than the current storage, thus the investment in steel tanks is undesirable. The highest achievable output from the investment in solar thermal is found at 27,000 m² installed solar collector area and a seasonal storage holding approximately 33,750 m³. This solution results in a net present value of about 21.9 million DKK over the investment period, which is about 1.6 million DKK higher than the optimal solution when not including any additional investment in storage capacity. With a solar collector area of 27,000 m² and a seasonal storage the solar thermal plant is responsible for about 46.8% of the annual heat production. This is considerably higher than the 20-25% that appears to be the norm in existing solar thermal plants. Because of this as well as the relatively modest improved income of a seasonal storage it has been decided to focus on a solar collector area of 21,000 m² with no additional storage capacity in the following analysis. This scenario has a net present value of 20.3 million DKK over the investment period. With an area of 21,000 m² the solar thermal plant produces about 34% of the annual heat demand which is still higher than the norm, but considered more realistic in a study attempting to simulate real district heating plants.

When running the generic system including 21,000 m² of solar collector area in energyPRO the following production pattern can be seen.

Solar thermal scenario	Heat production [MWh _{th} /year]	Heat production [%/year]
Gas engine	2,250.3	7.8%
Electric boiler	709.1	2.4%
Gas boiler	16,125.6	55.6%
Solar thermal	9,951.6	34.3%
Storage loss	-36.6	-0.1%

Table 7: Annual operation characteristics of the Solar thermal scenario. For operation details see Appendix H – Production and operation costs, Solar thermal.

When compared to the operation characteristics of the basic scenario it is clear that the solar thermal production induces a significant reduction in operation hours of both of the boilers as well as a smaller reduction in production from the engine. As solar thermal only covers 34.3% of the demand the system is, however, still relatively dependent on electricity and gas for additional production.

Figure 15 shows a duration curve of the heat demand as well as the annual heat production from the different units.

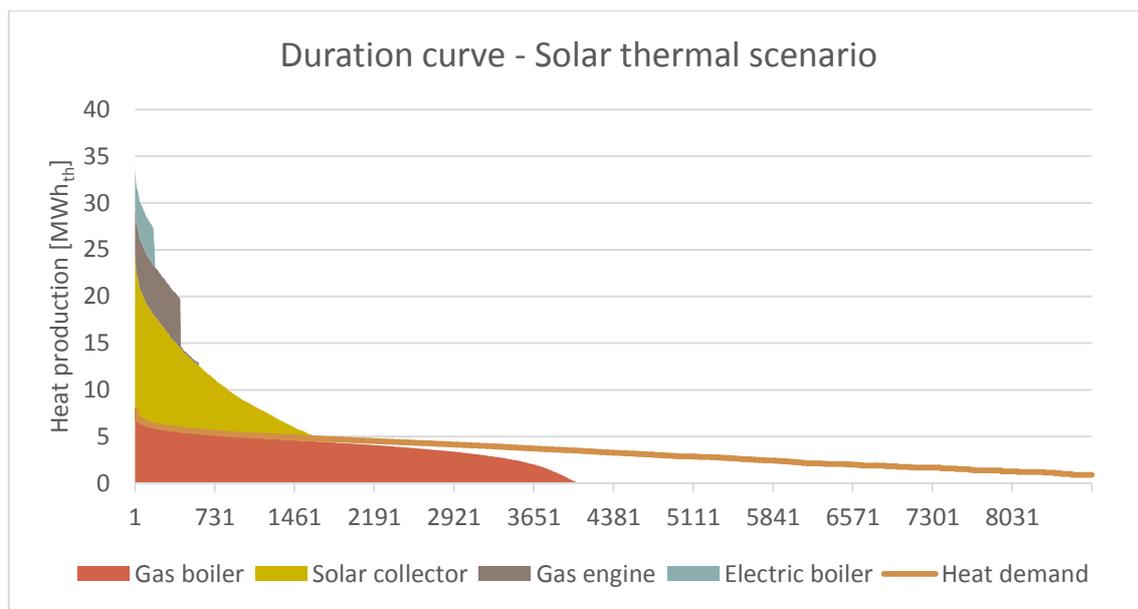


Figure 15: Duration curve of heat demand and annual heat production with a solar thermal area of 21,000 m².

The duration curve display some of the challenges linked to production from solar thermal. It is evident that the solar collectors have a very high maximum capacity significantly exceeding the relatively low heat demand of the summer months. At the same time, it is clear that this very high production is only available for a limited number of hours every year. The thermal store plays a critical role in balancing supply and demand in periods of high production from solar thermal.

Looking at the economy of the plant, the annual costs of the Solar thermal scenario have been reduced by 4.4 million DKK when compared to the Basic scenario and is now 8.9 million DKK. Cost reductions can be seen in all parts of the production but especially in regards

to fuel usage and energy taxes the Solar thermal scenario proves more economic. However, the reduced production from the engine also leads to fewer revenues from sales of electricity adding up to a total loss in income of 0.2 million DKK when compared to the Basic scenario. When comparing the annual costs and revenues a total deficit of about 3.1 million DKK remains. This means that the Solar thermal scenario is 4.2 million DKK cheaper than the Basic scenario on an annual basis. For comparison of the annual operation economy of the four tested scenarios, see Table 11.

6.4 HEAT PUMP SCENARIO

The Heat pump scenario tests the addition of a heat pump to the generic plant in order to determine the competitiveness of the technology compared to solar thermal. Before determining the capacity of the heat pump some basic data have to be applied. When determining the specifications of an electric heat pump both the COP and the production capacity are of specific importance. Looking into existing scenario reports, technology catalogues and data sheets the expected COP of large heat pumps for district heating purposes vary significantly between 2.8 and 3.5 (Clausen, Kim S.; From, Niels; Hofmeister, Morten; Paaske, Bjarke Lava; Flørning, John, 2014 B) (The Danish Energy Agency, 2012 A) (Mathiesen, et al., 2015). Generally, this value depends on several factors of which especially the heat source is important. Hence, the COP of a heat pump will vary from project to project depending on the available heat sources of a specific location. In this project an average COP of 3 has been applied.

The start-up time for a heat pump can be relatively long, in some cases several hours. It is, hence, relevant to minimise the stops in operation of the heat pump. Because of this a 1-hour start-up time as well as a minimum for consecutive operation hours of two hours has been set. The lifetime of the electric heat pump is set to be 20 years in accordance with the technology catalogue (The Danish Energy Agency, 2012 A). Examples from Sweden reveal that large heat pumps can last up to 30 years, which would improve the business-case of a heat pump. It can therefore be argued, that the applied lifetime of 20 years from the Technology Catalogue is a conservative estimation (Clausen, Kim S.; From, Niels; Hofmeister, Morten; Paaske, Bjarke Lava; Flørning, John, 2014 B).

According to Johnson Controls, partial load is not suitable for heat pumps (Johnson Controls, 2016). However, large heat pumps often consist of a number of smaller heat pumps coupled in parallel (Clausen, Kim S.; From, Niels; Hofmeister, Morten; Paaske, Bjarke Lava; Flørning, John, 2014 B). With several smaller heat pumps a variable operation is possible, e.g. only to use some of the heat pumps, and thus allow for partial load. In this study it is assumed that only one large heat pump is used, due to the testing of varying capacities. On this basis, partial load for heat pumps is not allowed. However, to allow for the optimal utilisation of favourable electricity prices the heat pump is allowed to produce to the heat store.

For electrical heat pumps the maintenance is primarily linked to the compressor e.g. for lubricant oil. A service check is recommended for every 5,000 operation hours. Every second year there is a mandatory service check of the pressure tanks and pipe system. For every fourth and eighth year a more comprehensive service check of the pressure tanks and pipe system is required. Additionally there is further service checks depending on the type of compressor used in the heat pump (Clausen, Kim S.; From, Niels; Hofmeister, Morten; Paaske, Bjarke Lava; Flørning, John, 2014 B). To allow for this maintenance two days in June are reserved for service checks of the heat pump.

The operation and maintenance of the heat pump is added as a fixed payment per installed MW_{th} capacity in accordance with the technology catalogue. In reality some of the operation and maintenance costs would likely depend on the actual operation of the plant, for instance change of lubrication oil or wearing parts. The price level for a service agreement would be about 10-20 DKK/ MWh_{th} (Clausen, Kim S.; From, Niels; Hofmeister, Morten; Paaske, Bjarke Lava; Flørning, John, 2014 B). This uncertainty might slightly over- or underestimate the actual operation and maintenance cost of the heat pump.

INVESTMENT COSTS

Existing cases of large electric heat pumps for district heating vary in installed capacity between 0.13 and 6.0 MW_{th} . The installed capacity depends on several factors including the size of the district heating system and the specifications of the heat source and it is difficult to deduce a specific rule-of-thumb for investment costs from the existing large heat pump projects. Utilisation of internal flue gas is the cheapest heat source at approximately 4.3 million DKK/ MW_{th} , while industrial waste heat and ground water is more expensive at respectively 7.0 and 7.6 million DKK/ MW_{th} . In each case the heat pump itself accounts for about half of the investment while the rest of the investment is for the heat source, buildings, SCADA (Supervisory Control and Data Acquisition) and connection (Ebbehøj, Oversigt over ansøgningerne og økonomi, 2015 A). Some of these costs have a longer lifetime than the heat pump while others are non-recurrent expenditures. Pipes are for instance expected to last for up to 50 years (Rasmussen, 2014), while buildings and counselling are one-time expenses. Therefore the life extension of a heat pump is considerably cheaper than the establishing of the heat pump, and thus more cost-competitive.

This, as well as lack of specific information on especially the investment costs of existing projects, makes it difficult to base the economic calculations of this study directly on existing projects. Instead the investment data from the Technology Catalogue is applied, see *Chapter 5 Economic factors*. The investment costs from the technology catalogue are somewhat simplified and are expressed as a price per MW_{th} . In reality, a district heating company would collect offers from heat pump producers and as each heat pump have different specifications, it is difficult to directly compare the investment costs. Furthermore local conditions have influence on the investment. Thus it can be concluded that the investment costs used in this study comes with some uncertainties, and that this will affect the profitability of the heat pump in the study.

DIMENSIONING THE ELECTRIC HEAT PUMP

In order to determine the optimal size of the heat pump in the generic plant, the simple pay-back time as well as the net present value are calculated for different electrical capacities ranging from 166.7 to 2000 kW_e . In the case of net present value the calculation includes a scrap value of the remaining 5 years of the unit's lifetime. As tests have shown no significant improvement in operation with additional storage capacity this option is not included in the calculation. The results are shown in Figure 16.

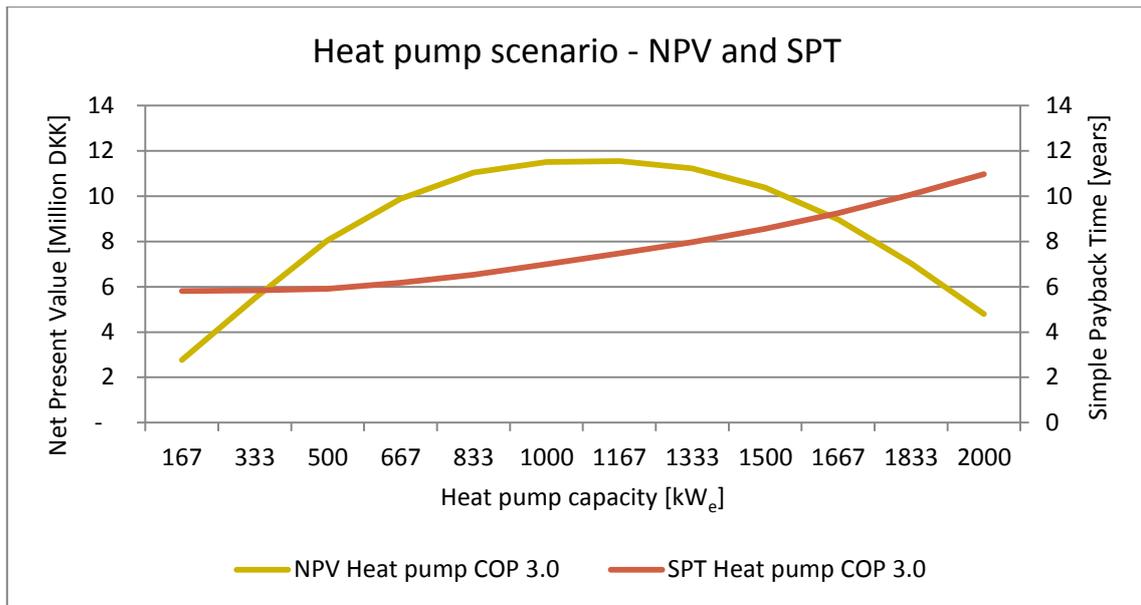


Figure 16: Net present value and simple payback time for different electric capacities of a heat pump.

In the case of the heat pump the simple payback time begins at its minimum and becomes longer as the capacity increases. As for solar thermal the simple payback time stays relative-ly short around 6 years for most of the examined capacities though the tendency shows an exponential increase for larger thermal capacities. The net present value increases until a maximum of 11.5 million DKK at an electrical capacity of 1166.7 kW_e. At electrical capacities higher than 1166.7 kW_e the net present value is again reduced.

When running the heat pump scenario with 1166.7 kW_e installed capacity in energyPRO the following production pattern can be seen:

Heat pump scenario	Heat production [MWh _{th} /year]	Heat production [%/year]
Gas engine	1,498.7	5.2%
Electric boiler	591.5	2.0%
Gas boiler	3,051.6	10.5%
Heat pump	23,898.0	82.4%
Storage loss	-39.7	-0.1%

Table 8: Annual operation characteristics of the Heat pump scenario. For operation details see Appendix I – Production and operation costs, Heat pump scenario.

When compared to the operation characteristics of the basic scenario, Table 8 shows a major replacement of the original production units by the heat pump. Especially the gas boiler sees a decline in operation as the annual production is reduced by 87% from the Basic scenario to the Heat pump scenario.

Figure 17 shows the duration curve of the heat demand as well as the annual heat production in the heat pump scenario.

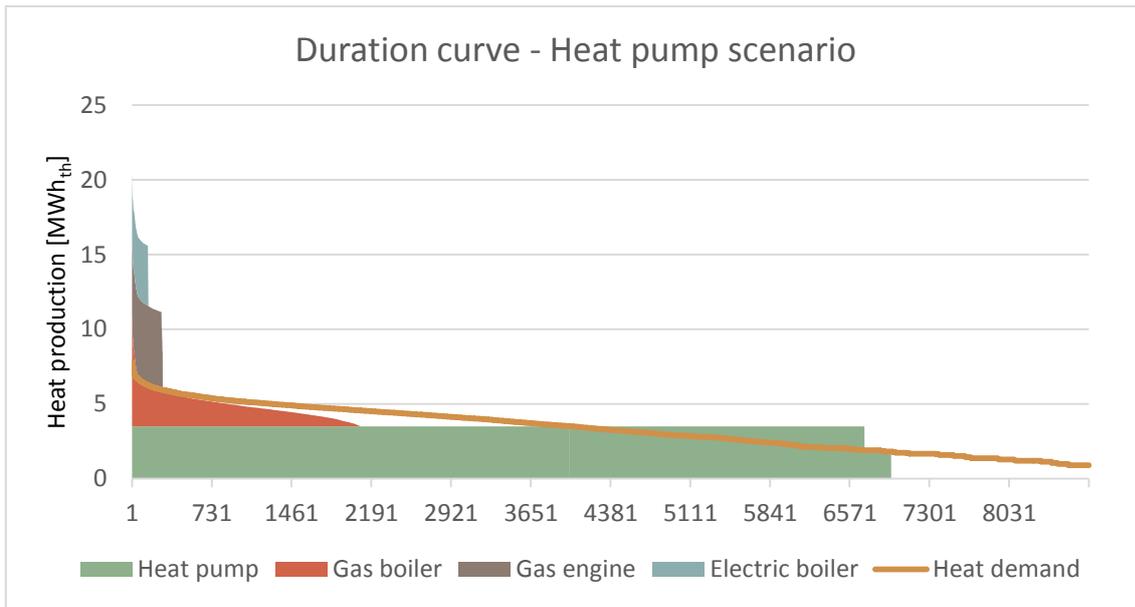


Figure 17: Duration curve of heat demand and annual heat production with an installed heat pump capacity of 1166.7 kW_e.

It is clear from the duration curve that the heat pump is responsible for by far the majority of the heat production and by far the most production hours. The heat pump operates almost 7000 hours of the year, which is in agreement with the 6000-8000 hours recommended by The Danish District Heating Association (Clausen, Kim S.; From, Niels; Hofmeister, Morten; Paaske, Bjarke Lava; Flørning, John, 2014 B). The fact that the heat pump is not allowed to run partial load means that the production from the heat pump will surpass the heat demand in some hours and the surplus heat will be delivered to the storage.

