The Potential of Implementing Thermal Energy Storage in an Energy System with a High Share of Wind Power

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Abstract
The project focuses on the issues with fluctuating RES in the energy system. The purpose of the study is to assess if TES in combination with HPs or EBs leads to increased flexibility in energy systems with high share of wind, and if other benefits can be obtained. Two different energy systems are analyzed; Eastern Denmark and the CTR transmission system in Copenhagen. Two numerical tools are used, EnergyPLAN for the case of East Denmark and EnergyPRO for the case of CTR. Both cases are analysed with regard to socio economy, fuel consumption use and system flexibility as the main indicators. The study is performed with reference to a system in 2025 with 50% wind power and a CO_2 neutral energy supply in Copenhagen.

The results for the case of East Denmark shows that the integration of TES is not a socio economically feasible investment and when HP/EB is included in the system the investment is even less feasible. It is indicated that there is a modelling error in the EnergyPLAN model though, so the results of the analysis may not be valid.

The analyses of the CTR transmission system shows that there is a socio economic potential in increasing TES capacity up to 21 GWh. The combination with HPs shows not to be feasible, but the combination with EBs can be feasible up to a TES capacity of 63 GWh and 3,000 MW of EB capacity. The share of heat production from peak load boilers can be significantly reduced with the implementation of TES combined with HP though so this needs to be considered.

Nomenclature

ATES	Aquifer Thermal Energy Storage
BTES	Borehole Thermal Energy Storage
CCP1	Copenhagen Climate Plan from 2009
CCP2	Copenhagen Climate Plan from 2012
CEEP	Critical Excess Electricity Production
CEESA	Coherent Energy and Environmental Systems Analysis
CHP	Combined Heat and Power
CO_2	Carbon Dioxide
COP	Coefficient of Performance
CTR	Metropolitan Copenhagen Heating Transmission Company
DEA	Danish Energy Agency
DH	District Heating
DHP	District Heating Plant
DKK	Danish Crownes
DONG	Danish Oil and Natural Gas
EB	Electric Boiler
EU ETS	European Union Emission Trading Scheme
GHG	Greenhouse Gas
HOFOR	The Capital Area Supply Company
HP	Heat Pump
HPC1	Heat Plan of the Capital Region from 2009
HPC2	Heat Plan of the Capital Region from 2011
HPC3	Heat Plan of the Capital Region, still in progress
IEA	International Energy Agency
LPG	Liquified Petroleum Gas
NCAR	The National Center for Atmospheric Research
NEP	New Electricity Price
NG	Natural Gas
NPC	Net Production Cost
PES	Primary Energy Supply
PP	Power Plant
PTES	Pit Thermal Energy Storage
RE	Renewable Energy
RES	Renewable Energy Sources
SEC	Socio Economic Costs
TES	Thermal Energy Storage
TSO	Transmission System Operator
TTES	Tank Thermal Energy Storage
VEKS	Western Municipalities Heat and Power Company

Preface

This report is the product of the master thesis for the 4th semester written on the Master of Science in Sustainable Energy Planning and Management (SEPM) at Aalborg University. The report has been developed through the time period from February to June 2013.

The study focuses on analyzing the potential of using thermal storage technologies in combination with heat pumps and electric boilers to make the energy system more flexible in order to handle the higher share of fluctuating RE energy that will be in the system in the coming years. The subject has been chosen due to the focus on converting the energy system from being fossil based to being based on RE resources in both a national and international perspective. The subject is seen as a relevant study in this process and will at the same time fulfill the academic criteria for a master thesis. To perform the analysis two software programs are used; EnergyPLAN and EnergyPRO. Additionally an appendix is provided with explanation of the inputs and data necessary to the performed modeling.

Harvard is used for referencing throughout the report, whereas the references given in the text include the author and the year of publication e.g. (Hansen 2012). The bibliography is placed at the end of the report, where the references are given in alphabetic order according to surname of the author or the name of the organization that published the document. All figures and tables are numbered sequentially according to each chapter. A CD with reference models used in the analyses is attached in the report. All economic values are mentioned in DKK and values from references given in € are converted at the rate of 7.46 DKK/€.

Different persons have been contacted during the project period, for interviews and to get inputs to the project, of which the authors are appreciative. A thank therefore goes to Jørgen Hvid, Chief Consultant at Rambøll, Anders Brix Thomsen, Climate and Energy Coordinator at Copenhagen Municipality and David Magnusson, Engineer at CTR, for giving interviews and information for the analyses of the project. Appreciations also go to Peter Sorknæs, Ph.D. student at Aalborg University for support in the use of the EnergyPRO software.

Executive Summay

In Denmark the wind power capacity is planned to increase to 50% in 2020 which means that the electricity system needs a higher degree of flexibility to utilize the excess electricity production. Previous years the excess electricity at days with high wind production have been sold to Denmark's neighboring countries utilizing some flexibility in their systems. These countries are however also starting to implement larger capacities of fluctuating RES like wind and solar PV. This means that in the future Denmark may not to the same extend be able to export its excess electricity production from wind power, and therefore has to find new ways to integrate the fluctuation electricity production in the energy system in Denmark. This may be by utilizing the large DH coverage and conversion of excess electricity to thermal energy and storing it in a TES capacity for later use. The purpose of this project is to assess and find a solution to the problem described above. The research question of the project is:

What is the potential of implementing thermal energy storage in combination with heat pumps and electric boilers in the Danish energy system for DH to increase the flexibility for the inclusion of renewable energy sources?

To answer the research question, first a review of the relevant technologies for the specific purpose is made. The review shows that currently there are four technologies relevant for thermal storage of which two are of particular interest regarding large scale TES; PTES and ATES. Further the two technologies for conversion of electricity to thermal energy HP and EB are presented.

A methodology has been used where two different computer models, EnergyPLAN and EnergyPRO are applied to analyze the integration of TES in combination with HP and EB. EnergyPLAN has been used to analyze the integration in the East Denmark energy system and the EnergyPRO model has been used for the local DH transmission system CTR in Copenhagen. This is chosen to utilize the different capacities and specifications of the two models. EnergyPLAN works on a highly aggregated level regarding the production capacities, focusing on the interplay between electricity production and DH systems and is designed to model systems with high shares of RES. EnergyPRO on the other hand is designed to model and optimize the operation of smaller and local energy systems and plants with a higher level of detail than EnergyPLAN.

Choice Awareness theory is applied as a framework for the analyses. Specifically, the importance of the socioeconomic feasibility is taken into account in the analyses as the socioeconomic costs in the analyses are seen as an important parameter. The reference scenarios for both models are based on data from the year 2011 and the development is projected to 2025 based on other projections and plans for the energy supply in 2025. The 2025 reference includes the increased wind share mentioned above and the changes in the energy supply in Copenhagen that follows the plans for CO_2-neutrality in Copenhagen in 2025. The three alternative scenarios are analyzed in parallel in both of the two computer models by increasing the capacities of TES and HP/EB. In that way it is possible to compare the tendencies in the results from the two models and point out the reasons for eventual differences. The three analyzed alternative scenarios are: 1. Increased TES capacity, 2. Increased TES and HP capacities and 3. Increased TES and EB capacities.

The analyses of the regional energy system of East Denmark show that integration of TES is not a socio economically feasible investment and when HP is included the investment is even less feasible. The analysis of integration of TES and EB shows some positive results, but this is just because increasing the EB capacity without increased TES gives a positive affect itself and the TES capacity only reduces the benefit. An assessment of how the EnergyPLAN model handles TES combined with HP and EB indicates that there is an error in the model so the results cannot be valid in that case though. The problem is that the TES capacity can only be charged by the heat production from the CHP and neither from HP nor EB. It is shown that in the scenarios with increased TES and HP there are hours where the TES is not fully charged, the HP capacity is not fully utillized and at the same time there is CEEP. This means that the model is not able to simulate the system and use the electricity from the wind turbines as effectively as expected.

The results of the analyses of the local energy system of the transmission system of CTR show that there is a potential in increasing the TES capacity up to 21 GWh from a socioeconomic point of view. In this system the annual costs are 86 M DKK lower compared to the reference. The combination with HP shows not to be feasible since for all the analyzed combination the total costs starts to increase when the HP capacity is increased. The combination with EB shows to be feasible up to a TES capacity of 63 GWh and 3,000 MW of EB capacity. This combination gives a reduction in the annual costs of 128 M DKK. Also at TES capacities lower than 63 GWh the increased EB capacity will result in a reduction of the annual costs. For 21 GWh TES the optimal EB capacity is 1,600 MW which gives a reduction in the annual costs of 122 M DKK. The results also show that the share of heat production from fuel based boilers can be significantly reduced with the implementation of TES combined with HP which is not the case to the same extent in the combination with EB. In the scenario combining TES and HP the boiler production share is reduced to only 0.5% of the boiler production in the reference. With increased HP without increased TES the boiler production share is reduced to 28%. The TES capacity alone is only able to reduce the boiler share to 50% of the values in the reference. The TES and EB can in the best case reduce the boiler share to 16% compared to the reference. This is an important point because the political goal as mentioned is to get a CO_2 neutral energy supply, where the only solution to the peak load production, in the current plans, is bio oil boilers for which the fuel price in 2025 is very uncertain.

From the EnergyPLAN analysis nothing can be concluded in relation to the research question because of the mentioned error in the model. From the results of the CTR analysis it can be concluded that there is a socioeconomic benefit to gain by increasing the TES capacity towards 2025. The potential in combining TES an HP is that it can reduce the fuel consumption on the boiler, compared to combining TES and EB which cannot reduce as much fuel consumption, but on the other hand gives a socioeconomic benefit.

Contents

Introduction 1

This chapter describes the introductory issues in relation to this project with point of departure in the challenges, when more renewable energy sources (RES) are implemented in the energy system. The perspectives in this initial description lead to the problem formulation that frames this project. Hereafter the report structure is presented and lastly the scientific relevance of the project is discussed with a short presentation of some articles related to the subject of this project.

1.1 The Challenge of Increasing RE Production Capacity

In many countries in Europe the energy production capacities using renewable energy sources (RES) are being developed and expanded to reduce CO_2-emissions and reliance on fossil fuels. More and more both national and local governments are setting ambitious targets for RE in the future energy supply and are implementing policies for the purpose (Harris 2011). This is causing new challenges to the development of the energy systems, where mainly the increasing share of intermittent RES, like wind and solar energy, is a challenge because it requires a certain degree of flexibility in the system.

Figure 1.1 shows that the share of electricity production from RES is increasing in especially Denmark and Germany, and in Sweden there is an increasing tendency. Norway has such a large hydro power production that it approaches 100% and therefore naturally do not increase further.