Looking into the economy of the plant, the Heat pump scenario has annual expenditures of 10.3 million DKK which is an annual reduction of 3.0 million DKK when compared to the Basic scenario. As in the Solar thermal scenario the Heat pump scenario sees a large reduction in costs for fuel and energy taxes compared to the Basic scenario. On the other hand, a significant increase in tariffs are seen from 0.3 million DKK in the Basic scenario to 3.1 million DKK in the Heat pumps scenario mainly due to PSO and other tariffs related to the use of electricity. As in the Solar thermal scenario the revenues from sale of electricity are slightly reduced as the engine does not operate as much as in the Basic scenario. When comparing the annual costs and revenues a total deficit of about 4.8 million DKK remains. This means that the Heat pump scenario is 2.5 million DKK cheaper than the Basic scenario on an annual basis. For comparison of the annual operation economy of the four tested scenarios, see Table 11.

6.5 COMPARISON OF SOLAR THERMAL AND HEAT PUMP SCENARIO

Having discussed both the Solar thermal and the Heat pump scenario, the following section compares the two with the intention to determine what technology is the more attractive investment in the specific case of the modelled generic district heating plant of this study.

Looking at the investment in solar thermal versus an electric heat pump over a time frame of 15 years, both are profitable investments. Seen in isolation the heat pump make up an attractive investment and furthermore offer a lower simple payback time than the Solar thermal scenario due to lower investment costs. However, looking at the net present value the Solar thermal scenario show the most promising result. With net present values of 20.3 million DKK for solar thermal and 11.5 million DKK for heat pumps (incl. scrap value) the solar thermal plant shows additional revenues of 8.8 million DKK within the time horizon of the investment.

These results are affected by a number of factors of which the discount rate deserves extra attention. As the investment in a solar thermal plant involves a large initial investment but very limited annual costs this type of investment benefits from a low discount rate. Opposite, the heat pump with considerable annual production costs would likely benefit from a higher one. Varying discount rates have been tested and the results are shown in Table 9.

Discount rate	2%	4%	6%
Solar thermal (area)	32.3 million DKK (29,000 m ²)	20.3 million DKK (21,000 m ²)	12.3 million DKK (17,000 m ²)
Heat pump (capacity)	16.8 million DKK (1333.3 kW _e)	11.5 million DKK (1166.7 kW _e)	7.8 million DKK (1000.0 kW _e)

Table 9: Maximum net present value with varying discount rates over a time horizon of 15 years incl. scrap value.

It is clear from Table 9 that even though the difference between the net present values of the two investments is reduced with higher discount rates the solar thermal plant proves most feasible in all cases.

6.6 COMBINED SCENARIO

In order to explore the potentials for district heating plants already using solar thermal to invest in heat pumps the following scenario combines solar thermal and heat pumps in one system. The model is run again with the original production units from the Basic scenario plus a solar collector area of 21,000 m² as a new Combined scenario, see Figure 18.

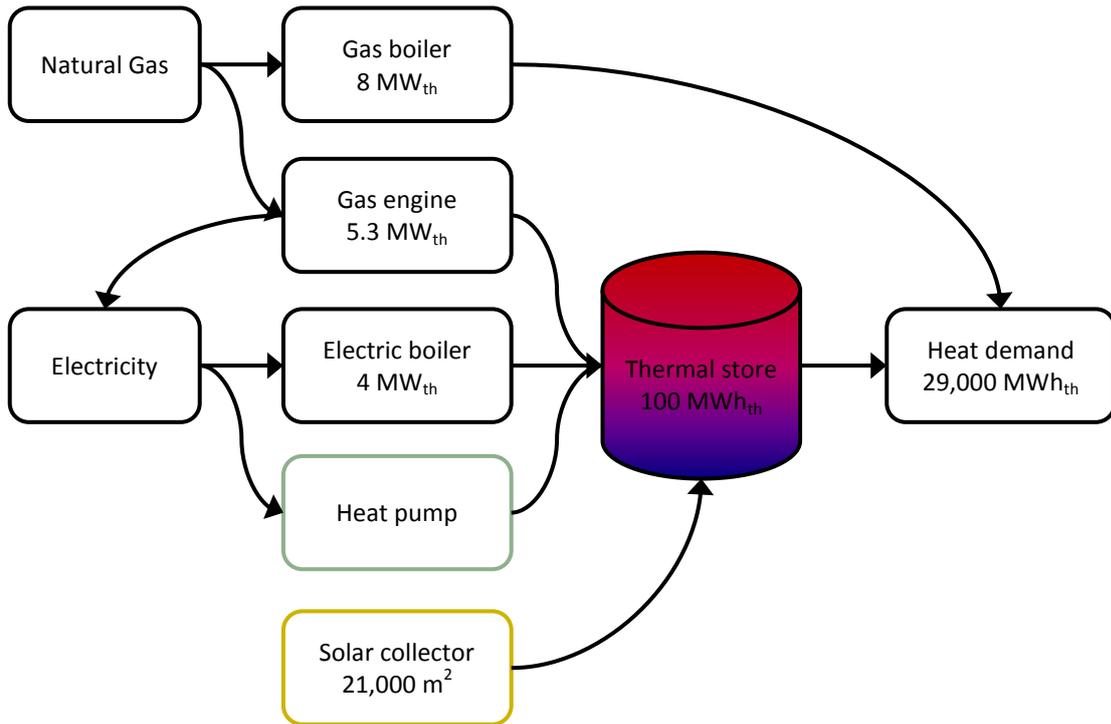


Figure 18: Diagram of the generic district heating system including solar thermal and heat pumps.

Knowing the costs linked to both solar thermal and electric heat pumps the production hierarchy can be updated, see Figure 19.

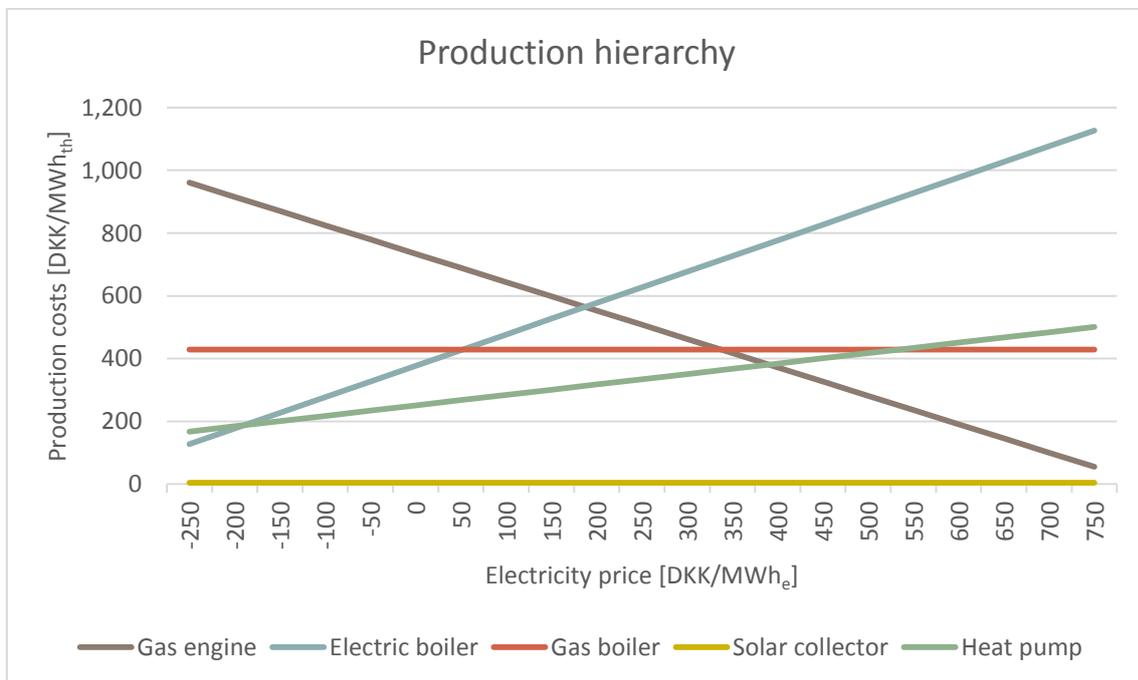


Figure 19: The production hierarchy of this study is not fixed but varies slightly from month to month with varying natural gas prices and PSO tariffs. The displayed production hierarchy is from January 2015. The production hierarchy does not include fixed operation and maintenance as this is given per installed capacity and independently of the actual production. This represents an uncertainty for production units that are only attributed a fixed operation and maintenance cost such as the heat pump.

As there are almost no operation cost linked to the production from solar thermal this is by far the preferred production unit in the hour-to-hour operation of the plant. Not surprisingly, the heat pump is an attractive production unit especially for low electricity prices and outmatches both the electric and the gas boiler the majority of the time. On the contrary, the gas engine favours high electricity prices and is preferred over the heat pump for electricity prices above 380 DKK/MWh_e.

By testing different heat pump capacities in the system it is, first and foremost, possible to determine if investing in heat pumps is an option for solar thermal district heating companies. Furthermore, it is possible to determine what size of heat pump could be considered an attractive investment for such a case. As both heat pumps and solar thermal are normally expected to operate as base load units it is expected that additional storage capacities could be beneficial for a system employing both technologies. As solar thermal is the least flexible of the two technologies the additional storage capacity is dimensioned to comply with the solar thermal production. As mentioned in *Section 6.3 Solar thermal scenario*, the storage capacity for solar thermal can be adjusted to fit either a steel tank or a seasonal storage. With a solar collector coverage of 21,000 m² a steel tank volume of 6,300 m³ is suggested. However, as this is for production shares ranging from 10-25% a seasonal storage appears to be necessary. According to the technology catalogue a seasonal pit storage of 26,250 m³ is suitable for a solar thermal coverage of 21,000 m². Both of these storage volumes are tested in energyPRO in order to find the optimum both in terms of production and economy. Figure 20 shows the simple payback time and net present value of investing in different heat pump and storage capacities over a time horizon of 15 years for a plant already employing solar thermal.

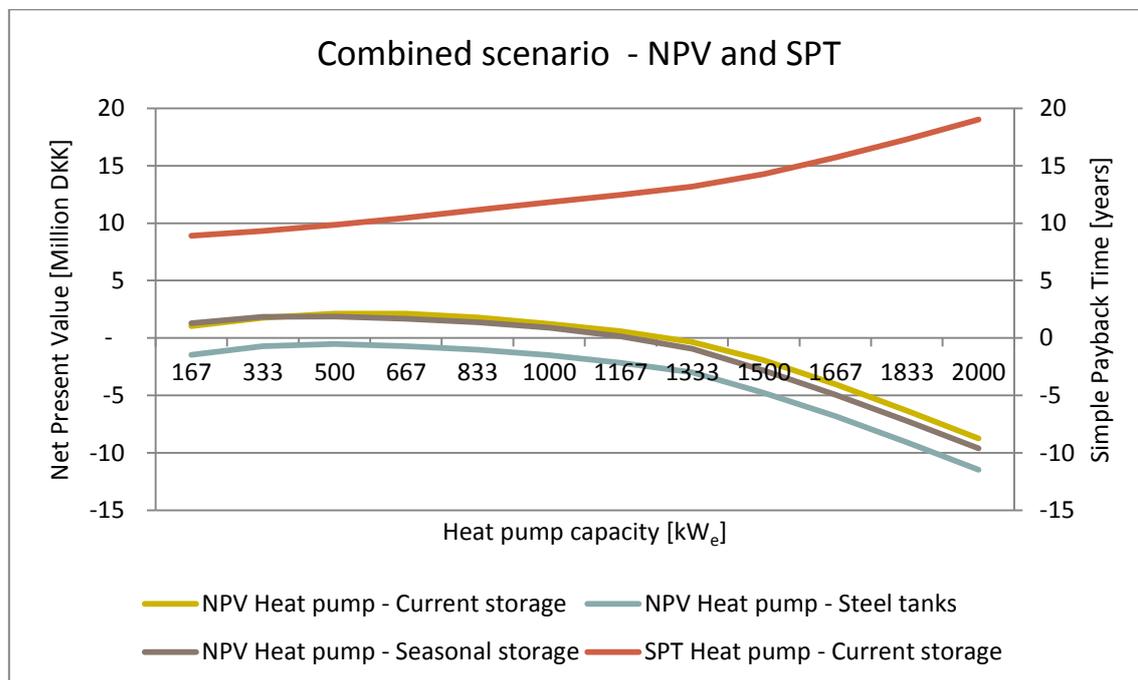


Figure 20: Simple payback time of different heat pump capacities with existing storage and net present value for different heat pump and storage capacities. The calculations include scrap values of both the heat pump and the added storage capacity.

Figure 20 shows a limited potential for the investment in heat pumps for plants that have already invested in solar thermal. The simple payback time is relatively high and only increases for higher capacities. A minor potential is seen for heat pumps with relatively small

electrical capacities with a maximum net present value of 2.1 million DKK for an electrical capacity of 666.7 kW_e. It is, however, questionable if this is enough to justify the relatively large investment of such a heat pump. At electrical capacities larger than 1333.3 kW_e the net present value becomes negative. Additional storage capacity does not improve the results.

When comparing a week of production in the Combined scenario with a week of production in the Heat pump scenario the challenge is evident.

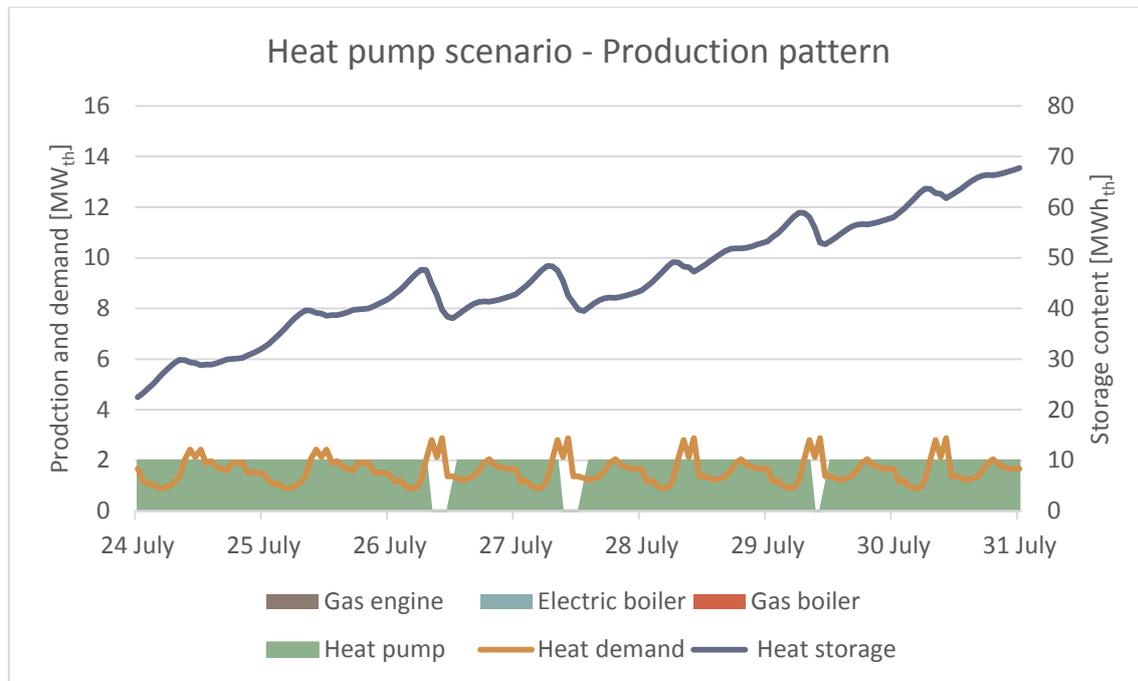


Figure 21: Demand, production and storage content in the Heat pump scenario from July 24 to 31. The installed capacity of the heat pump is 0.667 MW_e.

In the Heat pump scenario the demand in the summer months are almost entirely covered by the heat pump, see Figure 21. As this is a relatively flexible technology, the heat storage does not see major fluctuations. With the implementation of a solar thermal plant (creating the Combined scenario), the production pattern changes radically, see Figure 22.