The wind power capacity in Denmark have been developed and increased through several decades and it is still the policy to continue increasing the share of wind power. In 2011 the wind share in the electricity production was equivalent to 28% and it is the official goal to have 50% of the electricity produced from wind turbines in 2020. The hourly and daily variation in the production of electricity from wind is partly handled by up and down regulation of domestic thermal power production but also to a large extent by trading with neighboring countries. E.g. Norway and Sweden both have a high capacity of hydro power which is used as a balancing capacity for the wind production. When there is a high wind production the hydro power plants can stop their production and import Danish wind electricity, and at times where the wind production is low the hydro power plants can start producing electricity and eventually export to Denmark. (Energinet.dk 2012c)

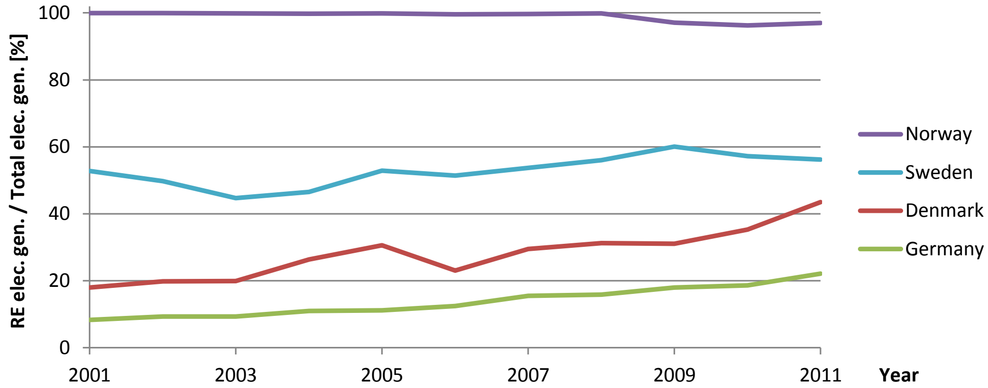

Figure 1.1: Historical development of RE electricity production share in the four countries; Norway, Sweden, Denmark and Germany (EIA 2011).

The problem in increasing the capacity of wind production in Denmark is that the interconnections with the neighbor countries are occasionally already at their limits when the wind production is high. Furthermore the neighbor countries, especially Sweden and Northern Germany are expanding own capacities of wind turbines. The weather patterns in the countries are rather similar, meaning that the peaks in wind production occur at the same time, hence reducing the potential of exporting the excess production (Pöyry 2011). An example of this occurred already in 2007 during a winter storm where a large amount of wind capacity temporarily had to be shut down in Denmark to avoid electricity overflow in the system because of a situation where the export capacity to Norway and Sweden was fully utilized and at the same time there was an overproduction in Northern Germany (Energinet.dk 2012c). Basically this situation is caused by a lack of flexibility in the Danish energy system and with an increased wind capacity it can be expected that situations like the one described will occur more often than now.

Another problem caused by increasing the wind production capacity is that it increases the fluctuations in the electricity prices (Harris 2011). In the Nord Pool market the cheapest capacity for each hour always gets the priority to produce and sell the electricity, hence the wind production will suppress the more expensive production capacities. This means that when there is a high wind production the prices are low and opposite when there is less wind. The increased fluctuation in prices reduces the willingness of investors to invest in new infrastructure because price fluctuations make it hard to predict the economic feasibility of an investment and this again will weaken the development of the system. (Pöyry 2011)

1.2 Flexible Resources

Basically the problem is that the intermittent RES used for producing electricity are out of sync with the demand and the challenges described in the previous section can be mitigated by integrating more flexible resources in the system. Flexible resources are capacities which can up or down regulate to balance the electricity transmission system. In a project from the International Energy Agency (IEA) the flexible resources are divided in four categories (IEA 2011):

1. Dispatchable supply
2. Storage
3. Interconnection
4. Demand Side Management

There are already many technologies in the electricity system in Denmark that contributes to the flexibility. In fact, Denmark is mentioned as the country with the largest amount of flexibility resources among all analyzed cases in the IEA project. (IEA 2011) As dispatchable supply there are a lot of decentralized CHP units that provide flexibility. Also the larger central CHP plants contribute with a significant amount of flexibility. The CHP plants can up or down regulate the production on rather short notice, depending on the type. This is a specific asset to the Danish electricity system because the CHP plants connect the electricity demand to the heating demand through the widespread district heating systems. There are also the interconnections to the neighbor countries and domestically between the regions.

The solution to increase the flexibility in Denmark does not seem to be found either in the interconnections or in the dispatchable supply. The increasing wind capacities in the neighbor countries means that increasing interconnection may not increase the flexibility and the CHP production is already widespread in Denmark. A solution to cope with the increasing fluctuating supply from wind is more likely to be found in the categories of storage or demand side flexibility

There is no significant electricity storage capacity in Denmark and demand side management is currently present mainly at some large industrial consumers. (Harris 2011) There are already many proposed technologies which can provide storage to the electricity system or serve to manage the end user demand to increase the flexibility. The most efficient and commonly used technology at large scale for electricity storage is pumped hydro. This technology requires a certain geographical elevation which is not present in Denmark in sufficient extent, which almost eliminates this option. Electrolyzes for producing hydrogen from excess wind electricity are an option that more likely will be relevant in the Danish context. The hydrogen can be stored and used to produce electricity and heat at a later time. Compressed air storage is another technology that is mentioned as an option in the future Danish energy system. Both of the two latter technologies are still at a developing stage and not economically feasible, hence these remain future potential options. (Connolly 2010) (Salgi and Lund 2008)

For proposed technologies that can increase the flexibility in the demand side category is smart grid mentioned as a predominant concept. The idea in the smart grid concept is to combine a number of different technologies and utilize potential flexibility in demand and production from small consumer like households that otherwise would not be utilized. Smart grid systems have a lot of integrated communication technology so that the electricity consuming or producing devices at the end consumer can be regulated intelligently to balance the electricity system in an optimal way. An example is having a heat pump (HP) with a heat storage tank for covering the heating demand in the household. This will create a potential of using electricity from the grid when the price is low and charging the storage tank to provide heating at a later time. It increases the demand for electricity but in a flexible way. (Energinet.dk 2012d)

Demand side systems can also be seen in a larger perspective; DH plants can have an electricity demand in electric boilers (EB) or large scale HP. This is a flexible resource like in the households but the operators of the plants can plan the production and consumption of electricity directly according to the Nord Pool spot market prices and thereby use the electricity in the most beneficial hours. (EA Energi Analyse 2010)

1.2.1 Thermal Energy Storage as a Flexible Resource

The flexible resource concept is initially thought for electricity systems but the extensive use of DH in Denmark gives a potential for improvements of flexibility to the electricity systems. Conversion of electric energy to thermal energy is only indirectly included in the demand side category since the thermal energy cannot easily be recovered into the electricity system. But there might be a more substantial amount of flexibility to gain from converting electricity to thermal energy for DH. If the electricity is only converted when there is a heating demand the full potential flexibility is not reached but if the electricity is systematically converted to thermal energy when the electricity price is low and stored as thermal energy for a future heating demand makes the benefit of conversion independent of the heating demand.

Some heat storage capacity is already present at most of the DH plants in Denmark to balance the hourly and daily variations in heating demand and the hourly changing prices of electricity sale. These serves to increase the flexibility of the dispatchable supply but not for the demand side flexibility. EB or large scale HP at DH plants alone only gives demand flexibility but combined with thermal energy storage it may increase the potential flexibility.

Depending on the local conditions and the annual heating demand of a DH plant large scale thermal energy storage can be an option. There is already deployed large scale TES a few places in Denmark in conjunction to solar thermal DH plants, so called seasonal storages. Here the excess heat from the solar production in the summer months is stored for the colder months with higher heating demand and lower production. This strategy can be applied for other heat sources as well, e.g. where there is an amount of waste heat or over production like from geothermal or waste incineration plants. Such a system can be integrated with an EB or large scale HP and thereby are able to utilize both excess electricity from wind turbines and make the electricity system more flexible and at the same time abate the out-of-sync heat production and demand.

With point of departure in this introductory description of the challenges of implementing higher share of fluctuating RE in the energy system and the use of flexible capacities it is found relevant to do an assessment of the potential of implementing large scale TES in combination with EB or HP in Denmark.

1.3 Problem Formulation

Based on the preliminary description of the issues of an increasing share of fluctuating electricity in the energy system, this project will analyse the potential of using thermal energy storages in combination with HP or EB to ease the implementation of RES. The research question for this report is given below:

> *What is the potential of implementing thermal energy storage in combination with heat pumps and electric boilers in the Danish energy system for DH to increase the flexibility for the inclusion of renewable energy sources?*

The research question has been approach from two different perspectives; from a regional and from a local perspective using two different numerical computer models, respectively EnergyPLAN and EnergyPRO. These are working with different focus and aggregation level and the purpose of doing this is to get information about the potential of TES on different energy system levels. The socio economic costs of the systems have been used as a main indicator in the assessment of a number of scenarios set up for the analyses. The TES technology is only combined with either HP or EB. This means that there are no scenarioes where the two technologies HP and EB are combined.

1.4 Report Structure

This report consists of 10 chapters plus bibliograpy and appendices. The structure of the report is illustrated in Figure 1.2.

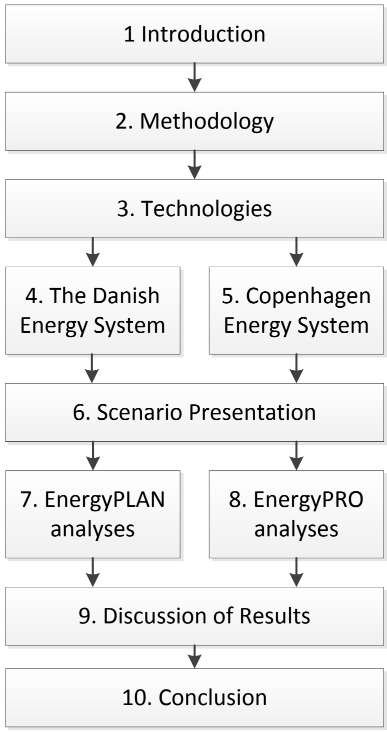

Figure 1.2: Report structure.

Technology Review: This part is carried out in Chapter 3 in order to provide an overview of the relevant technologies for the analysis. The relevant technologies are described and specifications for these are presented for later use in the analyses.

Energy Systems Analysis: A description and analysis of the energy system in Denmark and the Copenhagen area is given in Chapter 4 and 5 respectively with the main focus on the DH systems. These chapters provide an overview of the existing grids and further describe the political initiatives with regard to implementing RE in order to reach climate goals. These chapters thereby form the base of the technical and economic analyses that are performed in the next step of the research process.