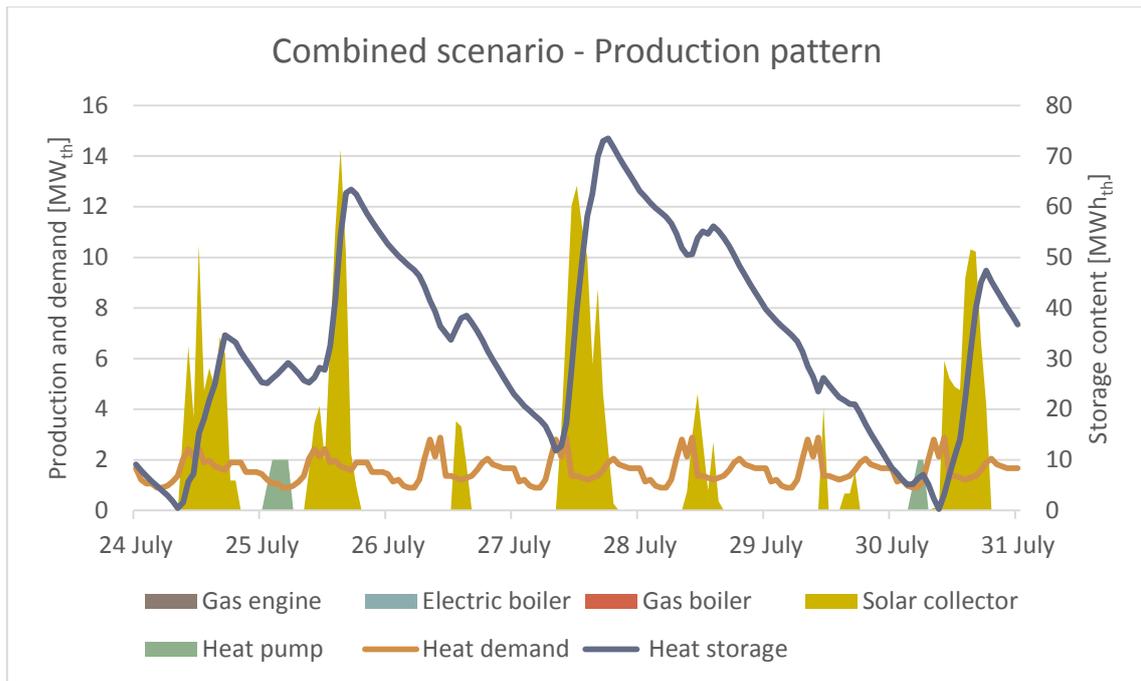


Figure 22: Demand, production and storage content in the Combined scenario from July 24 to 31. The installed capacity of the heat pump is 0.667 MW_e.

In the combined scenario solar thermal is the cheapest production unit and will always be prioritised over the heat pump. To allow for the most efficient use of solar thermal the heat storage is filling up and emptying in accordance with production and demand. In the Combined scenario, during the summer months, the heat pump no longer operates as a base load but only as a reserve for when the solar thermal plant does not produce enough heat. This makes it difficult for the heat pump to pay off its investment.

When running the combined scenario (21,000 m² solar collector area and 666.7 kW_e installed heat pump capacity) in energyPRO the following production pattern can be seen.

Combined scenario	Heat production [MWh _{th} /year]	Heat production [%/year]
Gas engine	1,501.2	5.2%
Electric boiler	537.5	1.9%
Gas boiler	6,370.6	22.0%
Solar thermal	9,951.6	34.3%
Heat pump	10,680.0	36.8%
Storage loss	-40.9	-0,1%

Table 10: Annual operation characteristics of the Combined scenario. For operation details see Appendix J – Production and operation costs, Combined scenario.

In the Combined scenario solar thermal produces to its maximum and is, hence, not affected by the presence of the heat pump. However, as the optimal heat pump capacity is smaller in the combined scenario it produces significantly less than in the Heat pump scenario with only roughly 36.8% of the total production. In the Combined scenario production from solar thermal and the heat pump combined make up about 71.1% of the total annual heat demand which is considerably lower than the heat pump production in the Heat pump scenario and the displacement of existing production units is, hence, poorer.

Figure 23 shows the duration curve of the heat demand as well as the annual heat production of the combined scenario.

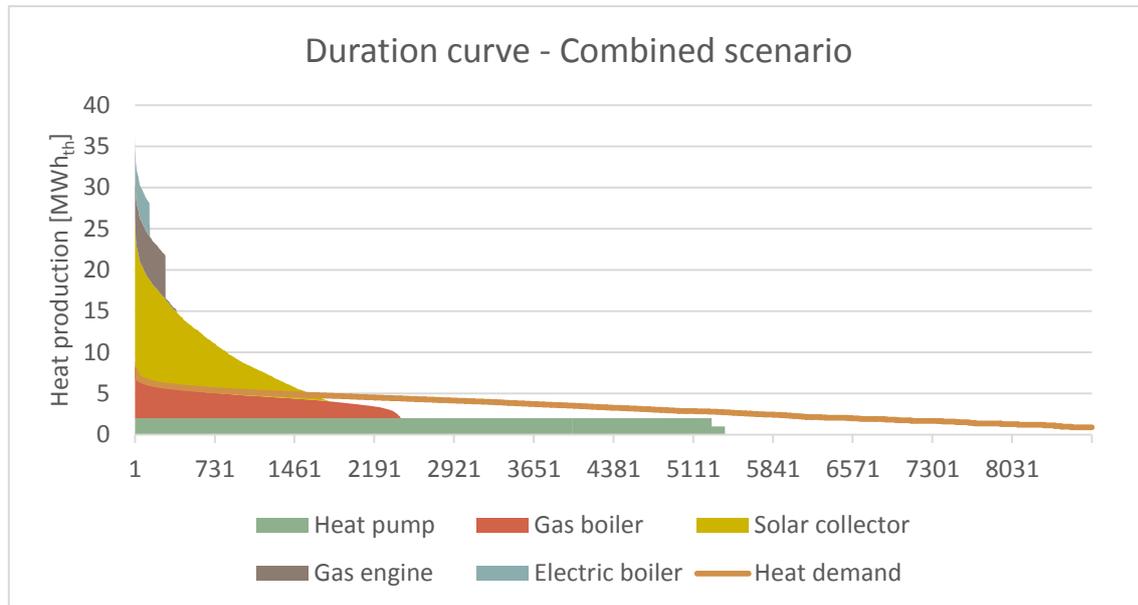


Figure 23: Duration curve of heat demand and annual heat production in the Combined scenario.

As seen in Figure 23 the production from the solar collectors has not changed from the Solar thermal scenario. The heat pump, however, produces significantly less than in the Heat pump scenario. As the installed capacity of the heat pump is smaller the heat pump covers a smaller part of the hourly demand and the presence of the solar collectors reduce the operation time of the heat pump by 1700 hours.

Looking at the economy of the plant, the Combined scenario show annual expenditures of 7.6 million DKK which is a reduction of 5.7 million when compared to the Basic analysis. As in the Heat pump scenario, the reduced expenditures are mainly from fuels and energy taxes while the tariffs have seen an increase of 1.1 million DKK mainly due to an increase in payments of the PSO tariff. The annual revenues are reduced by 0.5 million DKK from the Basic scenario as the CHP unit are allowed fewer production hours. All in all, the Combined scenario show an annual deficit (not including income from sale of heat) of 2.2 million DKK which is the lowest of the tested scenarios. However, looking at the net present value this reduction in annual deficit is apparently not enough to allow for the investment in a heat pump in the solar thermal district heating system.

For comparison, the annual operation economy of the four scenarios is presented in Table 11.

	Basic scenario	Solar thermal scenario	Heat pump scenario	Combined scenario
Revenues [DKK]	5,983,916	5,765,144	5,467,265	5,479,044
Expenditures [DKK]	13,259,296	8,924,456	10,278,617	7,633,163
Deficit [DKK]	-7,275,380	-3,159,312	-4,811,352	-2,154,119

Table 11: Annual revenues, expenditures and deficits from the operation of the four scenarios.

7 METHOD IMPROVEMENT

The standard analysis has been carried out using the standard functions in energyPRO. This means that some conditions such as supply and return temperature are not defined in the standard analysis just as the COP of the heat pump has been fixed over the year for reasons of simplification. The following chapter aims at testing the validity of the results by modelling a more accurate COP depending on a series of conditions including the supply and return temperature at the plant and the temperature of the specific source of the heat pump. For economic calculations on the different scenarios see *Appendix E – Economy data*.

7.1 SUPPLY AND RETURN TEMPERATURE

The first method improvement aims to include variable supply and return temperatures at the plant. These variable supply and return temperatures will later act as an input parameter when modelling a variable COP. First, the method is described and following, the different input parameters are determined.

7.1.1 METHOD

Generally speaking, the supply temperature in a district heating system needs to be set so that the consumer furthest away in the grid is able to receive acceptable temperatures for space heating and domestic hot water purposes. However, as factors such as soil temperature and grid flow vary depending on the circumstances the needed supply temperature will also vary and can be adjusted to optimise production efficiency.

The supply temperature at the plant can be expressed:

$$T_{sap} = \frac{C_{loss} \cdot T_{soil} - C_{loss} \cdot \frac{T_{sac}}{2} - \dot{m} \cdot c \cdot T_{sac}}{\frac{C_{loss}}{2} - \dot{m} \cdot c}$$

Similarly, the return temperature at the plant can be expressed:

$$T_{rap} = \frac{C_{loss} \cdot T_{soil} - C_{loss} \cdot \frac{T_{rac}}{2} + \dot{m} \cdot c \cdot T_{rac}}{\frac{C_{loss}}{2} + \dot{m} \cdot c}$$

In order to determine a varying district heating supply and return temperature both the varying district heating flow, \dot{m} , and a number of input parameters need to be defined.

FLOW IN GRID

The district heating flow of a given hour can be calculated based on the supply and return temperature at the consumer, the specific heat capacity of water and the heat demand in the hour in question. The flow can be calculated using the following formula:

$$\dot{m} = \frac{D_{DH}}{c \cdot (T_{sac} - T_{rac})}$$

SOIL TEMPERATURE

Soil temperatures for different areas can be found in the DRY data. The data for zone two (mid-Jutland) has been applied. This data has been measured at a depth of 30 cm but has been modelled to simulate temperatures at a depth of one meter, which is considered compatible with heating pipes (Lauritsen, 2015). At this depth, the soil temperature varies from 2.0 to 16.2°C. As pipes are in some cases installed at greater depths than one meter, the use of the DRY data will make up a small uncertainty in the analysis. Only daily values are given for the soil temperature and these are, hence, set to apply for all hours of a given day. The variation of soil temperature over the year is shown in Figure 24.

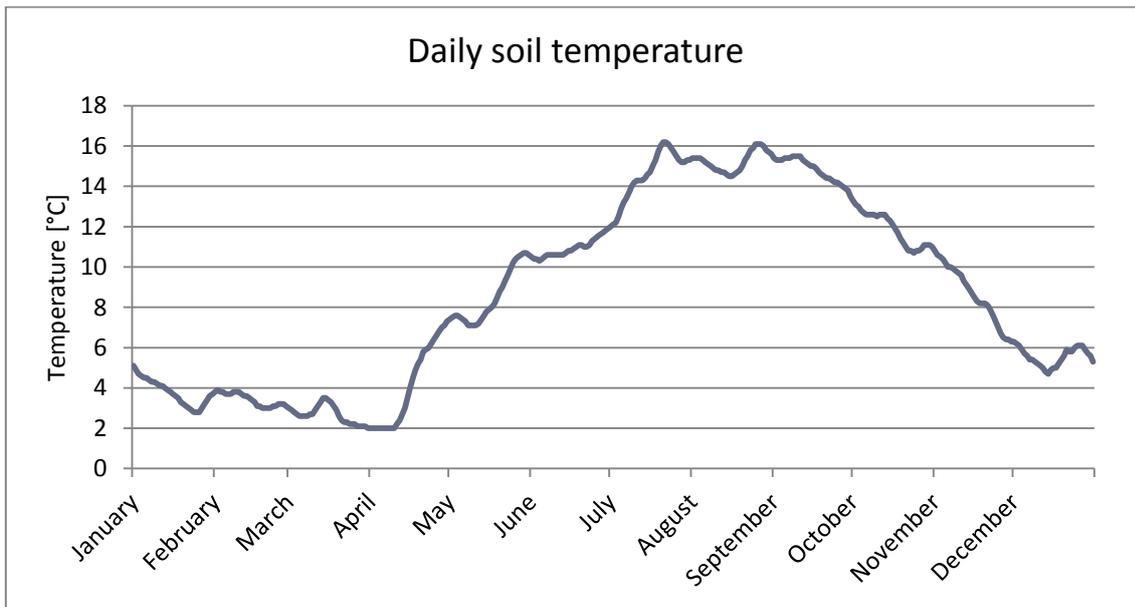


Figure 24: Daily soil temperature at one meter depth. The average temperature over the year is 8.7°C.

DISTRICT HEATING PIPE LOSS COEFFICIENT

The district heating pipe loss coefficient, C_{loss} , describes the overall rate of heat loss in the district heating system and is a fixed value calculated based on the annual grid loss, averaged for supply and return temperatures between the plant and the consumers and an average soil temperature. The principle is illustrated in Figure 25.

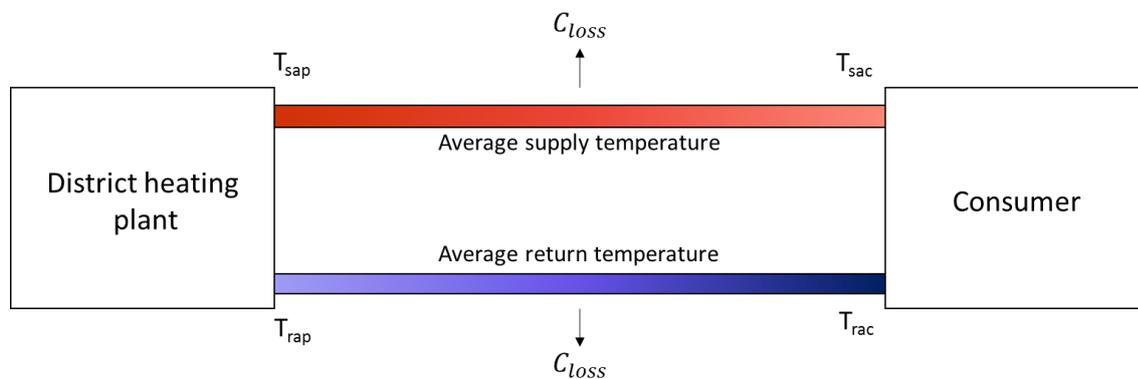


Figure 25: Principles of grid loss.

The grid loss in a given hour can be calculated as the average temperature in the supply and return district heating pipes compared to the surrounding soil temperature and multiplied by the district heating pipe loss coefficient expressing the rate of heat loss in the system. This can be expressed as:

$$DH_{loss} = \sum_{Hour=1}^{8760} \left(C_{loss}(T_{AvSupHour} + T_{SoilHour}) + \left(C_{loss}(T_{AvRetHour} + T_{SoilHour}) \right) \right)$$

For simplicity reasons the pipe loss coefficient is not calculated on an annual basis but using average numbers. When doing this C_{loss} can be isolated as follows:

$$C_{loss} = \frac{L_{DH}}{8760 \cdot (T_{AvSup} + T_{AvRet} - 2T_{soil})}$$

The annual grid loss of the system is, as previously stated, 7,250 MWh_{th}. The average temperature in the supply and return district heating pipes are set to be 80 and 40°C, respectively. With an average annual soil temperature of 8.7°C the district heating pipe loss coefficient can be calculated to 8.1 kW/K.

SUPPLY AND RETURN TEMPERATURES AT CONSUMERS

The supply and return temperatures at the consumer level need to be defined. As temperatures of 45°C or higher are needed in order for the legionelle pneumophila bacteria not to grow this temperature needs to be maintained for the last consumer in the grid (Werner & Frederiksen, 2013). The return temperature at the consumer level will, hence, be set at 45°C.

From the available literature an overall cooling of the district heating water of about 30-40°C from the first to the last consumer is preferred with greater cooling indicating a more efficient system (Energimidt, 2016) (SK Forsyning, 2005) (Thyborøn Fjernvarme a.m.b.a, n.d.). As the average temperature in the district heating supply pipes in this study has previously been set to be 80°C the supply temperature at the consumer level is set to be 75°C.

HEAT CAPACITY OF WATER

The heat capacity of a substance describes the relationship between the supplied thermal energy to a body and the resulting change in temperature in this. The heat capacity varies depending on pressure and temperature. In this analysis, a heat capacity of water of 4.184 $\frac{kJ}{kg \cdot K}$ has been applied (Young & Freedman, 2008).

DISTRICT HEATING DEMAND

The district heating demand of 29,000 MWh_{th} as defined in *Chapter 6 Standard analysis* with values for all hours of the year ranging from 0.9 to 7.8 MWh_{th} is applied in the study.

7.1.3 RESULTS

When including all the relevant input parameters the flow in the district heating system varies as illustrated in Figure 26.

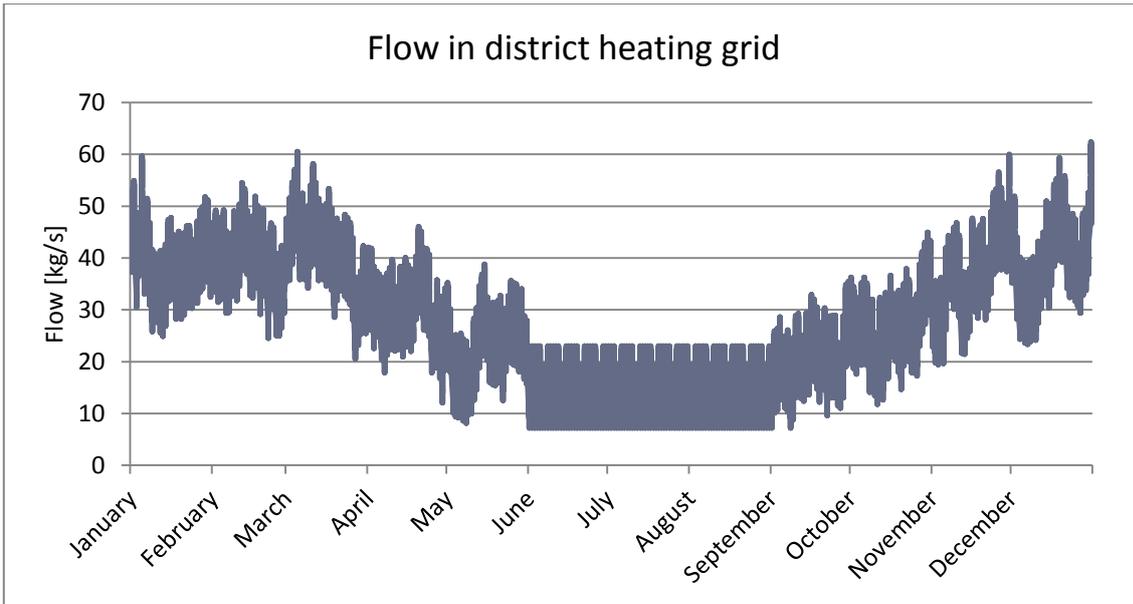


Figure 26: Hourly flow in district heating grid.

As the supply and return temperature at the consumer is fixed the flow only varies depending on the heat demand. This means that the flow is high during hours of high heat demand and low during hours of low heat demand.

The calculated supply and return temperature at the plant are presented in Figure 27.

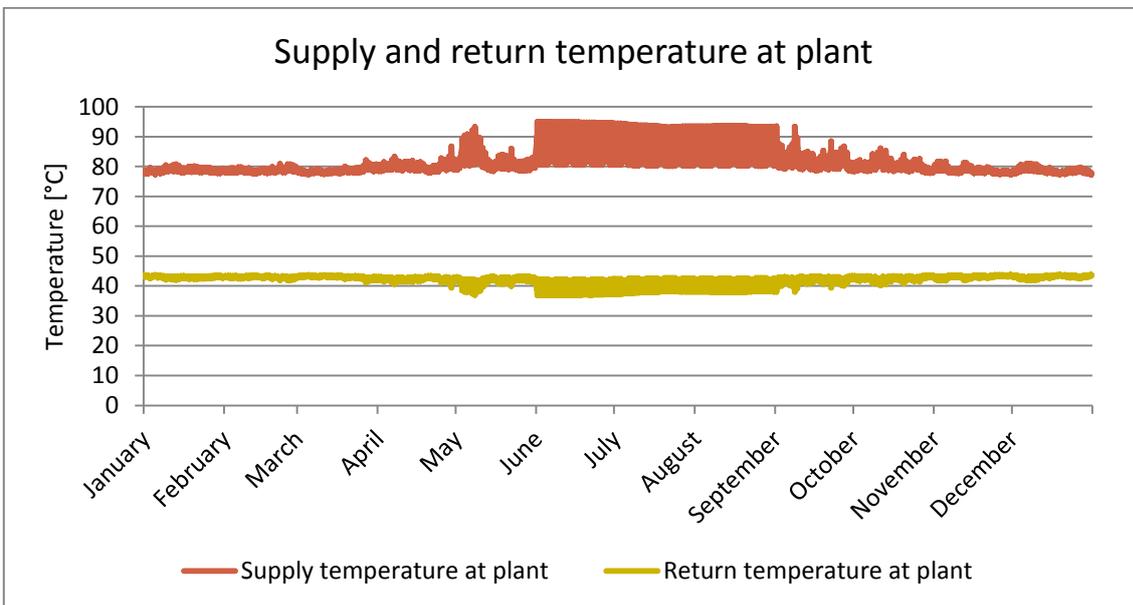


Figure 27: Hourly supply and return temperature at plant.

It is clear that both the supply and return temperatures at the plant are dependent on the flow in the grid. The high flow during the colder months reduces the grid loss and allow for a lower supply temperature. As the flow is lowered in the summer months the grid loss increases and a higher supply temperature is needed in order to ensure sufficient temperatures at the consumers. This relationship between flow and heat loss resulting in higher losses in the summer months is supported by acknowledged literature in the area (Werner

& Frederiksen, 2013). It is, however, somewhat contradictory to common practice as statistics show an average increase in supply temperature for Danish district heating plants of 4°C (76°C to 72°C) in the winter relative to the summer months (The Danish District Heating Association, 2015). According to Jørgen Risom, the reason for this can be that the district heating companies actively sustain a higher flow than necessary in order to supply at lower temperatures (Risom, 2016). The method applied in this study aims only at ensuring sufficient supply temperatures at the consumer. This is done by calculating the flow in the grid and the grid loss based on the known parameters. It is possible that an overall more efficient system or fewer grid losses could have been achieved by actively testing different supply or return temperatures or different flows.

The supply and return temperatures are inversely proportional. This is the case as the increased grid loss is, obviously, present for both the supply to and return from the consumers. As, however, temperatures are generally lower in the return water grid losses will be reduced and the return temperatures, hence, have smaller fluctuations than the supply temperatures.

7.2 MODELING OF HEAT PUMP

The second method improvement aims to model a more advanced heat pump with a COP that varies according to changes in the heat source and supply and return temperatures at the plant. First, the method is described and following, the different input parameters are determined.

7.2.1 METHOD

The more advanced heat pump simulation is made based on equations for the theoretical maximum efficiency of a heat pump as well as an assumed system efficiency, η_s , taking into account different parameters negatively affecting the efficiency of the system, such as losses in the compressor, fluids, pumps and valves. In this analysis, the system efficiency is set to be 50% (Clausen, Kim S.; From, Niels; Hofmeister, Morten; Paaske, Bjarke Lava; Flørning, John, 2014 B). For electric heat pumps, the theoretical maximum efficiency can be calculated based on the physical correlation between work and temperatures within the thermodynamic system. The two are interdependent meaning that a certain amount of mechanical work can create a certain temperature difference within the heat pump just as the opposite connection applies e.g. in the case of steam turbines (Clausen, Kim S.; From, Niels; Hofmeister, Morten; Paaske, Bjarke Lava; Flørning, John, 2014 B). The theoretical maximum efficiency of an electrical heat pump, the so-called Lorentz efficiency can be calculated as:

$$\eta_L = \frac{T_H}{T_H - T_L}$$

Where T_H is the logarithmic mean high absolute temperature (in the case of a heat pump, the mean high temperature of the condenser) and T_L is the logarithmic mean low absolute temperature (in the case of a heat pump, the mean low temperature of the evaporator). T_H and T_L are defined as:

$$T_H \text{ or } T_L = \frac{T_{in} - T_{out}}{\ln\left(\frac{T_{in}}{T_{out}}\right)}$$

Where T_{in} and T_{out} represent the input and output temperatures on the condenser side (T_H) and evaporator side (T_L), respectively, see Figure 28. This means that the varying supply temperature that has just been defined will be integrated in the calculation of the heat pump efficiency.

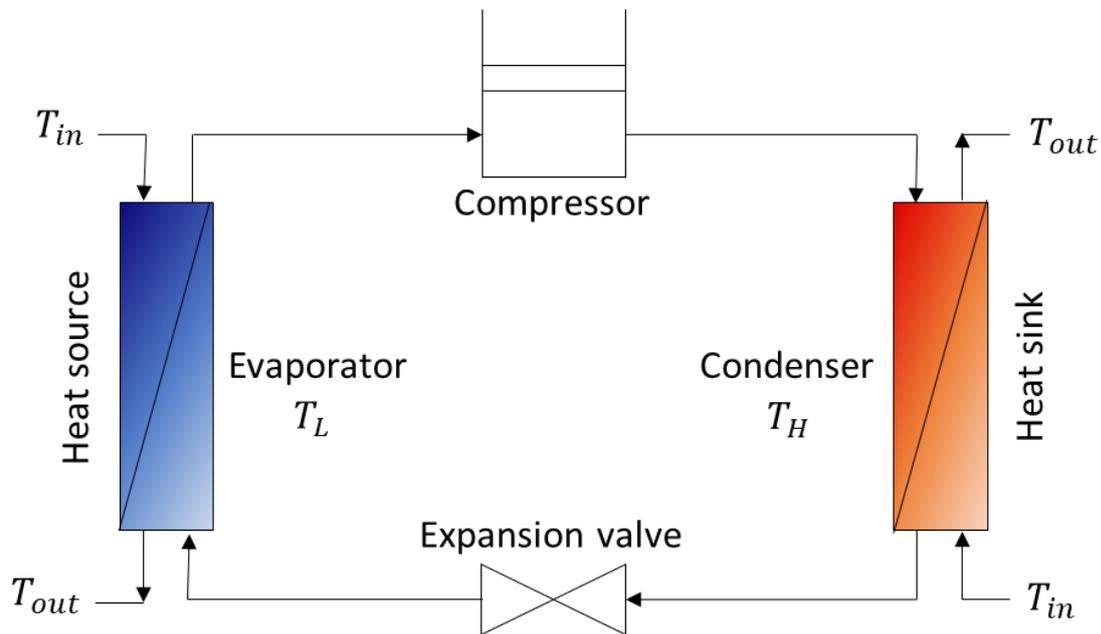


Figure 28: Schematic drawing of a heat pump showing the temperature in- and output at the condenser and evaporator side, respectively.

Having determined both the system efficiency and the Lorentz efficiency the overall heat pump efficiency can be calculated, using the following formula.

$$\eta_{HP} = \eta_L \cdot \eta_S$$

7.2.2 INPUT PARAMETERS

HEAT SOURCE

In this improved method the heat source inlet temperature is fixed at 9°C throughout the year. This corresponds to the temperature of ground water. The effects of alternative heat sources will be examined in *Chapter 8 Sensitivity analysis*.

Experiences from already established heat pump projects using ground water show a cooling of around 7°C independently of the season (Clausen, From, Hofmeister, Paaske, & Flørning, 2014 A). In this project, the heat source outlet temperature is, hence, set to be 2°C.

DISTRICT HEATING SUPPLY AND RETURN TEMPERATURE AT PLANT

The supply and return temperatures at the district heating plant as calculated in the previous simulation are applied in order to determine the precise COP of the heat pump.

7.2.3 RESULTS

When taking all of the parameters into account the COP varies as illustrated in Figure 29.

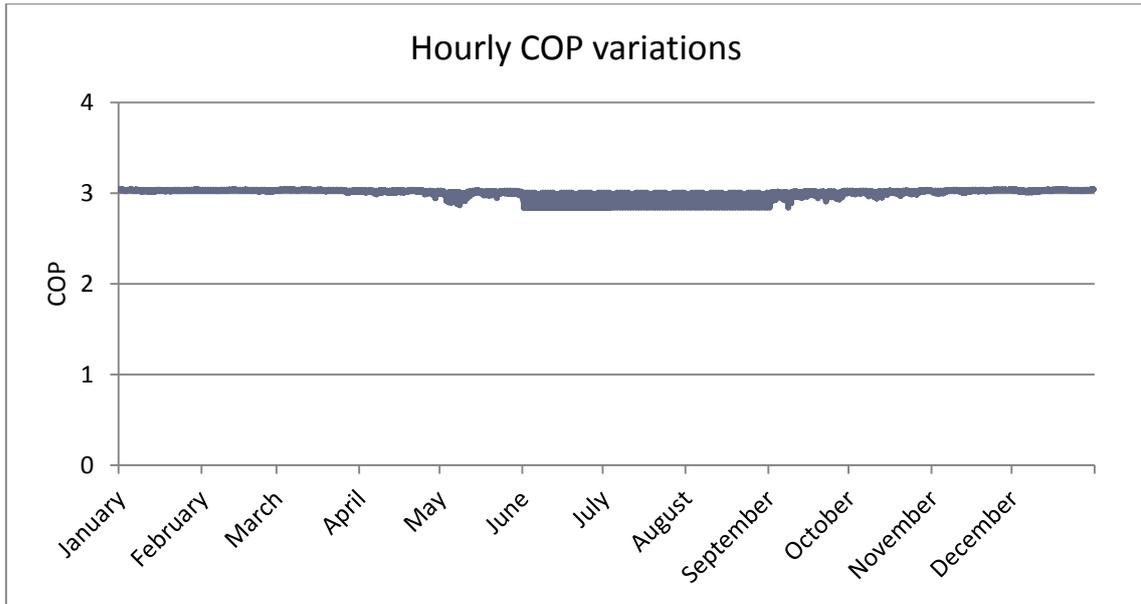


Figure 29: Hourly COP variations for heat pump using groundwater as a heat source. For calculation, see Appendix K – Method improvement.

With the given input and output temperatures only a minor variation in COP between 2.8 and 3.0 is seen. This limited variation in COP is a result of the fact that the temperature of groundwater does not vary over the year. The higher supply temperatures during the summer results in a slightly lower COP during these months. The average COP remains unchanged at 3.0.

7.3 RESULTS OF IMPROVED METHOD

In this section varying supply and return temperatures have been simulated and, based on these, an advanced heat pump with varying COP has been modelled. In the following these new, more advanced parameters will be tested to see if they influence the results of the Standard analysis. More specifically the Heat pump scenario and the Combined scenario are run again comparing the more advanced heat pump with the simple one originally used.

Figure 30 shows the simple payback time as well as net present values for different electric capacities of heat pumps modelled in a simple and more advanced way.

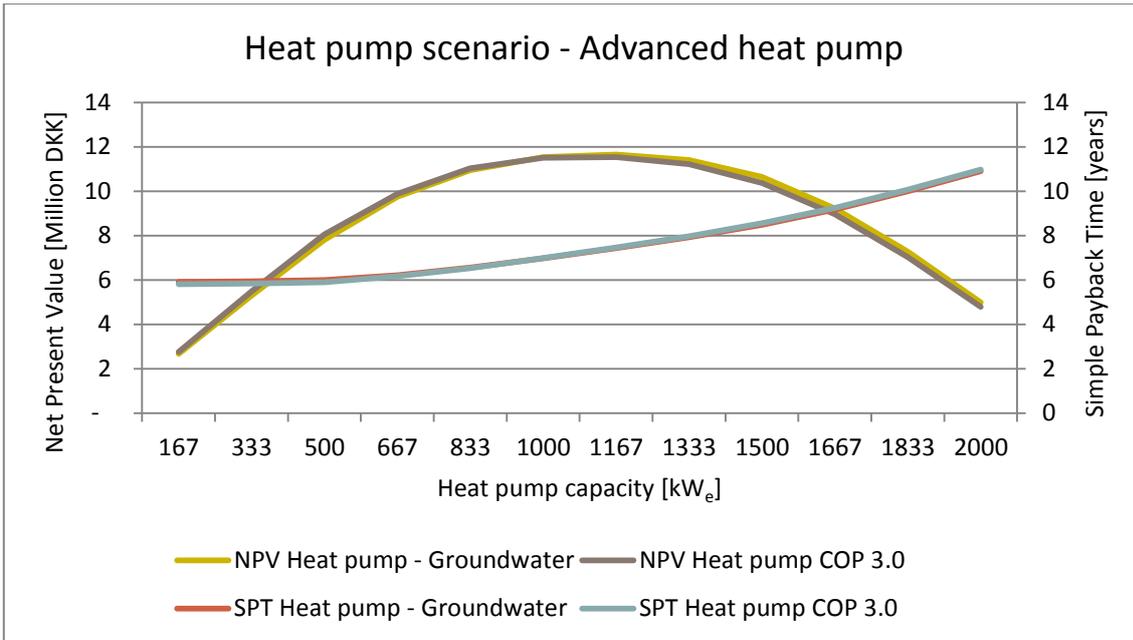


Figure 30: Net present value and simple payback time for the simple and more advanced heat pump in the Heat pump scenario.

As Figure 30 shows the difference between the fixed and the variable COP is minimal both in the case of simple payback time and the net present value. The tendency is that the fixed COP is slightly more feasible for lower thermal capacities and the variable COP slightly more feasible for higher capacities. The optimal electrical capacity is 1166.7 kW_e for both calculations. With the variable COP this capacity gives a net present value of 11.7 million which is about 0.1 million DKK better than the fixed COP.

The same tendency can be seen in the combined scenario, illustrated in Figure 31.