Technical and Economic Analysis: These are carried out through the Chapters 6, 7 and 8, where Chapter 6 provides an overview of the scenario analysis, some economics assumptions applied to the analyses and lastly a presentation of the computer models EnergyPLAN and EnergyPRO. The scenario analysis is used to assess the potential of TES in combination with either HP or EB. The DH systems of East Denmark and CTR are used as cases. Chapter 7 and 8 present the analysis performed on the systems together with the found results of each system.

1.5 Scientific Perspectives

In this section some articles in relation to the chosen subject field is presented in order to set the frame and perspective of the project in a scientific relation. The purpose of presenting these articles is to provide different perspectives on the use of TES and HP/EB in DH systems. The articles are presented by highlighting the important points in the article. The articles are further discussed in relation to the project.

> **1.** The Role of Large-scale Heat Pumps for Short Term Integration of Renewable Energy - Case Study of Denmark Towards 50% Wind Power in 2020 and Technology Data for Large-scale Heat Pumps (Mathiesen et al. 2011)

The article states that with the increasing share of intermittent RES in the electricity grid, an increasing demand for smart energy systems is required. It underlines the importance of smart energy systems to not only focus on the electricity grid but integrate several sectors and utilize the flexibility in demands and various storage options. As examples are given gas grids and liquid fuels that allow for long term storage while the electric vehicles and large HP allows for shorter term storage and flexibility. By integrating more sectors in the implementation of RE, it is predicted that the increased fuel efficiency will decrease costs of the total energy system. The article points at the integration between the heating and the electricity sectors as the most important step. The system today is capable of integrating 20-25% of the wind power, but to reach the goal of 50% wind in 2020 it is vital to implement large HP in DH areas, the article concludes.

By the statements in the article it relates to the purpose of this project to assess the potential of increasing the flexibility in a system by integrating a larger capacity of storage in the system in combination with HP.

> **2.** Towards an Intermittency-friendly Energy System: Comparing Electric Boilers and Heat Pumps in Distributed Cogeneration (Blarke 2012)

In this article it is investigated how the technologies of HP and EB can allow for distributed co-generators to better co-exist with intermittent RES by easing the intermittency in the operation. The baseline issue in this article is that the increasing share of fluctuating RE will jeopardize the system-wide energy, economic, and environmental benefits that distributed cogeneration provide. The solution therefore lies in adapting the technology and operational strategy for the distributed operators to achieve a better co-existence between cogeneration and wind power. Various options has been included in the analysis, where it was found that EB provides increased flexibility in the operation of distributed co-generation. It was further found, that the right design of HP-TES concepts are more cost-effective and states that the HP technology should be acknowledged for its ability to provide both heating and cooling simultaneously. The article does not point at any specific solution, but puts emphasis on the importance of strategic development to give a balanced and efficient use of electricity.

This article supports the idea of a smart energy system, which combines different technologies in order to ease the integration of intermittent RES in the energy system and also calls for combining the heat and electricity production. The statements in the article are therefore in line with the purpose of the project, where HP and EB is assessed in combination with TES.

3. Energy 2050 - The Wind Track (translated from Danish: Energi 2050 - Vindspor) (Energinet.dk 2011c)

The purpose of the research in this report is to provide perspectives on how the energy system can develop towards a system independent from fossil fuels in a cost effective way while still maintaining a high security of supply. Two important key characteristics to obtain in the energy system are high energy efficiency and high flexibility. The analysis points at different directions that can help reach the goal of being fossil independent in 2050, where the overall statement is integration of more sectors in the process. Each sector should provide storage and flexibility in order to utilize fluctuating energy. For the integration between the heat and electricity sector, the report states that HP in the DH heating system can provide significant flexibility. TES of more than 500 GWh is relevant in relation to integration of wind, especially days with high wind production. It is concluded that the mentioned heat technologies are sufficiently developed and the challenge is the integration of the technologies in relation to operation and markets in a smart grid energy system, incorporating more sectors; the gas grid, transportation, electricity and heat sector.

The importance of integrating more sectors in order to ease the implementation of fluctuating RE, especially wind, is pointed out as a key element in the project. Here the DH system can provide some flexibility to the process already, but integration of the technologies TES and HP can increase the flexibility even more and ensure that the excess fluctuating electricity is stored and utilized.

4. Large-scale Heat Pumps in District Heating Systems (translated from Danish: Store varmepumper i fjernvarmesystemer) (Tang 2011)

The premise of this article is that HP has a significant potential in regard to environment and efficient fuel use, since the technology in DH system is able to contribute to less waste and more efficient use of fuels. The analysis is in this article based on separate plants with focus on the use of HP in DH systems to utilize the waste heat from industrial processes and wastewater treatment plants. The analysis described in the article showed to have a great potential in this regard. In the conclusion it is also pointed out, the importance of dynamic tariffs and levies, that should promote the implementation of HP in order to balance the electricity and heat markets, i.e. make use of the smart grid concept.

This article adds an environmental perspective to the use of HP in DH systems, since the focus of the article is not just the balance of fluctuating wind, but the potential of a more efficient use of fuel in DH systems. The use of fuel is one of the parameters, which is analyzed in the modeling of the two DH systems in this project.

Theoretical Framework and Methodology 2

The purpose of this chapter is to give an understanding of the theory behind the project and the methods used in this project to address the problem formulation and answer the research question. The chapter is divided into two parts; a presentation of the theory applied in the project and the methods used for the analyses.

2.1 Choice Awareness

The theory of Choice Awareness by Henrik Lund, Professor, PhD, Dr.Techn at Aalborg University is applied in this project due to the political aspects of the thesis to reach the goal of being CO_2 neutral at both national and local level in Copenhagen. In this project, the focus is on analysing TES as one of the alternatives to help reach these goals.

Choice Awareness Theory is defined to address the societal level. The theory further encompasses and "concerns collective decision-making in a process involving many persons and organisations representing different interests and discourses as well as different levels of power to influence the decision-making process" (Lund 2009). The theory is based on having a *true choice*, which means having a choice between two or more real options. As the quote indicates, the theory includes working with different organisations, political actors and people in the society as well as employees in companies, i.e. what Lund calls a collective decision making process. It is acknowledged that the different parties understand things differently, but advocates that there should be a true choice (Lund 2009). The Choice Awareness Theory is hence outlined by two theses:

First Thesis: When society seeks to reach aims that imply a radical technological change, influence and discourse from existing institutions will affect the decision making process and will hinder the development of new solutions. The existing institutions will try to create a general perception of *no choice*, by exclusion of technical alternatives from the debate and the collective decision making process.

Second Thesis: Society will benefit from raising awareness and acknowledge that technical alternatives *do* exist and that it is possible to make a true choice. It is important to promote the technical alternatives necessary for a radical technological change, which for instance is done through description of the alternative technologies and feasibility studies in a public debate. (Lund 2009)

The general perception in the Danish society acknowledges the conversion to an energy system based on RES, which is based in the broad political movement, agreeing on the energy and climate policy in Denmark, and in local areas like Copenhagen that promotes and aims at a CO_2-neutral energy system. The political aims are assumed to be materialized and generally accepted in the society, which is an important factor in reaching the political goals.

2.1.1 Radical Technological Change

Technology is according to (Lund 2009) characterized as "one of the means by which mankind reproduces and expands it living conditions". In order to implement the political aims in Denmark after the oil crisis in the 1970s, a radical technological change was needed. Technology is defined to consist of four equally important elements: *technique, knowledge, organisation* and *product* (Lund 2009). The importance of *profit* is also pointed out in addition to this and is added as a fifth element to the definition of technology. A radical technological change is when two or more of the elements are affected through a change of technology. An example of a radical technological change is a transition from a fossil based energy system to an energy system based on RES, where all five elements are affected.

In Denmark this transition is now undergoing and has required investments in energy conservations, distribution and production from CHP plants together with utilizing biomass, wind turbines and solar energy. Denmark is still in the process with the overall goal of being CO_2-neutral by 2050. Many initiatives need to be implemented along the way and new technologies may be invented.

2.1.2 Choice Awareness Strategies

Choice Awareness can be promoted by four strategies that lead to a society where public awareness is enhanced and new alternatives are considered. In Figure 2.1 these strategies are presented, and explained in the following sections.

1. Technical Alternatives: The design, description and communication of technical alternatives are the first step to change focus in the public discussion. The promotion of technical alternatives is an important factor in raising awareness in society and change the general perception.

2. Feasibility Studies: Traditional neoclassical market economy is based on the concept of free market and assumptions which do not fulfill the real life market economics. The economy should therefore be seen as an institutional economy where feasibility studies include the design of feasible technological alternatives, an evaluation of the social, environmental as well as economic costs, an overview of the innovative potentials of these alternatives and an analysis of the institutional conditions that influence the implementation of the different alternatives. Thereby the feasibility studies reflect the actual reality of society and the economic movements better than the free market concept will be able to.

3. Public Regulation: The purpose of public regulation is to reach a situation, where the actors on the market act in accordance to what is best for society, i.e. to assure that the solution that is best for society also is the best solution from a business economic perspective. This is done by balancing the socioeconomic feasibility studies to business economic feasibility studies.

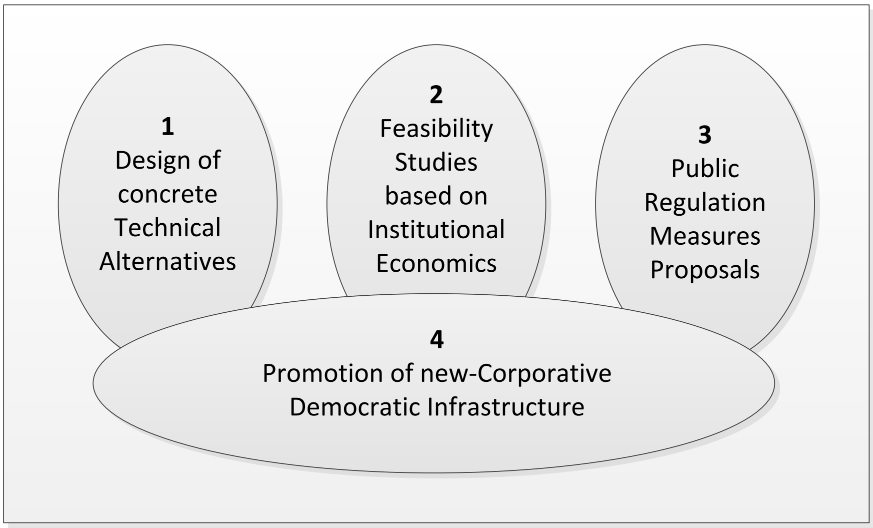

Figure 2.1: Choice Awareness Strategies (Lund 2009).

4. Democratic Infrastructure: A new-corporate democratic infrastructure is necessary to exert the three before mentioned strategies. A new-corporate democratic infrastructure is constituted by the representatives of future societal interests and representatives of potential new technologies, like citizens, NGOs companies and politicians.