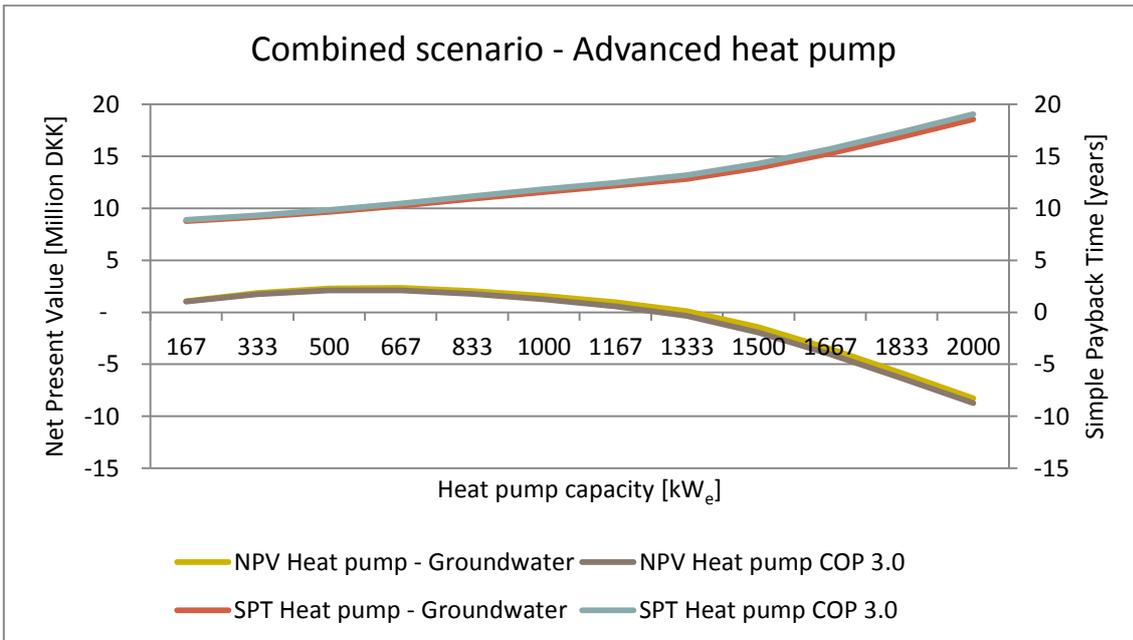


Figure 31: Net present value and simple payback time for the simple and more advanced heat pump in the Combined scenario.

Again, the two methods show hardly any difference and the optimal electrical capacity remains unchanged at 666.7 kW_e in the Combined scenario.

The analysis shows that the simulation of a more accurate heat pump does not change the overall results from the simpler method of a fixed COP. Variations in the supply and return temperatures, hence, do not appear to be a critical factor for the analysis. The conclusion expectedly depends on the fact that the variable COP and the fixed COP are on an annual average the same. Furthermore, it is not clear if varying heat source temperatures could create big enough fluctuations for the result to significantly differ. Sensitivity analyses of varying heat sources will be carried out in *Chapter 8 Sensitivity analysis*.

SHORTCOMINGS

By arriving at almost the same results, the method improvement confirms the credibility of energyPRO for simulations of heat pumps. However, as described in *Section 3.2 Computer tools*, energyPRO is a pure energy balance model and parameters such as temperature levels, flow in the grid and variable losses are only included in the method improvement of the heat pump. The flow in the district heating grid as well as the loss to the surroundings influence the supply temperature level needed to ensure a sufficient temperature at the consumer. Different temperature levels require different amounts of energy and these variations are neglected.

As mentioned in *Chapter 4 Technologies*, an operation strategy for the heat pump can be to use the heat pump to preheat the supply temperature and let e.g. a boiler increase the temperature to the desired level. This operation strategy is however not tested in this study, as temperature levels, flow and losses are only calculated for the heat pump. Another factor that has not been tested is the reduction of the supply temperature in the district heating grid. This would increase the COP of the heat pump and make it more feasible. Consequently the simulated energy system is a simplification of an energy system, purely focusing on meeting the heat demand in the cheapest possible way and disregarding any temperature conditions. As energyPRO is a commonly used tool in the Danish district heating sector (EMD International A/S, n.d.), it is believed that the lacking details of the energy system is of modest influence to the results.

8 SENSITIVITY ANALYSIS

A series of sensitivity analyses have been carried out with the purpose of testing the robustness of the results i.e. will changes in the basic conditions of the analysis make it more or less feasible for district heating plant that have already invested in solar thermal to invest in an electric heat pump? The sensitivity analyses test four basic conditions; electricity prices, natural gas prices, heat sources for the heat pump and taxes, tariffs and subsidies. For economic calculations on the different scenarios see *Appendix E – Economy data*.

8.1 ELECTRICITY PRICE

The electricity price is of great importance for the economy of an electric heat pump. The electricity prices have recent years been declining and were by 2015 at its lowest since 2002 (The Danish Energy Agency, 2015 A). In all the forecasts known to the project group, these are expected to increase in the future. This sensitivity analysis tests the effects of an increase in electricity prices using the electricity price forecast of Energinet.dk. This forecast predicts an average price of 433 DKK by 2035 which is about 2.5 times higher than the 2015 prices. The distribution of the electricity price forecast for 2035 is shown in Figure 32.

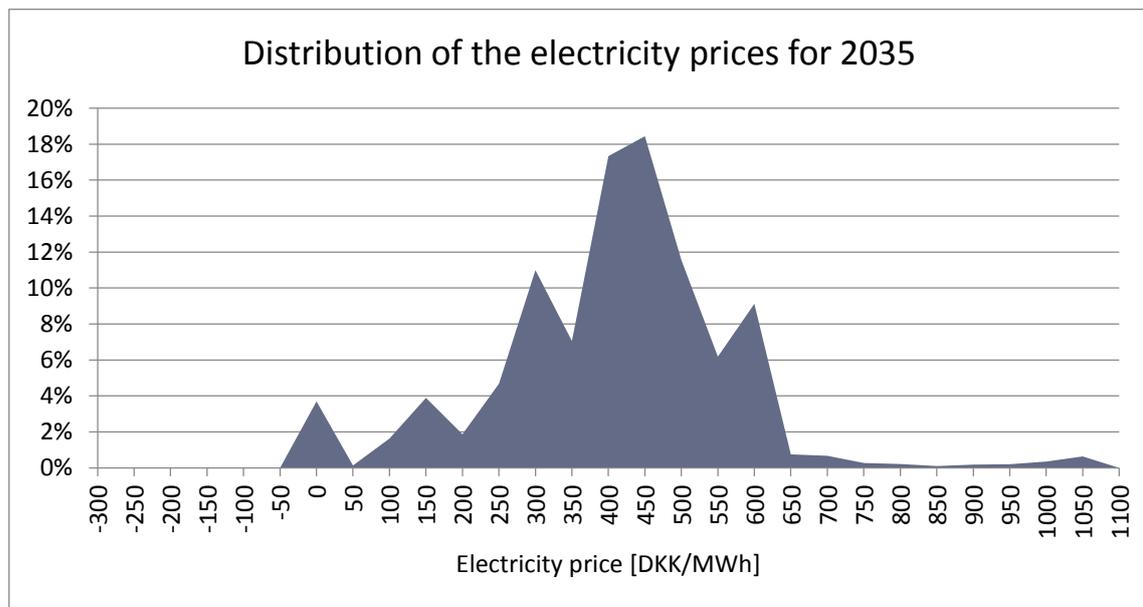


Figure 32: Distribution of electricity prices in the 2035 price forecast of Energinet.dk. Many uncertainties are linked to electricity prices and these must therefore be used with caution.

The sensitivity analysis for electricity prices are based on Energinet.dk's "Analysis Assumptions 2015-2035". The electricity prices are based on a simulation of the electricity market in Europe, including assumption of prices, production, consumption and transmission line capacities. The analysis also includes the goals from the Danish energy agreement from 2012. Taxes and subsidies are expected to continue to remain the same, however the basic subsidies for the decentral district heating plants are expected to change (Energinet.dk, 2015 B). In this sensitivity analysis only the spot price for electricity changes. For taxes and tariffs linked to the distribution of electricity 2015 values have been applied.

As an increase in electricity prices will naturally lead to a poorer economy of the heat pump it is expected that this sensitivity analysis will show even more pessimistic prospects for the

cooperation of solar thermal and electric heat pumps in district heating. It is, hence, not the purpose of this sensitivity analysis to pursue a more feasible scenario but rather to test the influence of electricity prices on the feasibility of heat pump projects in general.

Figure 33 shows the net present value for different electric capacities of a heat pump with 21,000 m² installed solar collector area and electricity prices according to the 2035 electricity price forecast by Energinet.dk.

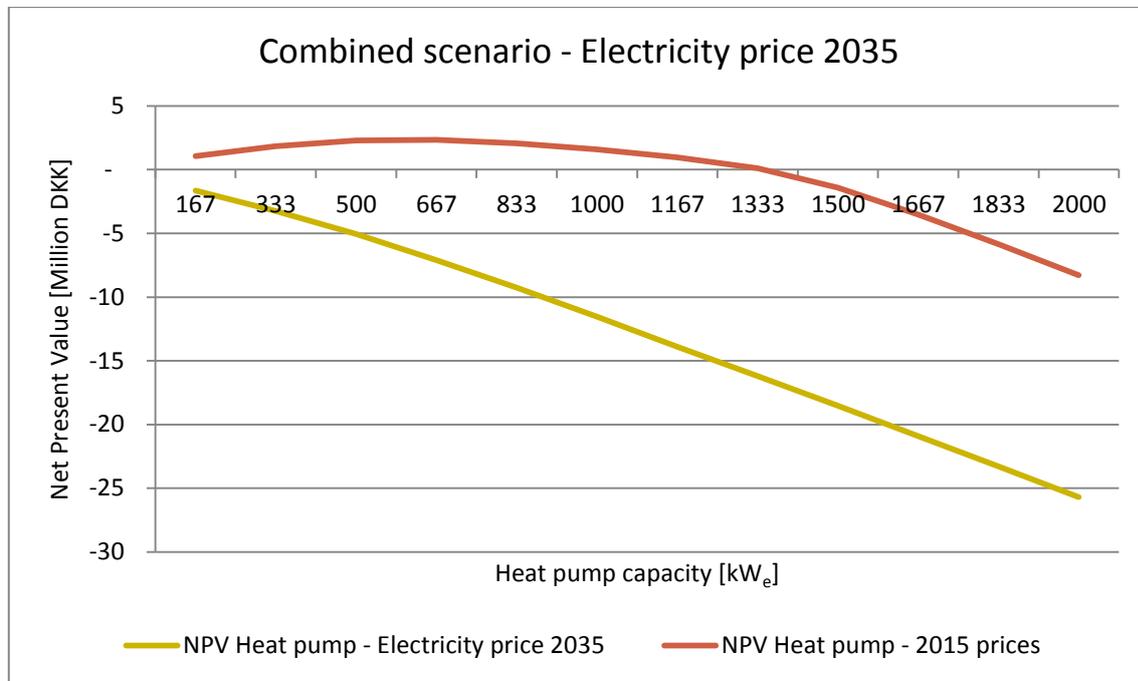


Figure 33: Net present value of different electric capacities of heat pumps in a solar thermal district heating system with 2015 prices and forecasted 2035 electricity prices.

First and foremost, applying the higher 2035 electricity prices is generally of profit to the system as a whole. With higher prices, the gas engine becomes significantly more attractive and the system sees a high increase in revenues from sale of electricity resulting in a considerable fall in annual operation costs from a deficit of around 3.2 million DKK to about 0.4 million DKK in the Solar thermal scenario (not including revenues from sale of heat). However, as seen on Figure 33 the prospects for implementing an electric heat pump into this system are poor as the heat pump struggle critically with the increased electricity prices making it an unattractive production unit most hours of the year.

8.2 GAS PRICE

In the Basic scenario of this study, natural gas is the primary fuel and used both in the engine and in the gas boiler. By varying the gas price, it is expected that technologies not using natural gas, such as solar thermal and electric heat pumps, will become more or less attractive for heat production in comparison with the gas-based technologies.

As natural gas is difficult to transport over large distances compared to coal and oil and often traded via long-term contracts the price of gas is not simply a question of global supply and demand but also of regional conditions. As an example the recent growth in the utilisation of shale gas in the United States has led to a fall in gas prices regionally as well as a fall

in coal prices globally as shale gas is substituting coal in this region, decreasing the demand for coal. The gas prices in Europe have, however, not been affected by this development (The Danish Energy Association, 2014). Consequently, there exists no global benchmark for gas prices and a future gas price has to be estimated based on regional forecasts.

In the analysis until now, the day-ahead spot price from Gaspoint Nordic from 2015 has been applied. This varies from month to month with an average price of 1.81 DKK/Nm³. The gas price in the Northern European region has recent years been relatively low and is generally expected to increase over the next decades (The Danish Energy Agency, 2015 B) (European Commission, 2013). For this sensitivity analysis a fixed price of 2.81 DKK/Nm³ has been selected based on the 2035 price estimate from the report “Prerequisites for socio-economic analyses in the energy sector” from the Danish Energy Agency (The Danish Energy Agency, 2016 B). While the spot price has been raised transmission and distribution tariffs etc. do not vary from their original level. Figure 34 shows the net present value for different electric capacities of a heat pump with 21,000 m² installed solar collector area and a natural gas price of 2.81 DKK/Nm³.

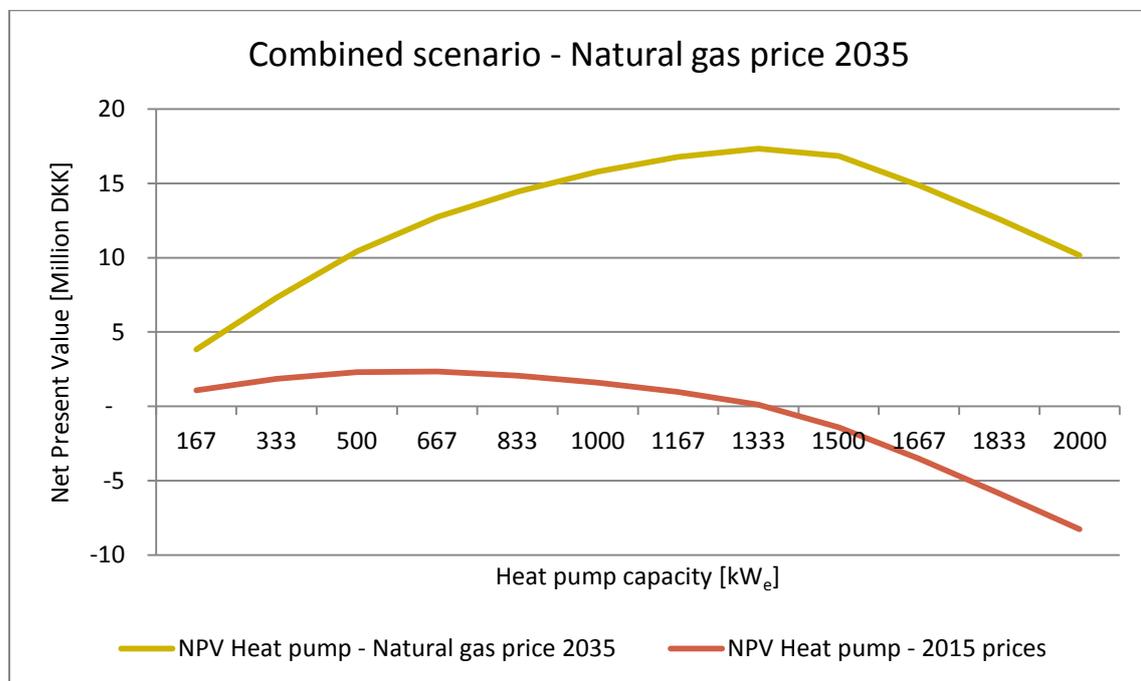


Figure 34: Net present value for different electric capacities of a heat pump in a solar thermal district heating plant with 2015 prices and a 2035 natural gas price of 2.81 DKK/Nm³.

As oppose to electricity prices, the overall economy of the system becomes worse with the increase in gas prices. For the solar thermal scenario, this means an increase in annual operation costs from 3.2 million DKK to 4.8 million DKK. However, as Figure 34 shows, the general economic potential of a heat pump in a solar thermal district heating plant is significantly improved with the higher gas prices. The reason for this is that the heat pump has become more attractive in comparison with the gas-based technologies. Not until electricity spot prices above 510 DKK/MWh_e does the gas engine become more feasible than the heat pump and the gas boiler cannot compete with the heat pump at electricity prices lower than 700 DKK/MWh_e.

With a gas price of 2.81 DKK/Nm³ a significant net present value of 17.3 million DKK can be obtained. This is possible with an installed electric capacity of 1333.3 kW_e. Such economic

prospects would very like make a heat pump an attractive investment. As gas prices are, however, continuously varying and difficult to predict an investment highly based on an expected development in gas prices must be considered risky.

8.3 HEAT SOURCE

Sensitivity analyses are carried out on two different heat sources for the heat pump, seawater and industrial waste heat, in order to test how sensitive the results are to variations in the COP of the heat pump. As previously mentioned the investment in a heat pump as given in the Technology Catalogue is set according to the installed thermal capacity. This means that variations in the COP of a heat pump exceeding 3.0 (the maximum COP of the method improvement using groundwater as a heat source) will lead to increases in the investment costs even if the average COP is not increased. This approach to calculating the investment costs favours heat sources allowing for a relatively stable COP over heat sources leading to high fluctuations in COP in a disproportional way. This uncertainty will be briefly discussed in the following sensitivity analysis.

8.3.1 SEAWATER

Seawater has been selected as the first alternative heat source for the heat pump. As seen in *Chapter 4 Technologies* seawater is, partly due to its low temperature, a relatively low quality heat source but is chosen as it is widely available and partly comparable with other sources such as lakes or streams. Seawater temperatures for different areas are given in the DRY data. Data for zone 22331 (Aarhus), varying between 0°C and 21.7°C, has been applied. This will function as the heat source inlet temperature in the analysis. The variation of seawater temperature over the year is shown in Figure 35.

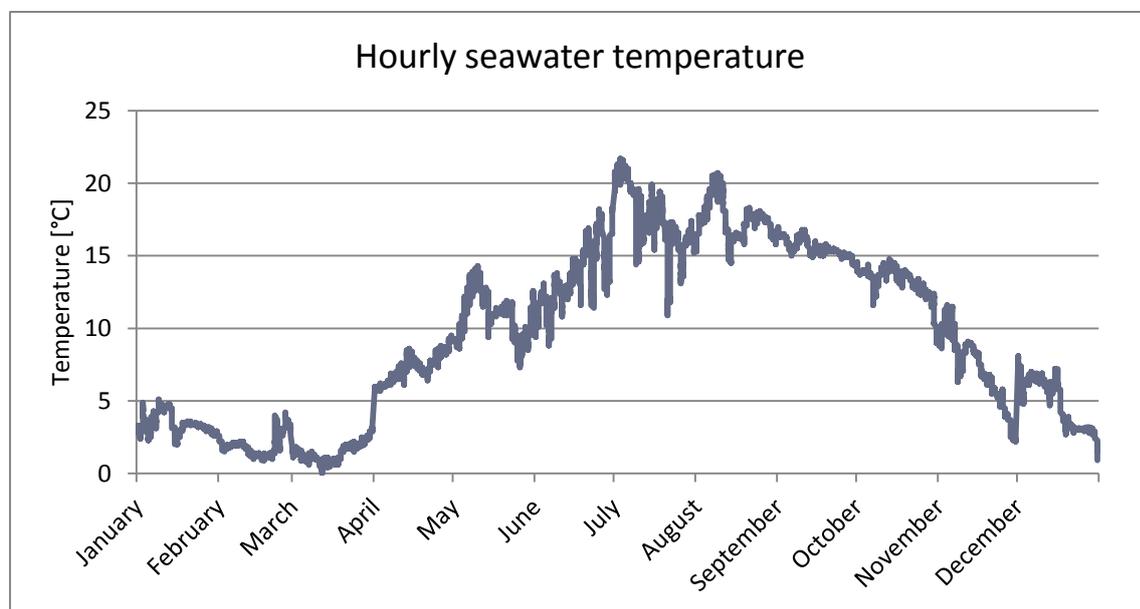


Figure 35: Hourly seawater temperature (The Danish Meteorological Institute, 2016).

Experiences from already established heat pump projects using relatively low temperature heat sources (lake or ground water) show a cooling of the heat source of about 3-5°C depending on the season (Clausen, From, Hofmeister, Paaske, & Flørning, 2014 A). In this pro-

ject, the heat source outlet temperature is set to be 4°C lower than the heat source inlet temperature, though never below 0°C. For resulting COP see Figure 36.

8.3.2 INDUSTRIAL WASTE HEAT

Industrial waste heat has been selected as the second alternative heat source as the high achievable temperatures of some industrial waste heat sources allow for considerably higher COP's than most other heat sources. Furthermore, unlike seawater, industrial waste heat generally does not vary in temperature over the year which allows for an efficient use of the heat pump independent of seasonal changes in weather. In this sensitivity analyses the heat source temperature is set to be 40°C throughout the year. Based on existing cases utilising industrial waste heat in an electric heat pump a cooling of 20°C is expected (Clausen, From, Hofmeister, Paaske, & Flørning, 2014 A). The heat source outlet temperature is, hence, fixed at 20°C.

TAXES

A major challenge to the utilisation of industrial waste heat for district heating purposes is the existing taxation. This is a practical as well as an economic challenge as the process of understanding the legal framework and collecting binding answers from the tax authorities is generally complex and time consuming (Risom, 2016).

The industrial company pays energy tax for the consumption of electricity and fuel for the daily operation of the company. The taxes on electricity and fuel specifically used for industrial processes are, however, reimbursed. When some of the process heat is used for district heating purposes this reimbursement is reduced. This reduction in the reimbursement of energy and electricity taxes is called the "waste heat tax". The purpose of the taxes on utilisation of industrial waste heat is to ensure the ongoing efficiency improvements of the industry i.e. the prospects for sale of waste heat should not end up working against the incentive to invest in more efficient technologies (The Danish Energy Agency, 2009). As an example, it should always be more attractive for an industrial company to invest in a new efficient unit for process heat than to keep an older inefficient one because of revenues from sale of waste heat.

The taxation on the utilisation of industrial waste heat depends on the specific setup of the project in terms of ownership. Furthermore, a number of special rules and exceptions exist that makes it very difficult to be sure what taxes apply without a declaration on the specific case from the tax authorities (The Danish Energy Agency, 2009). The calculation method used in this sensitivity analysis is, hence, not universal and to some extent simplified.

It is assumed, that the heat pump connected to the waste heat is owned by the district heating plant. In such a case, the district heating company pays a tax of 380 DKK/MWh_e on all electricity consumed by the heat pump. Furthermore, a payment for the waste heat is agreed upon between the district heating company and the industrial company. In this sensitivity analysis, three sizes of payments are tested in order to determine the influence of this additional cost on the final result. These are 200 DKK/MWh_{th}, 100 DKK/MWh_{th} and 0 DKK/MWh_{th}. Of these payment sizes 200 DKK/MWh_{th} is expected to be the most realistic for this temperature of industrial waste heat (The Danish Energy Agency, 2009) (Tang, 2015). The payment would be considerably larger if the waste heat could be used directly in the district heating system without further heating. As a general rule, the industrial company has to pay a waste heat tax of 180 DKK/MWh_{th}. The waste heat tax can, however, never exceed 33% of the payment (Houe, 2015).

Figure 36 shows the annual variation in COPs when using seawater and industrial waste heat as a source for the heat pump.

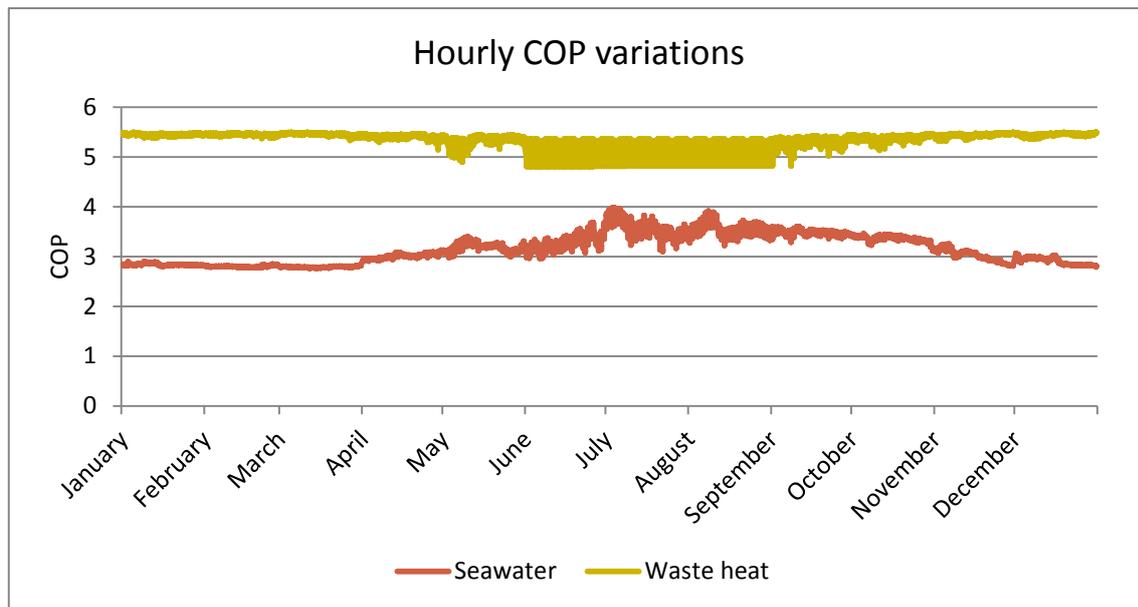


Figure 36: Hourly variations in COP when using a heat source of seawater and industrial waste heat.

When using seawater as a heat source the COP of the heat pump varies between 2.8 and 4.0 with an average of 3.2. The higher supply temperatures during the summer would expectedly lower the COP but as the seawater temperature is also raised in this period the total effect is an increase in COP. The production benefit of this high COP is, however, limited by the relatively small demand. During the winter, the COP falls below 3. This is increasingly critical as this is when the demand is at its highest.

When using industrial waste heat as a heat source the COP is significantly higher, varying from 4.8 to 5.5 with an average of 5.3. Opposite to the seawater case, the COP is at its lowest during the summer months. This is because of the increase in supply temperature during these months.

Figure 37 shows the net present value of using seawater and industrial waste heat compared to using ground water as a heat source as done in the Combined scenario in *Chapter 7 Method improvement*.

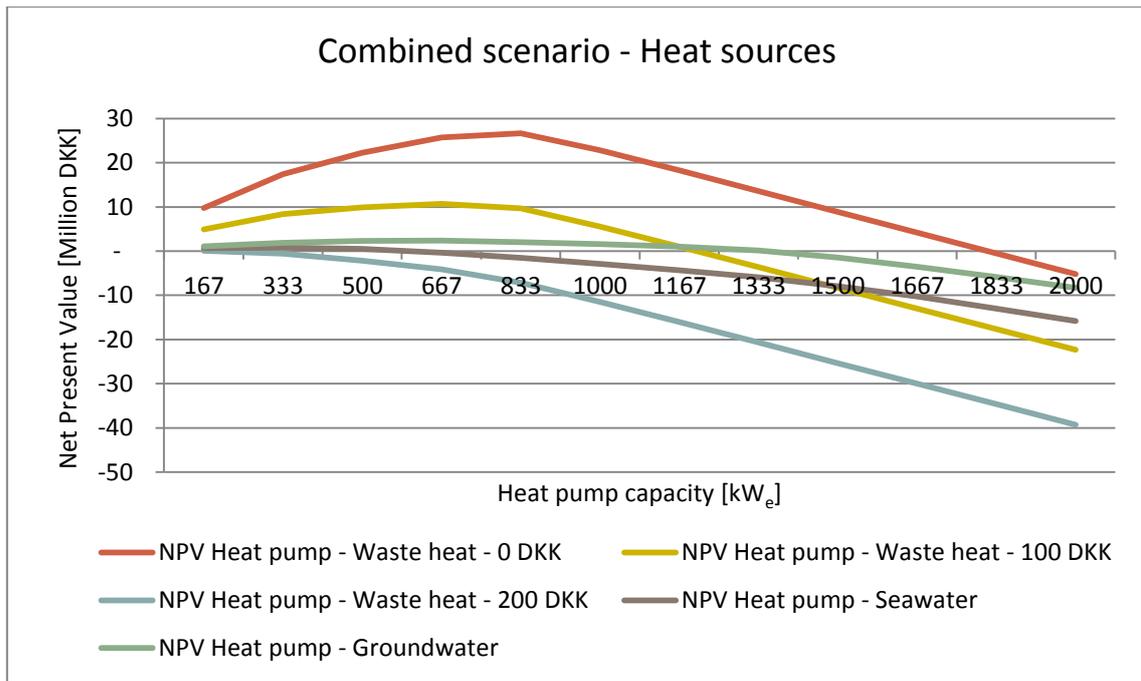


Figure 37: Net present value of different heat sources for a heat pump in the combined scenario.

It is clear from Figure 37 that some potential exist for the utilisation of industrial waste heat as the source for a heat pump. It is, however, also clear that this potential is critically dependent on the size of the payment for the waste heat. When the industrial waste heat is free, the heat pump clearly benefits from the increased COP and the investment looks highly profitable especially for smaller/medium sized heat pumps. As soon as a payment is required for the waste heat, however, the net present value is quickly reduced. With a payment of 100 DKK/MWh_{th} smaller heat pump capacities are still profitable, though it is questionable if a payment of 100 DKK/MWh_{th} would be accepted by the industrial company. With a payment of 200 DKK/MWh_{th} the investment in a heat pump will not create any profit no matter the size of the heat pump. Seawater is a free heat source which makes it attractive when compared to the most expensive waste heat scenario. However, compared to industrial waste heat, seawater leads to a relatively low COP and the overall economy of this scenario is poor. It is worth noticing that even though seawater leads to a higher COP than groundwater (an average of 3.2 compared to 3.0) the groundwater scenario show a higher net present value. The reason for this is that the maximum COP when using seawater is 4.0 while the maximum for groundwater is 3.0. As the investment costs are calculated based on the installed thermal capacity a high maximum COP will mean higher investment costs and in this case the seawater scenario is negatively affected compared to the groundwater scenario. As mentioned in *Chapter 6 Standard analysis*, this method for calculating the investment cost for the heat pump accounts for some uncertainty, but it is unsure to what extend these uncertainties affects the result.

8.4 TAXES, TARIFFS AND SUBSIDIES

It is clear from the Heat pump scenario that the economy of heat pump projects are highly dependent on taxes and tariffs not always supporting the use of this technology. In the following sensitivity analysis, different alternatives to the existing tax, tariff and subsidy struc-

ture are tested in order to figure out if a different economic framework might better allow the coproduction from solar thermal and electric heat pumps.

EXEMPTION FROM PSO TARIFF

District heating companies have to pay PSO tariff for their electricity consumption, also when the electricity is used for heat production. In this study, the PSO makes up about one fourth of the heat production costs of the heat pump. The purpose of the PSO tariff is to finance the transition towards a renewable energy system. The supported technologies are wind turbines, photovoltaic and other renewable forms of energy production, subsidies (in the form of the 1st and 2nd basic subsidy) for decentral district heating plants and research and development in renewable energy (Energinet.dk, 2015 C). Based on the general support for large electric heat pumps as an important player in the future energy system it can be argued that the PSO tariff should help promote and not, as now, work against the utilisation of this technology. Because of this, the first sensitivity analysis for taxes, tariffs and subsidies exempts heat pumps from the PSO tariff.

REDUCED ELECTRICITY TAX

As previously explained, there exist two methods for calculating the electricity tax of a heat pump, the thermal (212 DKK/MWh_{th} excluding PSO tariff) and the electric method (380 DKK/MWh_e including PSO tariff). This approach is favouring electric boilers over electric heat pumps with lower COPs which could be considered problematic, given that these heat pumps generally offer a more efficient use of electricity than electric boilers. To even out this difference and to offer a more simple system for electricity tax the second sensitivity analysis for taxes, tariffs and subsidies propose one fixed electricity tax for both heat pumps and electric boilers set at 212 DKK/MWh_e. This will not affect the cost of producing with the electric boiler as this is more or less 100% efficient meaning that the thermal output equals the electric input. In order to test the significance of a lowered electricity tax the PSO remains unchanged in this sensitivity analysis.

EXEMPTION FROM PSO TARIFF + REDUCED ELECTRICITY TAX

In order to test the combined effects of the two proposes changes to taxes and tariffs this third sensitivity analysis for taxes, tariffs and subsidies employs both an exemption from PSO and a reduced electricity tax of 212 DKK/MWh_e.

INVESTMENT SUBSIDY

Compared to other technologies heat pumps have relatively high investment costs that are often a discouraging factor for the investment in a heat pump. In 2015, grants ranging from about 13-30% of the investment have been granted to selected large heat pump projects through The Heat Pump Mobile Task Force formed by The Danish Energy Agency. Though the funding scheme was popular it was cancelled for 2016 (Riise-Knudsen, 2015). In order to test the effect of this type of subsidy the fourth sensitivity analysis employs a 25% subsidy on the investment for a heat pump.

The input data for the sensitivity analysis of taxes, tariffs and subsidies are presented in Table 12.