This project does not handle all these four strategies in depth but is seen as a contribution to these. In this project some technical alternatives are presented in Chapter 3 with technical and economic characteristics in order to compare applicable technologies. These applicable technologies are used in the two case studies of Eastern Denmark and CTR, where TES is combined with either HP or EB in different alternative scenarios, described in Chapter 6. Socioeconomic feasibility studies are carried out on all scenarios in Chapter 7 and 8, where the technical results of each case study are shown as well. The boundaries of the feasibility studies have been set in order to reflect the costs of the modeled society and it is important to be aware that not all costs are included in these calculations. Public regulation is just briefly discussed and how to create a new-corporative democratic infrastructure is not handled, but are seen as equally important in increasing the public choice awareness.

2.2 Methodology

In this section the specific methods used in the project are presented. For each method a description of the method and the purpose of using it is given followed by an explanation of how and for which part of the projects this method is applied.

2.2.1 Interviews

The conducted interviews are performed as semi structured mainly qualitative interviews. Using this specific method allows the interviewers to follow an interview guide, while at the same time being open to new information and alternative perspectives from the interviewees, i.e. making room for additional comments or input and being open for discussions on subjects that may not have been considered (Andersen 2005).

All interviewees are supplied with an agenda for the interview which also serves as interview guide. This is send to the interviewees some days before the interview, in order to give the interviewees time to prepare for the interview. For each interview the main ideas of this project are described to the interviewee at the beginning of each interview, in order to ensure a common understanding of the purpose of the project. The rest of the interview guides are individually designed.

The purpose of the two first interviews with Jørgen Hvid and Anders Brix Thomsen is to gain some specific knowledge about thermal and seasonal energy storage and its application in the Danish context and the plans and potentials in the area of Copenhagen. These are performed at an early stage of the project where all the details of the project and the analyses are still not certain. The interviews contribute to the project by refining the scope and the focus of the analyses in the project. The purpose of the last interview with David Magnusson from CTR is to get some detailed and more technical considerations regarding the outcome of the project, but also to get some specific data input for the analyses.

Jørgen Hvid is engineer and employed as chief consultant at Rambøll in Copenhagen. He is working with planning projects for the DH systems in the Copenhagen region and has a lot of knowledge about this through several years of experience, which is why it is chosen to interview him for this project. Anders Brix Thomsen is working in Copenhagen Municipality as Climate and Energy Coordinator and one of his main responsibilities is the efforts by the municipality in reaching the goal of being CO_2 neutral by 2025, which is the reason he is interviewed for the project. David Magnusson is engineer and working in CTR with the planning of the DH system and he is also involved in the process of the "Heat Plan of the Capital Region"-project. This is further described in Section 5.4 on page 39.

2.2.2 Numerical Modeling

The role of the numerical modeling tools in the analysis is to give a picture of the potential of implementing TES combined with HP or EB for a specific energy system. This will show how implementation of the technologies impacts the system where it is implemented. In the analyses two different computer modeling tools are applied to give two different perspectives on the impacts and potentials. EnergyPLAN is used to model the East Denmark region and will provide a large scale energy systems perspective. The other software, EnergyPRO, is used to analyze the details of the impact of implementing the technologies in the CTR DH area. Finally the findings of the two parts of the analysis will be compared and discussed.

Setup of Scenarios: The Danish Energy Agency states that a pivotal step of analyzing energy projects is to set up scenarios, including the limitation of the project by defining the reference situation, which the alternatives will be compared against (DEA 2007). This is also mentioned in the Choice Awareness (Lund 2009) and therefore a reference model is set up for each of the two analyzed systems. As a reference year 2025 is chosen because this is when Copenhagen expects to be CO_2 neutral, and the expected development is projected to 2025. The different analyzed changes are then implemented in the reference model whereby the results can be compared.

The reference models for the two analyzed systems are different in a number of ways which are important to keep in mind when comparing the results between the two models. The CTR system is one small case selected within the East Denmark region because the Copenhagen Municipality has ambitious CO_2 reduction targets for the energy supply. This means that in the CTR almost no fossil fuels are expected in the energy supply in 2025 whereas in East Denmark in general there is still expected a significant amount of fossil fuels in energy supply 2025. This gives two different starting points for the analyses and it gives an opportunity to identify if there is a better potential in implementing TES in CTR than in East Denmark in general. The details of the scenarios are presented in Chapter 6 on page 43.

EnergyPLAN: EnergyPLAN is chosen for modeling of the regional system of East Denmark, since the program is designed for analysis of larger national and regional energy systems. EnergyPLAN is available for free to download and is published by the Department of Development and Planning at Aalborg University. It is a deterministic model structured by input and output, and the model provides the user with a technical analysis and the total costs of the scenarios. By this, the user gets an overview of the operation of the system on an hourly basis, as well as the CO_2 emissions and annual costs. (Lund 2009).

The EnergyPLAN model and its application are explained in detail in Section 6.4 on page 45, the results of the analyses are presented in Chapter 7 on page 51 and the data in- and output is given in the Appendices A on page 105 and B on page 119 respectively.

EnergyPRO: EnergyPRO has been chosen for the analysis of the transmission system of CTR, since it is a modeling program that can be used to analyze complex energy system systems including economic analysis with a high level of detail. EnergyPRO allows the hourly optimization of the modeled energy units according to fixed tariffs for electricity or against the spot market prices, which is used in this project. EnergyPRO provides an overview of the hourly operation of the modeled production units and data reports for emissions of the modeled system. The data output from the model includes presentation of operation strategies, revenues and expenditures, energy balances and operation costs (EMD International 2012).

A detailed description of EnergyPRO and its application in this projects is given in Section 6.5 on page 48. A description of the specific assumptions, calculations and result of the analyses using this model is provided in Chapter 8 on page 71. Further details for input and output data, and references are provided in Appendix C on page 125 and D on page 133 respectively.

2.2.3 Literature Review

Literature review is used in certain phases of the project to build knowledge about TES and other applied technologies, the energy systems in East Denmark and CTR and about the history and political development about relevant issues. All the important information from references are as far as possible cross checked with other references to verify and make sure that the information is reliable. For the technology data from the Danish Energy Agency, DEA (2012d), is used as the main source as far as possible in the project, but in most cases supplemented or cross checked with other sources.

In the collection of data for the numerical models DEA is also the main source, but different reports, statistics and documents have been used. In some points other sources are used though because of a higher level of detail or because no data about a certain issue are found from DEA. For example electricity production, demand and projected demand are used from Energinet.dk, because the level of detail in the available data is better here. Generally, it is the aim to use as few different data sources as possible to avoid inconsistency in the used data.

Thermal Energy Storage and Electricity Conversion 3

This chapter describes thermal energy storage (TES) by theoretical characteristics and following considerations of how TES is applied in this project including a delimitation of which technologies will be applicable for this study. Four applicable technologies for thermal energy storage are presented and technical characteristics used for these technologies in the analyses are presented. Hereafter the heat pump (HP) and the electric boiler (EB) technology is presented together with technical and economic characteristics which are used in the analyses as well.

3.1 Classification of Thermal Energy Storage

The idea of TES is to store an amount of energy over time and thereby detaching the energy production from the demand. When the energy production can be out of sync with the demand it gives a flexibility to utilize other sources of energy that is not in sync with the demand. Thermal energy is available many places both naturally like solar heating or geothermal heat, or as a waste product from electricity production, industrial processes or waste incineration. These are sources that can be utilized, but the production is not in sync with the heating demand and hence a storage will enable these sources to cover a later demand and hereby save the dispatchable resources that alternatively would be used.

As described the purpose of a TES is to store an amount of energy to a later time where there is a need for it. This is basically done by charging the storage with an input of thermal energy and discharging it at a later time by having an output of thermal energy. There are many ways of doing this for different situations. TES differ on energy/temperature level, time horizon of storage and physical storage medium and these different characteristics gives different possibilities of application. Figure 3.1 on the following page illustrates some of the important criteria of a TES and the three important points of distinction between different TES, which are described as follows.

Temperature level: A TES can be used to store energy for either heating or cooling so that if the storage temperature level is high it can be used for heating and if it is low it can be used for cooling. In some cases the same storage can be used for both purposes e.g. storing energy at a high temperature level in the summer for heating in winter and opposite storing energy at a low temperature level in the winter to use for cooling in the summer. (Lee 2013)

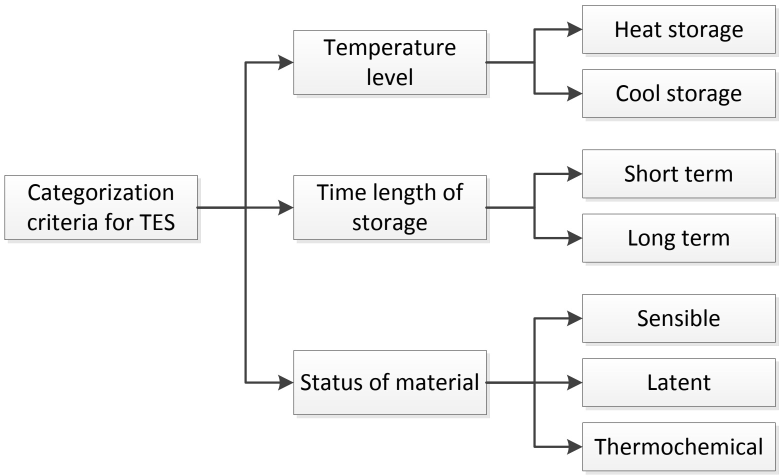

Figure 3.1: Criteria for TES in the three groups; temperature level, time length of storage and status energy storage material. (Lee 2013)

Time length of storage: In the figure short term and long term are suggested, but of course there will be many options in between. The time length the storage can cover depends on the requirements and the design of the specific storage. Short term storages can be used to level out fluctuations of production and demand over a day or a week. Long term storage can be used to store energy over months, from one season to another. This is also what is called seasonal storage. (Lee 2013)

Status of energy storage material covers three specific types of storage. Sensible heat storage is basically when the energy is stored by changing the temperature of the storage material, so in a heat storage to increase the temperature and thereby storing the thermal energy in the volume of the storage material. Latent heat storage is when the storage is using a change of phase in the storage material and in this process using the phase change energy as storage. E.g. when a material is melting, changing phase from solid to liquid, it takes some energy and conversely when the material freezes again, changing phase from liquid to solid, it releases some energy. In this way the material can have a rather constant temperature during charging and discharging, but sensible and latent storage can also be combined in one. The last type mentioned is thermochemical storage which is when a chemical process is utilized to store the energy. This is usually by splitting a substance into two components that can be stored separately by applying thermal energy, when charging the storage, and bringing the two components back together which releases thermal energy. (Lee 2013)

In this project the focus is on the potential of integrating large scale TES into the DH systems. Therefore it is chosen to focus on heat storages and not cool storages or combined heat and cool storages even though there might be a good potential here as well. Regarding the time length of the storage it is not necessarily only long term or only short term, but more like a combination of the two. The type of TES will be sensible heat storage. The other options have a potential as well, but they are currently being developed and are not cost effective compared to sensible heat storage. There will also be other factors to consider such as space requirements, but it is chosen to prioritize sensible heat storage. (Lee 2013)

3.2 Applicable Technologies for TES

The choice of technology for TES is highly dependent on the context in which it is to be implemented. As described above there are several criteria to consider in this regard. For the case of heat storage in DH systems, as for this project, there are a limited number of proven technologies available. According to (DEA 2012d) and (Harris 2011) there are currently four different relevant technologies of TES to consider for implementation in Denmark. These are tank, pit, aquifer and borehole TES. In Denmark there are mainly experience with tank TES and pit TES, (Harris 2011) but in the following sections the four different technologies are handled to give an overview of the different options. The question if there is a HP connected to discharge the store or not has a rather large impact on the total efficiency of all the technologies since the HP can boost the temperature to the required level for DH supply (DEA 2012d). Heat pumps are handled separately in Section 3.3.

3.2.1 Tank Thermal Energy Storage

A tank thermal energy storage (TTES) is a tank typically made of stainless steel, concrete or glass-fiber reinforced plastic. The tank is filled with water which works as the physical storage medium. TTES can be located above ground level which is the most common case, but it can also be located under ground level. See Figure 3.2 and 3.3. The tanks are insulated according to their environment and application, typically with 30-45 cm of mineral wool to keep the heat losses low (DEA 2012d). In the tank there is a vertical temperature distribution so that the temperature in the top of the tank is high and the temperature in the bottom of the storage is low. This serves to keep a high efficiency of the storage. In Figure 3.2 the grey background tone indicates the temperature where the darker tone the higher temperature. To manage the temperature distribution in the TTES, a distribution system is installed which in Figure 3.2 is indicated in the blue pipes. Depending in whether the storage is above or under ground level it will more or less dominant in the landscape and if the storage is under ground the surface area can even be used for other purposes as well.

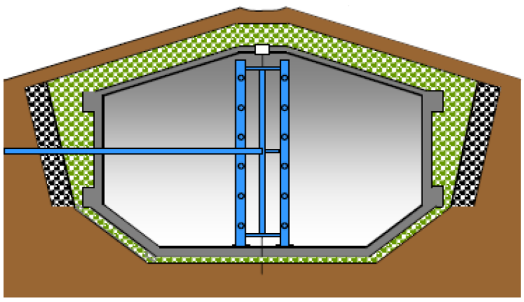

Figure 3.2: Cross sectional drawing of underground TTES. (DEA 2012d)

Figure 3.3: Picture of TTES at the central CHP plant Avedorevaerket. (Brandenborg 2008)

TTES is the most commonly used TES technology in Denmark. The majority of DH plants have TTES connected to balance the supply and demand of heating. The capacity of the plant can be designed more efficiently if there is a TTES connected to and a TTES also allows the plant to operate on the electricity spot market (Harris 2011). The development of TTES at CHP plants and the electricity market is described further in Chapter 4 on page 25.

The sizes of the used TTES in Denmark are typically between 1,000 m^3 and 5,000 m^3 and the specific capacity of the storage is 60-80 kWh/m^3 depending on the use of the storage. Even though TTES is usually applied for relatively small volumes the largest tanks are above 50,000 m^3. The efficiency also depends on the temperature level in the storage, the insulation level and the volume/surface-ratio, but when operated between 50°C and 90°C it will typically be around 95%. The TTES is rater flexible with regard to charge and discharge and by the vertical temperature distribution it is able to keep a supply temperature at 90°C. Economy-of-scale applies for the TTES up to a size of around 50,000 m^3 where a facility of 1,000 m^3 costs around 1,800 DKK/m^3 and for a storage of 50,000 m^3 the costs are around 520 DKK/m^3 (DEA 2012d).

3.2.2 Pit Thermal Energy Storage

A pit thermal energy storage (PTES) is a large pit dug in the ground fitted with a membrane, typically of plastic, on the bottom and walls of the pit to keep the storage from leaking. Like for the TTES, the PTES is also using water as the storage medium. The pit is covered with an insulating lid to reduce the energy losses from the storage which can be floating on the surface of the water. The side walls and bottom of the storage are often not insulated because the ground material, soil or sand etc. has an insulating effect itself and the additional costs for improving the insulation are not covered by the reduced energy losses (DEA 2012d).

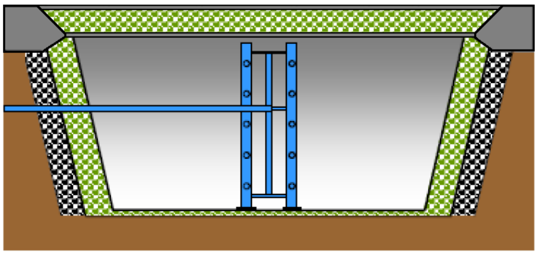

Figure 3.4: Cross sectional drawing of a PTES (DEA 2012d)

Figure 3.5: Picture of a PTES construction in Marstal (PlanEnergi 2012)

Similar to the TTES, PTES also has a vertical temperature distribution in the storage to increase the total efficiency of the storage. See Figure 3.4. The same kind of system to manage this temperature distribution is also fitted here and indicated in the blue pipes in the figure. In Figure 3.5 is show a picture of a PTES during the building process. Here it is also possible to see the pipes for the temperature management system. The PTES requires a relatively large amount of space because of the dimensions, but if the lid is constructed for it, it will be able to carry a significant weight, e.g. for a parking lot. A weight carrying lid construction will significantly increase the investment costs though (Hvid 2012).

For large scale TES this is the most common technology in Denmark even though the technology is still in an initial phase. PTES is currently used and planned for use as seasonal storage in conjunction to solar thermal DH production. In Marstal there is in total 85,000 m^3 of PTES installed where the first 10,000 m^3 have been operated for several years and the additional 75,000 m^3 is recently constructed. In the case of Marstal the coverage of solar thermal energy for the district heating supply is around 55 % (Marstal District Heating 2012). In Dronninglund the construction of a PTES of 60,000 m^3 is being constructed (Torp 2012), (Pedersen 2009) and in Gram a large storage of 110,000 m^3 is being planned (Goodstein 2012).

The sizes of the used PTES in Denmark as mentioned are between 10,000 m^3 and 110,000 m^3 and the specific capacity of the storage is 60-80 kWh/m^3 like for TTES. The efficiency depends on the temperature level in the storage, the insulation of the lid and the volume/surface-ratio and whether a heat pump is used to discharge the storage, but will typically be between 80% and 95%. Economy-of-scale also applies for the PTES up to a size of around 50,000 m^3. The expected costs for a storage of 60,000 m^3 is around 260 DKK/m^3 (DEA 2012d).

3.2.3 Aquifer Thermal Energy Storage

An aquifer is a permeable underground geological layer that contains ground water. An aquifer thermal energy storage (ATES) consists of at least two wells into the same aquifer with a sufficient distance between them. The one well is called the hot well because here is the hot water injected to charge the storage and to discharge the storage hot water is extracted from this well. The other well is called the cold well because cold water is injected when the storage is discharged and when charging the storage cold water is extracted. This is illustrated in Figure 3.6 where the grey background tone indicates the relative temperature level. The left well in the figure is the hot well and the right is the cold well.

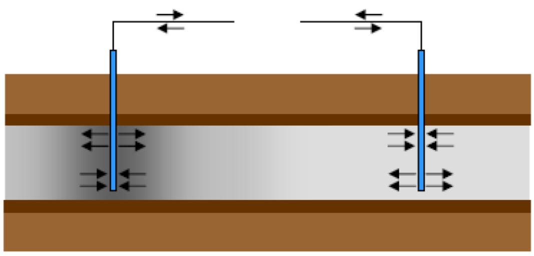

Figure 3.6: Cross sectional drawing of an ATES (DEA 2012d)

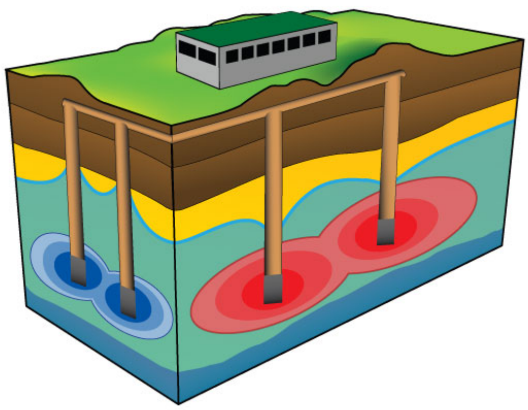

Figure 3.7: Three-dimensional drawing of ATES (SPL Beatty 2013)

Figure 3.7 shows a three-dimensional drawing illustrating how the ATES is located in the ground. The physical storage medium is partly the water that is injected into the well and partly the material of the aquifer. Insulation of the storage itself is not necessary for ATES since the energy is store at a depth where the natural temperature level is constant and not affected by the weather or seasonal changes. Unlike the other technologies described in this chapter ATES directly extracts the ground water, it passes through a heat exchanger and is injected into the ground again. This makes it necessary to consider the security of the ground water resources when using this technology. The space requirements for ATES are not big since it only needs few wells, but it still can be difficult to find the space in dense urban areas. (Lee 2013)

There is currently no application of ATES in Denmark and no planned projects have been identified. In Sweden ATES is a commonly used technology which is mainly used at building level, but also for HP supply. It has also been indicated that there is a potential for using the technology in Denmark the same way (Harris 2011).

ATES systems are mainly applied in low capacity systems for one or a few buildings. Since 2000 in the Netherlands a few case of application for DH supply have been developed. The capacities are usually between 0.5 and 2.0 MW, but the largest facility in the Netherlands has a capacity of 20 MW. For an ATES 60% of the stored heat can be recovered or more depending on the circumstances (Underground Energy 2011). Regarding the costs of an ATES system it is found that the initial investigation costs and maintenance costs are higher than for borehole thermal energy storage (BTES), see Section 3.2.4, which often is the direct alternative. On the other hand ATES has a higher efficiency and a lower general investment cost than BTES so if it is applicable under the given conditions ATES is preferable to BTES. An example of the costs of an ATES system is for the Norwegian airport Gardermoen, where an ATES supplies 7 MW heating in the winter and 6 MW cooling in the summer. The investment cost was 17.2 M DKK and has an annual supply of 11 GWh (Lee 2013).