Sensitivity analysis	Electricity tax [DKK/MWh _e]	PSO tariff [DKK/MWh _e]	Investment subsidy [%]
Exemption from PSO	380	-	-
Reduced electricity tax	212	225*	-
Exemption from PSO + reduced electricity tax	212	-	-
Investment subsidy	380	225*	25%

Table 12: Input parameters for the sensitivity analysis of taxes and tariffs.*The actual PSO prices of 2015 have been applied in the sensitivity analysis, while the 225 DKK/MWh_e represents the average price of 2015.

Figure 38 shows the net present value of the four different sensitivity analyses of reduced electricity tax, PSO tariff exemption and investment subsidy in the combined scenario.

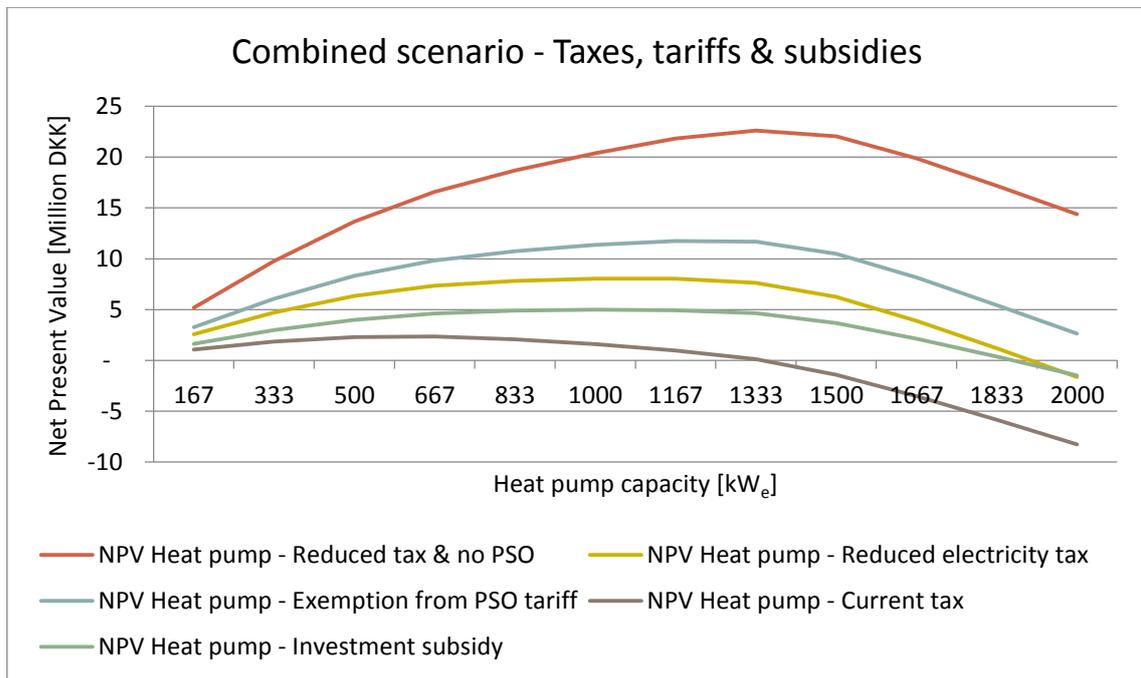


Figure 38: Net present value of different scenarios of reduced electricity tax, PSO tariff exemption, investment subsidy and current taxes in the combined scenario.

According to Figure 38 all the proposed changes show a certain potential in the effort to fit an electric heat pump into a solar thermal district heating system. The 25% investment subsidy shows an improved overall economy with a maximum net present value of about 5 million DKK for medium-sized heat pumps. It is uncertain if this profit is high enough for district heating companies to agree to the risks of such an investment. Experiences from the Heat Pump Mobile Task Force do, however, show that the investment subsidies awarded to heat pump projects do lead to the implementation of these (Riise-Knudsen, 2015). Even though these implemented projects do not necessarily include solar thermal plants, this speaks for the use of investment subsidies as a tool for promoting large electric heat pumps in district heating.

More promising, the PSO tariff exemption and electricity tax reduction show a considerable improvement especially on the medium-sized heat pumps represented in Figure 38 while the potential is reduced for the larger electric capacities. Especially the exemption from PSO tariff shows potential for the inclusion of electric heat pumps in solar thermal district heat-

ing while the combination of PSO tariff exemption and electricity tax reduction carry, by far, the largest potential. Hence, it is clear that the economic framework made up by taxes, tariffs and subsidies are a major influence on the feasibility of heat pump projects.

8.5 RESULTS OF SENSITIVITY ANALYSES

The analyses show a considerable sensitivity of the results especially in relation to the more direct economic factors such as electricity prices and taxes, tariffs and subsidies. As electricity prices are expected to increase in the future the potentials for using heat pumps both in general and in combination with solar thermal will likely worsen. An increase in the gas prices could partly “even out” the negative effects on the heat pump of increased electricity prices but existing forecasts expect a significantly lower increase in gas prices than in electricity prices. In any case, an increase in electricity prices will affect the competitiveness of the heat pump when compared to non-fuel technologies such as solar thermal.

The economic framework of an electric heat pump is a major barrier for its usage. The sensitivity analyses shows that the economy of a heat pump in a solar thermal district heating system is significantly improved with the exemption from the PSO tariff potentially combined with electricity tax reductions.

The conclusions of the analysis appear to be less sensitive towards changes in heat source for the heat pump. An improved COP could potentially influence the results of the analysis but as this is, in the case of industrial waste heat, generally followed by a significant increase in production costs the overall potential is relatively modest.

9 DISCUSSION

The study reveals somewhat pessimistic prospects for the inclusion of heat pumps in solar thermal district heating systems and the result is largely supported by the sensitivity analyses. As, however, the study is only carried out for one generic plant the results cannot be broadly transferred to all district heating systems. The following chapter discusses the uncertainties of basing the study on a generic plant and, based on this, reflects upon the meaning and application of the findings for the district heating sector as a whole and the possibilities for further studies on the subject.

9.1 THE METHOD

This study takes its point of departure in a generic district heating plant designed with the intention to make the results generally applicable to most plants relevant for investments in solar thermal and electric heat pumps. As this generic plant is the foundation of the study, it should be discussed whether it can actually be considered generic. There are obvious uncertainties linked to basing a study like this on one single type of district heating plant making this a representative of all others in a complex analysis. Some of these uncertainties have already been discussed in *Chapter 6 Standard analysis*. The generic district heating plant of this study has been designed to comply with both most official energy scenario reports predicting solar thermal and heat pumps in smaller district heating systems and statistics of existing cases with the two technologies confirming this prediction. However, it is not given that future solar thermal and heat pump projects will be limited to these smaller district heating systems. Examples are seen of still larger plants employing solar thermal solutions and there are no technical barriers hindering the use of heat pumps in larger plants (Silkeborg Forsyning, 2015). It is difficult to speculate exactly how the use of a larger district heating system would have affected the results. Most likely, the overall conclusion would not have changes radically as long as the ratio between the different installed capacities remain the same.

In terms of technology, the constellation of a natural gas CHP and boiler as well as an electric boiler is considered common but in no way applicable to all cases and especially the focus in renewable technology is allowing for a new diversity in production units in Danish district heating systems. A district heating system largely based on gas will, due to relatively high production prices, generally be suitable for renewable technologies such as solar thermal and heat pumps (Clausen, Kim S.; From, Niels; Hofmeister, Morten; Paaske, Bjarke Lava; Flørning, John, 2014 B). On the contrary, systems largely based on low-cost production units such as biomass boilers will have a harder time integrating these technologies. It is, hence, decisive for the results of the analysis what technologies are already operating in the designed district heating plant. By basing the generic plant of this study on natural gas, both solar thermal and heat pumps are given an advantage in the calculations. Compared to e.g. the 2035 district heating scenarios of The Danish Energy Agency these predict that as much as 83% of all heat production from smaller district heating systems will come from solar thermal, electric heat pumps or electric boilers (The Danish Energy Agency, 2014 B). If this is to be realised, these technologies will in some cases likely have to be integrated alongside with biomass boilers. According to The Danish Energy Agency by 2012 180 out of 388 smaller district heating plants have some production from biomass and since then another 85 plants have been given free fuel choice allowing them to switch away from natural gas potentially for a biomass solution (The Danish District Heating Association, 2014) (The

Danish Energy Agency, 2012 B). By only considering a gas-based plant this study, hence, does not fully address all the potential challenges faced by the two technologies.

Finally, the economic and legal conditions of district heating plants vary significantly depending on factors such as the size, year of construction, availability for up- and downregulation, technologies applied etc. For example, only plants established before the 1st of April 2004 are entitled to the 1st basic subsidy while only plants established before the 1st of July 2002 are entitled to the 2nd basic subsidy (The Danish Energy Regulatory Authority, 2015). Similarly only some plants are allowed net settlement of their production exempting them from certain taxes on delivering to and taking from the electricity grid.

The many potential variations in size and composition of technologies as well as economic and legal framework for different district heating plants make it impossible in practice to design a “typical” or generic plant. It is, hence, important to stress that the results of this study are not broadly applicable to the district heating sector as a whole and should be viewed within their context. However, as the generic plant is designed to fit specific criteria of plants often linked to solar thermal and heat pumps the plant is believed to offer a useful representation of these types of systems.

Another uncertainty linked to the methodology of the study concerns the dimensioning of the solar thermal plant for the Solar thermal and Combined scenario. The constructed generic plant imitates a typical district heating plant that has invested in solar thermal. There is however some divergence between what is known to happen in real life and what the results of this study show. As mentioned in *Section 6.3 Solar thermal scenario*, the optimal solar thermal share for the generic plant is approximately 34% of the annual heat demand. This is considerably larger than the typical solar thermal share of 20-25% for the existing solar thermal plants (Clausen, Kim S.; From, Niels; Hofmeister, Morten; Paaske, Bjarke Lava; Flørning, John, 2014 B). As only one size of district heating plant and solar thermal capacity is tested, it remains unknown if another setup would allow for a better incorporation of a heat pump together with solar thermal. The study group is aware of the difference, and recognises that there are potentially more hours for heat pumps to operate in, with a smaller share of solar thermal as in the existing solar thermal plants. Thereby the conclusion may underestimate the potential for establishing heat pumps in district heating plants with solar thermal.

9.2 THE RESULTS

The study shows a potential profit of a net present value of 2.1 million DKK for the most feasible electric heat pump in a solar thermal district heating system. It is not clear if this is considered an acceptable outcome for a 10.5 million DKK investment with this time horizon. As previously mentioned economic theory would consider all profitable investments attractive investments no matter the size of the profit. As, however, the sensitivity analyses show considerable changes in the results when varying the basic conditions of the analysis the final profit could be considered too small and uncertain for such an investment to be attractive. Both views are supported by Jørgen Risom from The Heat Pump Mobile Task Force. Generally, district heating companies will be willing to invest as long as this would lead to any reduction in the heat price. In a simplified calculation the distribution of 2.1 million DKK over 15 years of 29,000 MWh_{th} heat demand would give a heat price reduction of approximately 4.8 DKK/MWh_{th} equivalent of 87.4 DKK per year for an average Danish household

with an annual heat demand of 18.1 MWh_{th} (The Danish District Heating Association, 2014). On the other hand, according to Jørgen Risom, it is clear the heat pumps are currently struggling with a poor reputation and the framework surrounding these is generally not trusted (Risom, 2016). This means that many district heating companies are reluctant to invest in heat pumps and would often prefer other technologies even if these are not as promising under the existing framework.

Finally, the study does not consider any alternatives to the heat pump as an additional investment. The analyses of investments in solar thermal and heat pumps separately in the Standard analysis show net present values as high as 20.7 and 11.5 million DKK, respectively. This is considerably higher than the maximum output of the Combined scenario and raises the question if an electric heat pump is really the most feasible addition to a solar thermal district heating system. It is possible that an expansion of the existing solar thermal plant or the investment in additional storage capacity or technologies that are more suitable for peak load production such as biomass boilers, would show a bigger profit. As district heating companies would always go for the more profitable solution, within the framework of optimising socioeconomy, the competition from other renewable technologies could likely be the biggest thread to the implementation of electric heat pumps in solar thermal district heating.

9.3 FURTHER STUDIES

The purpose of this study is to account for the possible conflict between solar thermal and electric heat pumps in district heating systems. This is analysed with the intent to analyse and draw attention to what might pose a challenge to meeting the energy system goals of the future. It is not possible, based on this study, to quantitatively express the scope of the potential conflict between the two technologies, i.e. it is not possible to say what capacity of installed solar thermal in the district heating sector will be too much to allow for the desired development in electric heat pumps. A further study of this subject could focus on the implement of the findings on a larger scale, thereby possibly map out where and to what extent solar thermal is limiting the implementation of electric heat pumps in the district heating sector. This would clarify the need for actions and specify how such actions could be taken to possibly limit the implementation of solar thermal district heating or, even better, create a more favourable legal and economic framework for electric heat pumps.

Another idea could be to focus specifically on the interaction between solar thermal and electric heat pumps and the potentials for integrating these better through alternative technical solutions. This could mean analysing the potentials for improving the efficiency of the solar collectors by lowering the temperature in the water supplied to these. Alternatively, the solar collectors or a seasonal heat storage could be used as a heat source for the heat pump. District heating system better integrating the two technologies might show a larger potential than found in this study.

10 CONCLUSION

The following research question formed the point of departure for this study:

Is the current development in solar thermal district heating hindering the implementation of large electric heat pumps in the Danish district heating sector, and what external factors are influencing this?

First and most importantly, it is important to note that the study is a simplified generalisation. The results of the study are, hence, not directly transferable to other cases. The study does, however, show a tendency that is expected to be representative of most district heating systems.

The analysis shows that, under the conditions of this specific study, solar thermal is the most economically feasible of the two technologies for smaller district heating systems. This tendency is supported by the fact that the legal and economic framework of heat pumps is generally considered unreliable (Risom, 2016). A continuous favouring of solar thermal over electric heat pumps can, hence, be expected in the future of the district heating system.

The prospects for a solar thermal district heating system to invest in electric heat pumps are present but not overwhelming. The analysis shows a maximum profit of 2.1 million DKK over the 15-year time horizon of the investment. This is a sizable profit but likely not big enough to compete with alternative technologies. The analysis shows that the presence of solar thermal blocks the heat pump many hours of the year significantly reducing its production hours. The loss in production hours makes it difficult for the heat pump to pay off its own investment. The results are not conclusive but indicate that electric heat pumps will generally have a hard time operating alongside solar thermal and that this will critically minimise the investment in heat pumps in solar thermal district heating systems.

The sensitivity analysis shows that all the tested external factors do, to some extent, affect the result. One very significant factor is, however, taxes and tariffs and with the existing tax and tariff structures, it appears that both heat pump generally and specifically the combination of solar thermal and heat pumps will always be challenges financially. Of the proposed changes to the tax and tariff structures especially the removal of the PSO tariff show a promising result with a net present value of 11.7 million DKK making the combination of solar thermal and heat pumps not only possible but also attractive. A significant increase of natural gas prices will work in favour of electric heat pumps but an expected increase in electricity prices will, most likely, neutralise the effect and even possibly worsen the economy of the technology. Finally, it is clear that the heat source of the heat pump is of great importance to the results. As, however, the most promising heat sources are linked to both practical challenges and considerable additional expenses the potential is questionable.