3.2.4 Borehole Thermal Energy Storage

A borehole thermal energy storage (BTES) consists of a number of boreholes dug in the ground in which pipes are placed. The storage is charged by pumping hot water through the pipes in the boreholes which then transmits thermal energy to the material in the ground surrounding the boreholes. Figure 3.9 shows a three-dimensional drawing illustrating how the BTES is located in the ground. When discharging, cold water is pumped through the pipes in the boreholes and the stored energy in the ground is absorbed in the water and can be used for heating. The storage medium here is the material in the ground surrounding the boreholes and not the water in the pipes which is just a transfer medium. There is usually a layer of insulation on top of the area where the boreholes are located to reduce heat losses.

BTES is not a common technology in Denmark, but in 2012 the first case of BTES was put in operation in Brædstrup for DH supply in conjunction with a large solar thermal capacity (Energy Supply DK 2012). The facility consists of 48 boreholes of 45 m in depth with a total storage volume of 19,000 m^3 and increases the solar thermal supply to 20% annually (Brædstrup District Heating 2012). The borehole storage is the largest BTES facility for DH in Europe and if the initial installation shows good results it might be expanded further to 300-400 boreholes and together with an increased solar thermal capacity cover 60% of the annual heating demand (Rehau 2012).

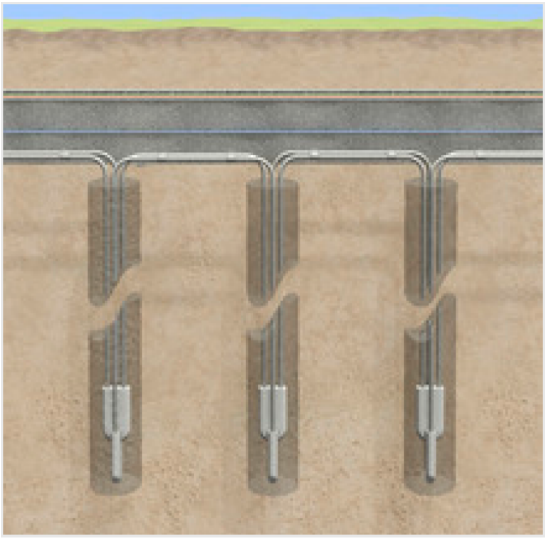

Figure 3.8: Cross sectional drawing of a BTES (Rehau 2012)

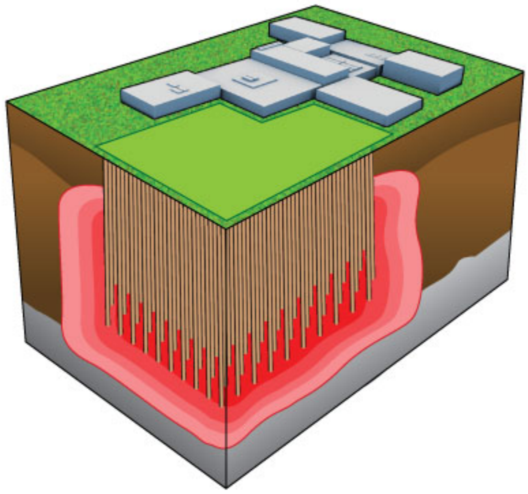

Figure 3.9: Three-dimensional drawing of BTES (SPL Beatty 2013)

The capacity of BTES can be anything between one borehole for the use of one single household to large scale storages of several hundred boreholes. The specific capacity of the systems is estimated to being 15-30 kWh/m^3 of storage material (DEA 2012d). The efficiency depends a lot on the size of the storage. For small systems the efficiency can be as low as 60% where for large systems of above 100,000 m^3 the efficiency can reach 85-90%. The charge and discharge effect is limited by the convection from or to the storage material in the ground and the transferring medium in the ground pipes and this is why BTES mainly is used for base load capacity. The investment costs are sensitive to the ground properties of the location where the storage is to be constructed. Since it requires many boreholes for large facilities a difficulty in drilling the boreholes can increase the investment costs significantly. An example is a BTES in Norway for a hospital used to supply both heating and cooling with annual supply of 26 GWh and 8 GWh respectively. The storage consists of 350 boreholes of 200 m and the total investment cost including piping and a HP was 112 M DKK (19.5 MUSD). (Lee 2013)

3.2.5 Summary of TES Technologies

In Table 3.1 on the next page the key parameters mentioned in the sections of the four technologies above are summarized to give an overview and comparison between the technologies.

For large scale TES, PTES has the advantage of lower specific investment costs compared to TTES, which are similar in many other characteristics, they both use water as storage medium, have relatively high efficiencies and high charge/discharge capacities. The area requirements are the most significant disadvantage of PTES. ATES has the lowest investment costs of the assessed technologies, but it requires a suitable aquifer and BTES on the other hand can be implemented more independent of the geological properties. The BTES has higher investment costs that ATES though because of the higher number for boreholes. Another issue with BTES is that it has a relatively low charge/discharge capacity which can be a problem depending on the specific application of the technology.

	TTES	PTES	ATES	BTES
Storage medium	Water	Water	Ground water and aquifer material	The material surrounding the boreholes
Capacity [MWh]	60-400	600-80,000	11,000*	34,000**
Efficiency	95 %	80-95 %	60-95 %	60-95 %
Specific investment costs [DKK/MWh]	6,500-30,000	3,300-6,000	1,600*	3,300**
Advantages	High charge/discharge capacity	High charge/discharge capacity and low investments costs	Low investment costs	Most underground properties are suitable
Disadvantages	High investment costs	High area requirements	Requires initial geological investigation and a suitable aquifer	Low charge/discharge capacity

Table 3.1: Summary of key parameters regarding the four assessed technologies. */** Data from specific projects in Norway where both heating and cooling capacities have been utilized.

3.3 Technologies for Conversion of Electricity to Thermal Energy

To be able to balance the electricity production in a future sustainable energy system as suggested in the introduction a capacity for conversion of electric energy to thermal energy is required. Here the two relevant technologies, according to (DEA 2012d), for this purpose are presented and described. The two technologies are electric HP and EB.

3.3.1 Heat Pumps

There are two types of HP, an electric heat pump and an absorption heat pump. The electric HP uses electricity in a pump as the drive energy whereas the absorption HP uses a high temperature heat source as the drive energy. Since the absorption HP does not use electricity it cannot help the purpose of balancing the electricity production and therefore it is not considered here even though it might be a good solution for some cases. From here, electric HP are just referred to as HP (DEA 2012d).

The purpose of a HP is to transfer energy between two systems from a low temperature level to a higher temperature level so the temperature of the 'hot' system is increased and the temperature of the 'cold' system is decreased. The heat source for a HP can be ambient temperatures from the ground, a river or the air or it can be waste heat from exhaust gasses, industrial processes or waste water treatment facilities (DEA 2012d). Depending on the temperature of the heat source and the required output temperature of the HP, the system will have a certain coefficient of performance (COP) which is given by the following equation:

$$COP = \frac{Heat\ output}{Energy\ input} = \frac{T_{hot}}{T_{hot} - T_{cold}} \tag{3.1}$$

T_{hot} [K] is giving the output temperature and T_{cold} [K] is giving the input temperature of the heat source. E.g. with an input of 10°C (283.15 K) and output of 80°C (353.15 K) the COP is 5.0 which means that with an input of 1 unit electricity there will be an output of 5.0 units of heat. This is a theoretical value, the so called Carnot efficiency, but in reality this would be lower because of losses in the system (DEA 2012d).

There are not many applications of HPs in Denmark today because of a tradition in the energy planning of limiting the use of electricity for heating purposes. The levies on electricity for heating have been high which have limited the use to a minimum. (Harris 2011) A new legislation from January 1^{st} 2013 reduces the levy on electricity for heating for companies by more than 50% from 0.526 DKK to 0.233 DKK (Ingeniøren 2012). The Danish District Heating Association expects that this will give an incentive for district heating plants and industries with waste heat to implement HPs for DH production since these will have a good heat source for the HP and thereby might be able to reach a high COP with a HP (Ingeniøren 2012).

Large HPs are available at capacities from 25 kW to 3-5 MW heat output. Larger HP capacities will typically be more HP units connected in parallel. HPs can be regulated continuously and can start from cold to full load in less than 5 minutes. The efficiency of a HP will usually be around 50-65% of the theoretical COP. The COP will vary between 2.5 and 6.3 depending on the temperature and the cooling of the heat source and the required output temperature (Harris 2011). The investment costs, variable and fixed operation costs for HP can be found in Table 3.2 on the following page.

3.3.2 Electric Boilers

An electric boiler is a technology that simply converts electric energy to thermal energy by heating up some water. There are basically two technologies for EBs. The one is by applying an electric resistor located in a water container which is the same concept as electric kettles used in kitchens. The other technology is by using electrodes. This system consists of three-phased electrodes and a neutral electrode located in a water tank and the electric current flows directly through the water which here by is heated (DEA 2012d).

Like for the HP, EB have not been used much in Denmark for heat production because of the levies to avoid electric heating. In 2008 a new law for a limited period of time was passed in the Danish parliament reducing the levies on electricity used in EBs for DH to make a better use of occurring overproduction from wind turbines. Since then a number of DH plants have invested in EBs to get a benefit from the occasionally very low electricity prices, and the law was made permanent in 2009 (Danish Ministry of Taxation 2009). The EB enable the plant to operate on both the Nord Pool Spot-market and regulating power markets because the boilers can start, stop or regulate the load on very short notice (DEA 2012d).

The efficiency of EB is close to 100% or equivalent to a COP of 1 which is low compared to a HP. The investment costs for a 10 MW boiler will be 450-670,000 DKK/MW and one of 20 MW will be 370-520,000 DKK/MW which also is low compared to a HP (DEA 2012d).

The data for the EB and HP is seen and compared in Table 3.2 . It is clear that the investment costs for HP are higher, but the COP of the EB is lower. The full list of costs and other data input can be found in Appendix A on page 105 and C on page 125.

Parameter	**EB**	**HP**
Investment [M DKK/MW-e]	0.52	20.14
Fixed operation [DKK/MW-e]	8,200	40,200
Variable operation [DKK/MWh-e]	3.7	2.0
Life time expectancy [years]	20	20
COP	1.0	1.95/3.0

Table 3.2: Specific costs for HP and EB (DEA 2012d).

The Danish Energy Supply 4

This chapter gives an overview of the Danish energy supply system with a focus on the aspects that affect the technologies of study in this project; TES, HP and EB and the feasibility of these. The purpose is to provide a foundation for the analyses and the output of the chapter is some central assumptions for the analyses in Chapter 7 and 8. In the chapter three main areas are covered; the electricity system, DH supply systems and national political goals for the development of the energy sector, but first the historical development within these fields is briefly presented to give an indication of why the systems are as they are today and how the development can be expected in the future.

4.1 Historical Development in the Electricity and Heat Supply

Due to lack of fuels during World War I, new electricity plants were built, including plants based on wind and water power. Later, the electricity system expanded to include more than 500 small electricity companies primarily based on oil. This became a problem during World War II when the oil import was ceased and the electricity system was changed to fewer and bigger steam based power plants that were based on coal and domestic fuels. At this point the utilization of the waste heat from the electricity production was very limited (DEA 2012b).

The centralization continued and all minor electricity plants were closed down until and around 1970. Despite the limits to the oil import during the war, the production based on oil continued and had a share of 80% of the fuel at power plants up until the oil crises in 1973 and 1979. The first DH plant was built at Frederiksberg Hospital already in 1903, but the first major public heat installations were developed in Copenhagen in the 1930s, based on surplus heat from the local power production and the public heat supply expanded rapidly in all bigger cities in the 1950-60s. The oil crises led to an active political involvement in the energy sector which had not earlier been seen (DEA 2012b).

4.1.1 Political Involvement in the Energy Sector

By the first heat supply law from 1979 around 700,000 DH installations were already in place, but the law had the purpose to increase the use of DH to improve the energy efficiency and reduce the dependence of import of oil which had been the problem in the oil crises. This was followed up by an energy agreement in 1986, mainly with the purpose to improve the coproduction of heat and electricity. With this agreement authorities were also given the power to implement mandatory connection in areas with NG or DH supply to give a security for the investments in the needed pipe systems. In 1988 a new law was passed, prohibiting electric heating within the areas with access to public heat supply, also to use the resources more efficiently (DEA 2012b).

The heat supply law was revised in 1990 and should ensure that heat supply could adapt to future tasks in the public heat supply. The agreement included a conversion from pure DH production on mainly oil and coal to a production where oil, coal and natural gas as far as possible is used CHP production and use of biomass at the decentralized plants without natural gas available. To further motivate the development of local CHP a premium per kWh of power production of 0.10 DKK was introduced in 1992. These two policies paved the way for towns in the size of 500 to 40,000 inhabitants to implement CHP based DH systems (DEA 2012b).

Recently a new policy regarding HP has led to a reduction of the levies on its electricity consumption. Ingeniøren (2012) acknowledge the potential in large-scale HP, which is capable of converting waste heat into DH, leading to a more efficient use of fuel and at the same time integrate large share of wind production into the energy system. What has so far been a barrier in the investment in this technology is the economy because of high tariffs on electricity for heating purposes. In the finance act proposal in 2013 is a law propound to reduce the energy tariff for electricity used for heating purposes from 526 DKK/MWh down to 233 DKK/MWh. According to John Tang, Consultant from Dansk Fjernvarme, who is cited in this article, this is what, is needed in order to expand the use of waste heat from the industry. John Tang further states that the potential is significant and refers to a report made by the Danish Energy Agency in 2010 which showed an estimate for 70 of the major companies included in the EU ETS that could deliver enough waste heat to supply 46,000 households with DH. If the potential of waste heat from decentralized CHP plants is included, it is around 174,000 households that can be supplied in this manner. The waste heat from the flue gas in the decentralized plants is a foundation for implementation of 100 MW controllable HP capacities.

The focus here is on the importance of designing regulation rules in order to promote the use of the HP technology to reach the benefits from more efficient fuel use and integration of fluctuating wind power. If it is not economically beneficial to implement HP in the system, the technology is not likely to be implemented. The article therefore underlines the importance of political decisions and the influence this has on the investments that are made.

4.1.2 Triple Tariff and Market Based Electricity Pricing

The tariff periods and prices are set in accordance with the law by the companies that are responsible for ensuring the electricity supply. The price is calculated by Danish Energy Agency. As an example, Table 4.1 shows the used time-period tariffs in the first half of 2002 (DEA 2005).

	Low load	**Medium/high load**	**Peak load**
Time of day	Night	Day, except peak hours	Morning and evening
Price [DKK/kWh]	0.21	0.45	0.57

Table 4.1: Time-period tariffs used in the first half of 2002 (DEA 2005).

Since the implementation of the triple tariff, especially the decentralized CHP plants have become experienced in optimizing the electricity production against this tariff and are organizing the production according to when to start and stop the CHP units in order to maximize the profit. The design of the CHP plants has also been optimized and most plants have invested in TES capacity to increase the performance and optimize production (Lund and Andersen 2005). This is a clear example showing that the heat and electricity production have become closely connected since a regulation in the electricity sector has the effect that TES capacity for DH is being implemented in large numbers.

Until the late 1990s the Danish electricity sector was in reality a monopoly, where production and supply was not regulated by market forces, which is to some extent still the case for DH. Mainly due to a pressure from the manufacturing industry and others that wanted to be able to freely choose electricity supplier reorganization in the electricity sector took place. The newest Energy Agreement from 2012, mentioned in Section 4.4, includes a number of activities that aims at improving the possibilities of the electricity market to deal with the fluctuating electricity production from wind turbines and other RE electricity producers (DEA 2012b).

4.2 Electricity Supply

The electricity system and how it works is important to understand in relation to TES and the area of study in this project because TES combined with HP or EB is highly influenced by the electricity market and prices. Implementation of RES and the fluctuations in the electricity price is here a key issue.

The task in balancing the electricity production in Denmark is becoming more complex as more fluctuating RE enters the system. Electricity is traded both bilaterally and via the Nord Pool Spot Market (NordPool) and the electricity supply in Denmark is linked to the rest of Europe via interconnectors which means that the RE production in the neighbor countries is affecting the electricity prices in Denmark as well. Figure 4.1 on the next page shows the Danish electricity system and the international connections.

4.2.1 The Nord Pool Spot Market

In 2012 77% of the total electricity consumption in the Nordic countries was traded on the Nord Pool Spot Market, corresponding to 432 TWh. The rest is traded on the regulating power market operated by the TSO or through bilateral contracts. The Eastern part and the Western part of Denmark are treated as two different bidding areas, which mean that the prices in the two different areas are not always the same. The prices are calculated based on supply, demand and transmission capacity.

A transmission market at the size of the Spot Market should be able to balance power prices at all times, but when constraints or unbalances occur, this is handled by letting the power flow from a low price bidding area to a high price area. According to (Nordpool 2012) this is right for society, since the commodity then move toward a high price where the demand for power is highest. Despite of this system, there are sometimes seen problems with under- or over-supply leading to very high or very low electricity prices. Some electricity can even be traded at negative prices, which for instance was seen in some hours in January 2011, to avoid market rejection for oversupply. With the negative prices power producers either have to pay for the electricity supplied to the market or they will have to adjust the production to the demand. In Denmark, the negative prices are expected to give an incentive to the CHP plants to adjust their production, since wind power producers have no fuel costs and are typically guaranteed a feed in tariff (Energinet.dk 2012c). This means that the production from wind turbines can force the prices to be very low or even negative when the wind is blowing a lot. If the wind production capacity is increased this tendency can be expected to be enhanced.

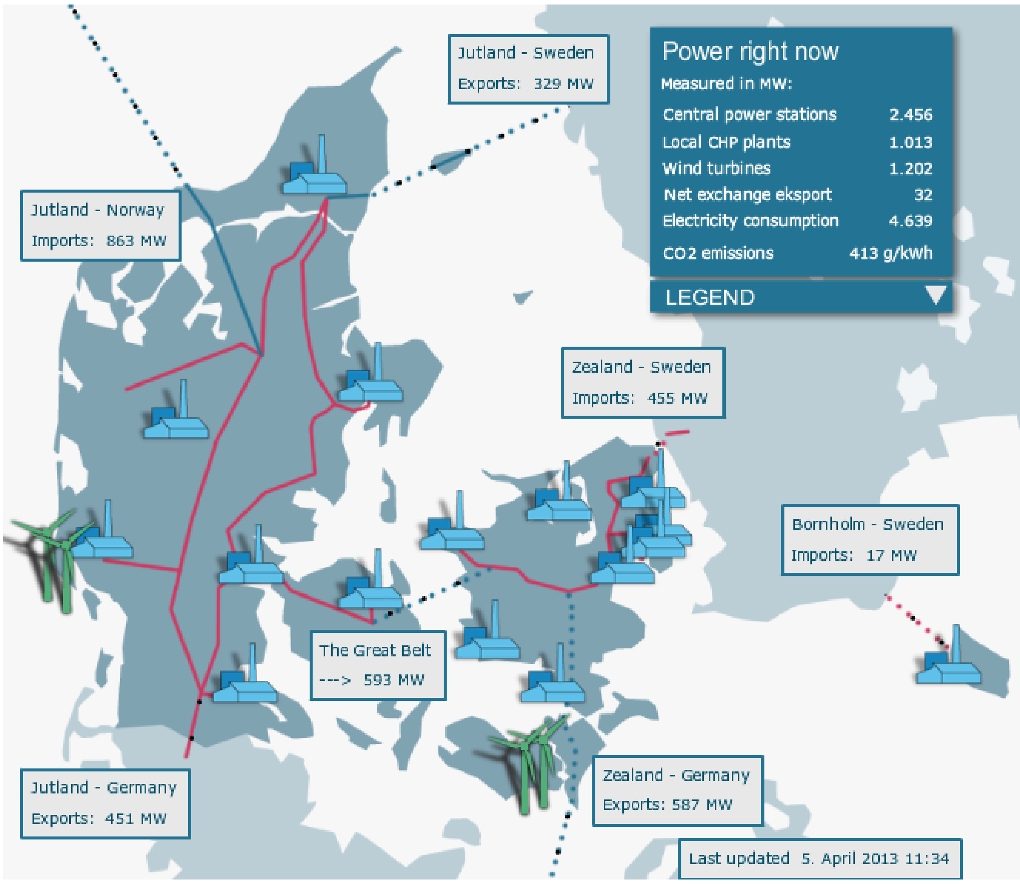

Figure 4.1: The power supply in Denmark, 5th of April 2013 (Energinet.dk 2012a).

4.2.2 Potentials Development in the Electricity System

With the visions of more RE in the system, see Section 4.4, more flexibility in the electricity system is necessary and there are several opinions on how this can be achieved. In Energinet.dk (2011c) it is suggested to integrate significant storage capacities in the electricity and overall energy supply through HP, the DH system and electric cars. The report points out the challenge of integrating significant amounts of RE in the transmission system and gives perspectives on how to solve and manage these challenges:

- Integration at international level of increased RE by expanding the international connections
- Combine the electricity system with the remaining energy systems, where heat is mentioned, to give additional flexibility at daily and longer term perspectives in combination with other technologies like smart grid in the transport sector

It is important in the overall energy supply to utilize the fluctuating electricity production in a cost effective way, especially in the transmission where the challenges are significant with the higher RE share. A concerted planning strategy of the electricity system with other energy systems like transport, heat and gas, is necessary. Here, transportation and heat is thought to help increase the flexibility at daily basis, heat at weekly basis and the gas system can provide high flexibility and integrate seasonal variations. The development of Smart Grid is appointed as a key element to achieve increased flexibility in the electricity system when higher shares of RE is integrated. (Energinet.dk 2011c)

In Lund et al. (2012) it is stated that the electricity system will expand in the future to also include transportation, electrical HPs and other technologies driven on electricity. An electrification of systems which have previously been fuel based, like the transportation system, is necessary to create an appropriate storage capacity to the high share of fluctuating RE. Here it is also mentioned that an "electricity smart grid" is not enough to include the high shares of fluctuation electricity that is planned, but a "smart energy system" where also heat, fuel and gas is included must be the aim of the planning.