11 BIBLIOGRAPHY

- Albertsen, I. (7. March 2016 B). Grundbeløb. Fredericia, Denmark.
- Albertsen, I. (7. Marts 2016). Energinet.dk. (K. B. Madsen, Interviewer)
- Andersen, A. N., & Østergaard, P. A. (2015). *Optimal use of heat pumps in district heating systems – individual booster heat pumps vs central heat pumps*. Aalborg.
- Arcon-Sunmark. (u.d.). Arcon-Sunmark Solfanger Type HT-HEATboost 35/10. Skørping.
- Clausen, K. S., From, N., Hofmeister, M., Paaske, B. L., & Flørning, J. (2014 A). *Inspirationskatalog for store varmepumpeprojekter i fjernvarmesystemet*. Copenhagen: The Danish Energy Agency.
- Clausen, Kim S.; From, Niels; Hofmeister, Morten; Paaske, Bjarke Lava; Flørning, John. (2014 B). *Drejebog til store varmepumpeprojekter i fjernvarmesystemet*. Copenhagen: Danish Energy Agency.
- Connolly, D., Lund, H., Mathiesen, B., & Leahy, M. (2009). A review of computer tools for analysing the integration of renewable energy into various energy systems. *Applied Energy*, 1060-1071.
- Connolly, D., Møller, B., Lund, H., Mathiesen, B. V., Hvelplund, F., Sperling, K., . . . Ridjan, I. (2013). *Smart Energy Systems*. Aalborg: Aalborg University.
- Danish Energy Agency. (2012). *Technology data for energy plants*. Copenhagen: Danish Energy Agency.
- Den store danske. (24. March 2012). *Energiafgift*. Hentet fra http://denstoredanske.dk/Samfund,_jura_og_politik/%C3%98konomi/Energi-_milj%C3%B8-_og_forurenings%C3%B8konomi/energiafgift
- Dronninglund Fjernvarme. (2014). *Dronninglund solfangeranlæg*. Skørping: PlanEnergi.
- Ea Energianalyse. (2011). *Afgifter på varmepumper i fjernvarme*. Copenhagen: Ea Energianalyse.
- Ebbehøj, S. L. (17. December 2015 A). Oversigt over ansøgningerne og økonomi. Copenhagen, Sjælland, Denmark.
- Ebbehøj, S. L. (2015 B, December 17). Debat og evaluering. Copenhagen, Sjælland, Denmark.
- EMD International A/S. (16. December 2014). User's Guide energyPRO. Aalborg Ø, Nordjylland, Denmark.
- EMD International A/S. (n.d.). *Articles*. Retrieved May 22, 2016, from <http://www.emd.dk/energy-system-consultancy/articles/>
- Energimidt. (22. April 2016). *Få sat skik på afkølingen i dit varmeanlæg*. Hentet fra <https://www.energimidt.dk/privat/fjernvarme/udnyt-fjernvarmen/>

- Energinet.dk. (6. June 2013). *Tariferingsgrundlag*. Hentet fra <http://www.energinet.dk/DA/GAS/Produkter-og-handel/Transmissionstarif-prisblad/Sider/Tariferingsgrundlag-metode.aspx>
- Energinet.dk. (10. January 2015 A). *Arkiv*. Hentet fra <http://www.energinet.dk/SiteCollectionDocuments/Danske%20dokumenter/El/Tarifarkiv%20pr.%202015.10.01.xlsx>
- Energinet.dk. (2015 A). *Energikoncept 2030*. Fredericia: Energinet.dk.
- Energinet.dk. (14. September 2015 A). *Energinet.dk*. Hentet fra <http://www.energinet.dk/DA/El/Saadan-driver-vielsystemet/Produkter/Sider/default.aspx#Regulerkraftmarkedet>
- Energinet.dk. (14. October 2015 B). Energinet.dk's analyseforudsætninger 2015-2035. Fredericia, Sønderjylland, Denmark.
- Energinet.dk. (8. September 2015 C). *Spørgsmål og svar om PSO-tariffen*. Hentet fra <http://www.energinet.dk/DA/El/Engrosmarked/Tariffer-og-priser/PSO-tariffen/Sider/Spoergsmaal-og-svar-om-PSO-tariffen.aspx>
- Energinet.dk. (15. January 2016 A). *Dansk vindmøllestrøm slår igen rekord - 42 procent*. Hentet fra <http://energinet.dk/DA/El/Nyheder/Sider/Dansk-vindstroem-slaar-igen-rekord-42-procent.aspx>
- Energinet.dk. (12. April 2016 B). *Aktuelle tariffer og gebyrer*. Hentet fra <http://www.energinet.dk/DA/El/Engrosmarked/Tariffer-og-priser/Sider/Aktuelle-tariffer-og-gebyrer.aspx>
- Energinet.dk. (2016). *Retningslinjer for nettoafregning af egenproducenter under Engrosmodellen*. Fredericia: Energinet.dk.
- Energinet.dk. (11. April 2016). *Udtræk af markedsdata*. Hentet fra <http://energinet.dk/DA/El/Engrosmarked/Udtraek-af-markedsdata/Sider/default.aspx>
- European Commission. (4. April 2016 A). *2020 climate and energy package*. Hentet fra http://ec.europa.eu/clima/policies/strategies/2020/index_en.htm
- European Commission. (2013). *EU energy, transport and GHG emissions - Trends to 2050*. Luxembourg: Eusropean Commission.
- European Commission. (4. April 2016 B). *2030 climate & energy framework*. Hentet fra http://ec.europa.eu/clima/policies/strategies/2030/index_en.htm
- European Commission. (4. April 2016). *The EU Emissions Trading System*. Hentet fra http://ec.europa.eu/clima/policies/ets/index_en.htm
- HMN GasNet. (1. January 2015). *Distributionstariffer for 2015*. Hentet fra <http://gasnet.dk/priserogbetingelser/distributionstariffer/2015/>
- HMN Naturgas. (2016). *Sådan er din gaspris sat sammen*. Hentet fra <https://www.naturgas.dk/gaspriser/gasprisen-sammensaetning>

- HMN Naturgas. (n.d.). *Transmission*. Retrieved from <https://www.naturgas.dk/erhverv/gaspriser/betingelserogafgifter/transmission>
- Houe, S. (17. December 2015). Afgift på overskudsvarme. PwC.
- Hougaard, P., & Tang, J. (u.d.). Varmepumper i fjernvarmesystemet. Danish District Heating Association.
- Johnson Controls. (2016). Johnson Controls.
- Koch, J. (18. December 2015). Feedback fra fjernvarmebranchen. Kolding, Denmark: The Danish District Heating Association.
- Kommunekredit. (24. May 2016). *Lån i Kommunekredit*. Hentet fra <http://kommunekredit.dk/L%C3%A5n/Om-l%C3%A5ngivning.aspx>
- Krebs, L. (2013). *Energiteknologi - en introduktion*. Nyt Teknisk Forlag: Copenhagen.
- Lauritsen, A. B. (2015). *Varmeståbi*. Odense SØ: Praxis - Nyt Teknisk Forlag.
- Lund, H. (2014). *Renewable Energy Systems*. Oxford: Elsevier.
- Lund, H., & Østergaard, P. A. (2010). *Fundamental Investment Theory*. Aalborg: Aalborg University.
- Marx, R., Bauer, D., & Drucek, H. (2013). Energy Efficient Integration of Heat Pumps into Solar District Heating Systems with Seasonal Thermal Energy Storage. *Energy Procedia*, 2706-2715.
- Mathiesen, B. V., Lund, H., Hansen, K., Ridjan, I., Djørup, S., Nielsen, S., . . . Østergaard, P. A. (2015). *IDA's Energy Vision 2050*. Aalborg: Aalborg University.
- Nagel, K. (2015). *Fremme af fleksibelt forbrug ved hjælp af tariffer*. Kolding: Grøn Energi.
- Nagel, K. (10. March 2016). The Danish District Heating Association. (M. Lebeck, & K. B. Madsen, Interviewere)
- Nord Energi Net. (6. January 2016). *Priser og gebyrer*. Hentet fra http://www.nordenerginet.dk/media/50950_Prisoversigt_pr_1-4_2016.pdf
- Østergaard, P. A. (2015). Reviewing EnergyPLAN simulations and performance indicator applications in EnergyPLAN simulations. *Applied Energy*, 921–933.
- Østergaard, P. A., & Andersen, A. N. (2016). *Booster heat pumps and central heat pumps in district heating*. Aalborg: Applied Energy.
- Paar, A., Herbert, F., Pehnt, M., Ochse, S., Richter, S., Maier, S., . . . Weidlich, I. (2013). *Transformationsstrategien von fossiler zentraler Fernwärmeversorgung zu Netzen mit höheren Anteilen erneuerbarer Energien*. Heidelberg: Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit.
- Paaske, B. L. (17. December 2015). Tekniske forhold og erfaringer. Copenhagen, Sjælland, Denmark.

- Paaske, B., Pijenburg, B., & Tang, J. (2013). *Varmepumper på decentrale kraftvarmeværker*. Aarhus: Teknologisk Institut.
- Parbo, H. (31. August 2015). Indkøb af regulerkraft, specialregulering og øvrigesystemydelse. *Kraftvarmeværkers deltagelse i elmarkederne*.
- PlanEnergi. (2013). *Summary technical description of the SUNSTORE 4 plant in Marstal*. Skørping: PlanEnergi.
- PlanEnergi. (2015). *Oversigt over store el-drevne varmepumper som leverer varme til danske fjernvarmenet*. Skørping: PlanEnergi.
- PwC. (2015). *Afgiftsregler for kraftvarmeværker*. Hellerup: PwC.
- PwC. (2016). *Afgiftsvejledning 2016*. Hellerup: PwC.
- Rasmussen, F. L. (November 2014). Fjernvarmens nettab bliver mindre – og det gør varmeprisen også. Denmark: Energiforum Danmark.
- Reinholdt, L. (2015). Højtemperaturvarmepumper - potentiale, implementering og status for udvikling. *Varmepumpers rolle i energisystemet*. Kolding.
- Riise-Knudsen, I. (December 2015). Status for Energistyrelsens demonstrationsprogram for store el-drevne varmepumper. The Danish Energy Agency.
- Risom, J. (28. April 2016). Special consultant. (K. Brun Madsen, Interviewer)
- Rugholt, P. S. (10. Februar 2016). Sæby Varmeværk a.m.b.a. (M. Lebeck, & K. B. Madsen, Interviewere)
- Silkeborg Forsyning. (24. October 2015). *Varme udvider produktionsanlægget bl.a. med solvarme*. Hentet fra <http://www.silkeborgforsyning.dk/Aktuelt.aspx?ID=2361&Action=1&NewsId=1694&M=NewsV2&PID=3818>
- SK Forsyning. (2005). *Bedre udnyttelse af fjernvarmen*.
- Social Democrats, The Danish Social-Liberal Party, The Socialist People's Party, The Liberal Party of Denmark, Danish People's Party, Red-Green Alliance and Conservative People's Party. (2012). *Aftale mellem regeringen (Socialdemokraterne, Det Radikale Venstre, Socialistisk Folkeparti) og Venstre, Dansk Folkeparti, Enhedslisten og Det Konservative Folkeparti om den danske energipolitik 2012-2020*.
- Solvarmedata. (2016). *Solvarmedata.dk*. Hentet fra [Solvarmedata.dk: http://www.solvarmedata.dk/](http://www.solvarmedata.dk/)
- Solvarmedata. (2016). *Solvarmedata.dk*. Hentet 3. Marts 2016 fra [Solvarmedata.dk: http://solvarmedata.dk/](http://solvarmedata.dk/)
- Sørensen, P. A., Paaske, B. L., Jacobsen, H. L., & Hofmeister, M. (2013). *Udredning vedrørende varmelagringssteknologier og store varmepumper til brug i fjernvarmesystemet*. Skørping: PlanEnergi.
- Statistics Denmark. (1990-2015). *Statistics Bank*. Hentet fra Inflation - årsstigning i procent: <http://www.statistikbanken.dk/statbank5a/default.asp?w=1366>

- Svedan Industri Køleanlæg A/S. (2015). Svedan Industri Køleanlæg A/S. *Varmepumpers rolle i energisystemet*. Kolding.
- Tang, J. (2011). Store varmepumper i fjernvarmesystemer. *Fjernvarmen*, 34-37.
- Tang, J. (2015). Overskudsvarme afgiftsregler.
- The Danish Building Research Institute. (2009). *SBi 2009:10: Varmt Brugsvand*. Hørsholm: The Danish Building Research Institute.
- The Danish District Heating Association. (13. November 2013). *Stor forskel på kommunale lån*. Hentet fra <http://www.danskfjernvarme.dk/nyheder/presseklip/arkiv/2015/151113stor-forskel-paa-kommunale-laan>
- The Danish District Heating Association. (7. May 2014). Bilag 1. Oversigt over nuværende og kommende afgifter. Kolding, Denmark.
- The Danish District Heating Association. (24. November 2014). *Endelig udsigt til løsning for 50 barmarksværker*. Hentet fra <http://www.danskfjernvarme.dk/nyheder/nyt-fra-dansk-fjernvarme/arkiv/2014/141124-endelig-udsigt-til-loesning-for-50-barmarksvaerker>
- The Danish District Heating Association. (2014). *Fjernvarmeprisen 2014*. Kolding: The Danish District Heating Association.
- The Danish District Heating Association. (2015). Benchmarking statistik 2014/2015. Kolding: The Danish District Heating Association.
- The Danish District Heating Association. (2015). *Nøgletal Benchmarking 2015*. The Danish District Heating Association.
- The Danish Ecological Council. (24. October 2014). EU's nye klimamål er utilstrækkelige. Copenhagen, Sjælland, Denmark.
- The Danish Energy Agency. (2005). *Vejledning i samfundsøkonomiske analyser på energiområdet*. Copenhagen: The Danish Energy Agency.
- The Danish Energy Agency. (2009). *Virksomhedsrentabel udnyttelse af overskudsvarme*. Copenhagen: The Danish Energy Agency.
- The Danish Energy Agency. (2012 A). *Technology data for energy plants*. Copenhagen: Danish Energy Agency.
- The Danish Energy Agency. (2012 B). *Fjernvarme fordelt på brændsler 2012*. Copenhagen: The Danish Energy Agency.
- The Danish Energy Agency. (2014 A). *Energiscenarier frem mod 2020, 2035 og 2050*. Copenhagen: The Danish Energy Agency.
- The Danish Energy Agency. (2014 B). *Fjernvarmens rolle i den fremtidige energiforsyning*. Copenhagen: The Danish Energy Agency.
- The Danish Energy Agency. (2015 A). *Energistatistik 2014*. Copenhagen: Danish Energy Authority.

- The Danish Energy Agency. (2015 B). *Baggrundsrapport B: Brændsels- og kvotepriser*. Copenhagen: The Danish Energy Agency.
- The Danish Energy Agency. (17. November 2015). Tekniske forhold og erfaringer. Copenhagen.
- The Danish Energy Agency. (3. February 2016 A). *Årlig energistatistik*. Hentet fra <http://www.ens.dk/info/tal-kort/statistik-noglestal/arlig-energistatistik>
- The Danish Energy Agency. (2016 B). *Forudsætninger for samfundsøkonomiske analyser i energisektoren*. Copenhagen: The Danish Energy Agency.
- The Danish Energy Agency. (n.d.). *Kvoteomfattede aktiviteter og virksomheder*. Retrieved from <http://www.ens.dk/klima-co2/co2-kvoter/fakta-vejledning-co2-kvoter/kvoteomfattede-virksomheder>
- The Danish Energy Association. (2013). *Scenarier for dansk el og fjernvarme 2020 til 2035*. The Danish Energy Association.
- The Danish Energy Association. (2014). *Elprisscenarier 2017-2035*. The Danish Energy Association.
- The Danish Energy Regulatory Authority. (2015). *Energinet.dk's anmeldelse af metode til indkøb af strategiske reserver i Østdanmark for perioderne 2016-18 og 2019-20*. Copenhagen: The Danish Energy Regulatory Authority.
- The Danish Energy Regulatory Authority. (2015). *Energitilsynets prisstatistik for fjernvarmeområdet*. Copenhagen: The Danish Energy Regulatory Authority.
- The Danish Energy Regulatory Authority. (January. 21 2016). *Statistik om gaspriser*. Hentet fra <http://energitilsynet.dk/gas/priser/statistik-om-gaspriser/>
- The Danish Government. (2011). *Vores Energi*. Copenhagen: Regeringen.
- The Danish Meteorological Institute. (2016). *Tekniske Rapporter*.
- The Danish Meteorological Institute. (17. May 2013). *Meteorologisk leksikon - G*. Hentet 6. April 2016 fra <http://www.dmi.dk/laer-om/generelt/leksikon/leksikon-g/>
- The Danish Meteorological Institute. (2013). *Technical report 13-19 - 2001-2010 Danish Design Reference Year*. The Danish Meteorological Institute.
- The European Central Bank. (2016). *Monetary Policy*. Hentet fra <https://www.ecb.europa.eu/mopo/html/index.en.html>
- The Minister of Climate, Energy and Buildings, The Danish Energy Association, HMN Natural Gas, DONG Gas Distribution, Natural Gas Fyn Distribution, The Danish District Heat Association, The Association for Danish CHPs and Energy and Oil Forum. (13. November 2012). *Energiselskabernes energispareindsats*.
- The Ministry of Finance. (31. May 2013). *Ny og lavere samfundsøkonomisk diskonteringsrente*. Hentet fra <http://www.fm.dk/nyheder/pressemeddelelser/2013/05/ny-og-lavere-samfundsoekonomisk-diskonteringsrente>

- Thyborøn Fjernvarme a.m.b.a. (n.d.). *Bedre udnyttelse af fjernvarmen*. Retrieved from <http://www.thyboron-fjernvarme.dk/gode-raad-om-fjernvarme/afkoeling>
- Urbanek, T., Oppelt, T., Platzer, B., Frey, H., Uhling, U., Göschel, T., . . . Rabe, D. (2014). Solar district heating in East Germany – Transformation in a cogeneration dominated city. *Energy Procedia*, 587-594.
- Videnskab.dk. (3. November 2014). Forskere: Urealistisk at holde global opvarmning under to grader. Valby, Sjælland, Denmark.
- Werner, S., & Frederiksen, S. (2013). *District Heating and Cooling*. Lund: Studentlitteratur.
- Wittrup, S. (18. December 2015). Nu etableres 10 store varmepumper i fjernvarmen. *Ingeniøren*.
- Young, H. D., & Freedman, R. A. (2008). *University Physics*. Sn Francisco: Pearson Education.