4.3 Heat Supply

Today more than 55% of the net energy demand for heating is being covered by DH (DEA 2012b) and about 80% of DH supply today is co-produced with electricity. Besides DH there are also other technologies for heating and domestic hot water. Table 4.2 provides an overview of the used technologies for the total heat supply to the 2.5 million households (DEA 2012a).

Technology	**Percentage**
Electric heat	6%
Heat pumps	0.4%
Oil	18%
Solid fuel	3%
Natural gas	15%
DH without electricity generation	4%
Co-generated heat and electricity in small and medium-sized cities	17%
Co-generated heat and electricity in large cities	37%

Table 4.2: Technologies used in the Danish heat supply (DEA 2012a).

58% of the heat consumers receive heat from DH, which is primarily in areas where households or businesses are in close proximity, i.e. in towns and cities. The heat supply is divided into three categories; DH, natural gas and individual heating (also known as Area IV). These areas are results of the heat planning in the decade after the oil crises in the 1970's. Figure 4.2 on the following page shows a map of the supply areas in Denmark.

According to Dansk Fjernvarme et al. (2010) some of the areas currently supplied by natural gas or individual heating can be converted to DH and thereby reduce the total fuel consumption because of the higher efficiency at DH plants compared to combustion in individual boilers. The number of households that can be converted in an economically feasible way to a high extent depends on the development of the fuel prices. If DH systems are expanded and the number of connected consumers is increased the potential in the DH system will also increase and the flexibility to the total energy system will also be increased. It also mentions the importance of a combined effort that includes energy savings as well as public supply and efficiency measures.

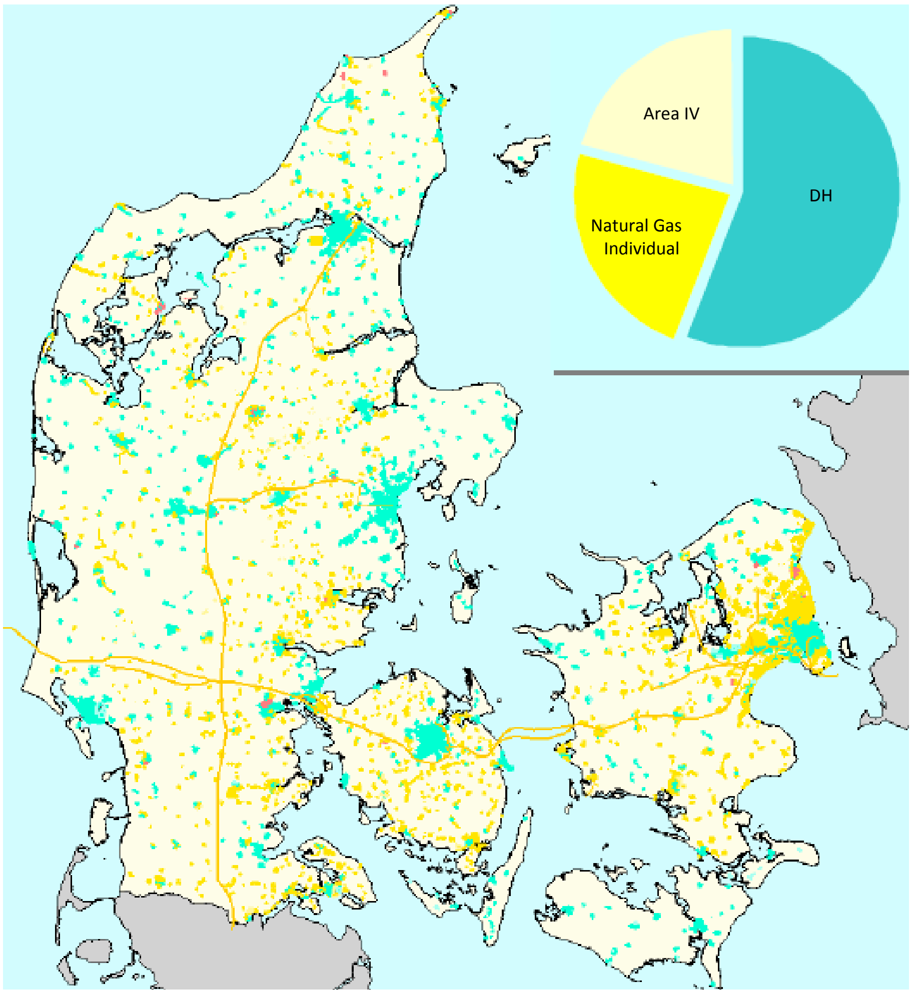

Figure 4.2: Map of heat supply areas in Denmark (Energinet.dk 2011b).

The DH production plants can be categorized into three groups;

1. DH plants which only produces heat mainly on biomass
2. Decentralized CHP plants which produce heat and electricity in a fixed ratio, mainly using natural gas and
3. Large central CHP extraction plants which produce heat and electricity in an adjustable ratio and can produce electricity alone. These are using different fuels including coal, oil, natural gas and biomass.

These will be referred to from here and the groups are used in the analysis of the East Denmark system in EnergyPLAN as well. The specific application of the groups in EnergyPLAN is explained in Section 6.4.1 on page 47.

4.4 Political Goals

In order to realize the main objectives in the Danish energy policy, various strategies are being followed and Denmark has an energy policy for implementation and utilization of RES with the overall goal to become carbon neutral by 2050. The policies include development and utilization of new energy technologies and has another objective to strengthen energy technology that can be produced and exported by Danish industry (DEA 2012b). The goals and measures for the Danish energy policy towards 2050 based on DEA (2012c):

Energy Efficiency: Denmark is investing 90 - 150 M DKK in energy efficiency and RE and is further working to make the goal of 20% increased energy efficiency by 2020 binding for Member States in the EU.

RE Sources: In 2020 approximately 50% of the electricity consumption will be supplied by wind power, and more than 35% of the final energy consumption will be supplied from RE sources. In the EU climate and energy package from 2008 it is a binding target that at least 30% will be RE in Denmark's final energy consumption by 2020. In addition, there is a binding target of 10% RE in the transport sector by 2020.

Energy Savings: Initiatives agreed in the energy policy is expected to result in a reduction of 7.6% in 2020 relative to 2010.

Climate Policy: Denmark has committed to meeting a binding target for reducing greenhouse gases by 2020 and must reduce the GHG emissions from Danish non-ETS sectors by 20% relative to 2005. The official goal by the Government is to reduce GHG emissions by 40% by 2020 in relation to 1990 level.

The energy agreement was reached in March 2012 with a 95% majority in the parliament and contains a wide range of initiatives toward bringing Denmark closer to the overall goal of 100% RE in the energy and transport sectors by 2050 (DEA 2012b). The agreement further contains milestones towards the overall goal in 2050 in the period from 2012 to 2020:

- More than 35% RE in final energy consumption
- Approximately 50% of electricity consumption to be supplied by wind power
- 7.6% reduction in gross energy consumption in relation to 2010
- 34% reduction in greenhouse gas emissions in relation to 1990

(DEA 2012b) In relation to the focus of this project this means that there is a broad political will to take action on the energy and climate issues. The higher share of wind power which will be sold on the Nord Pool Sport Market will increase the fluctuations in the electricity prices as explained previously in this chapter.

As the gross energy consumption should be reduced, wind should be increased and GHG emissions should also be reduced. TES combined with HP or EB could be a part of the solution to meeting thedescribed targets, as the HP/EB can utilize some excess electricity and store it in the TES and thereby reduce the alternative energy consumption.

4.5 Summary

The history shows that the heat and electricity systems have been more and more integrated with each other over the last decades with increased CHP production and the TES capacity to balance the day and weekly imbalances between heat and electricity demands. The ban for electric heating have been slightly loosened up in the last couple of years with the EB law and the reduced taxes on HP for DH, which is increasing the integration of the two sectors and the current policies for this area indicates that the development may continue.

District Heating in the Copenhagen Area 5

In this chapter the DH area in the Copenhagen region is presented. The DH systems in this area are wide spread across many different municipalities, with many companies and actors involved and the management and operation is complex. Therefore the purpose of this chapter is to give an understanding of the case area for this project, the *Metropolitan Copenhagen Heating Transmission Company*, also known as CTR, and the context in which it is operating.

The chapter firstly provides a description of the DH supply system including the development of the DH systems, the fuel use and the different plant types. Secondly, a presentation of the actors, important to the CTR, in the DH sector in the Copenhagen area is given. Lastly, a presentation of the future plans and projects for the DH systems in the region as a foundation for the specification of the scenarios which are presented in Chapter 6.

5.1 Overview of the District Heating Area

The DH supply system connects 16 municipalities in the greater metropolitan area of Copenhagen. The area is seen in Figure 5.1 on the following page, which also shows the different supply areas and distribution companies. CTR covers five municipalities and VEKS (Vestegnens Kraftvarme Selskab/Western Municipalities Heat and Power Company) covers 11 municipalities, indicated on the map with red and blue respectively. The two municipalities in the green area, the West Incineration area, are not directly connected to the other systems, but the incineration plant, Vestforbrænding (VF), supplies surplus heat to CTR and VEKS.

The yellow areas in the map are DH supplied in the form of steam. There are two steam supplied systems in Copenhagen, which are independent of the water DH systems in the surrounding areas. The steam for these systems are produced at the central CHP stations located in conjunction with the steam systems (Copenhagen Energy 2010a).

5.2 Plants and Fuels

The total heat production for the DH system of around 35,000 PJ comes from four central CHP plants; Avedøreværket, Amagerværket, Svanemølleværket and H.C. Ørsted værket, three waste incineration plants; Amagerforbrænding, Vestforbrænding and KARA/Noveren, see Figure 5.1 on the next page, and more than 50 peak load boiler plants. The production between the plants is operated so that the waste incinerators have the highest priority of production, the CHP the second priority and the peak load boilers as the last priority. In addition to the waste incineration plants there are also a demonstration geothermal plant and a waste water treatment plant that supplies waste heat to the DH grid and the production from these are prioritized together with the waste incineration plants (CTR et al. 2011b).

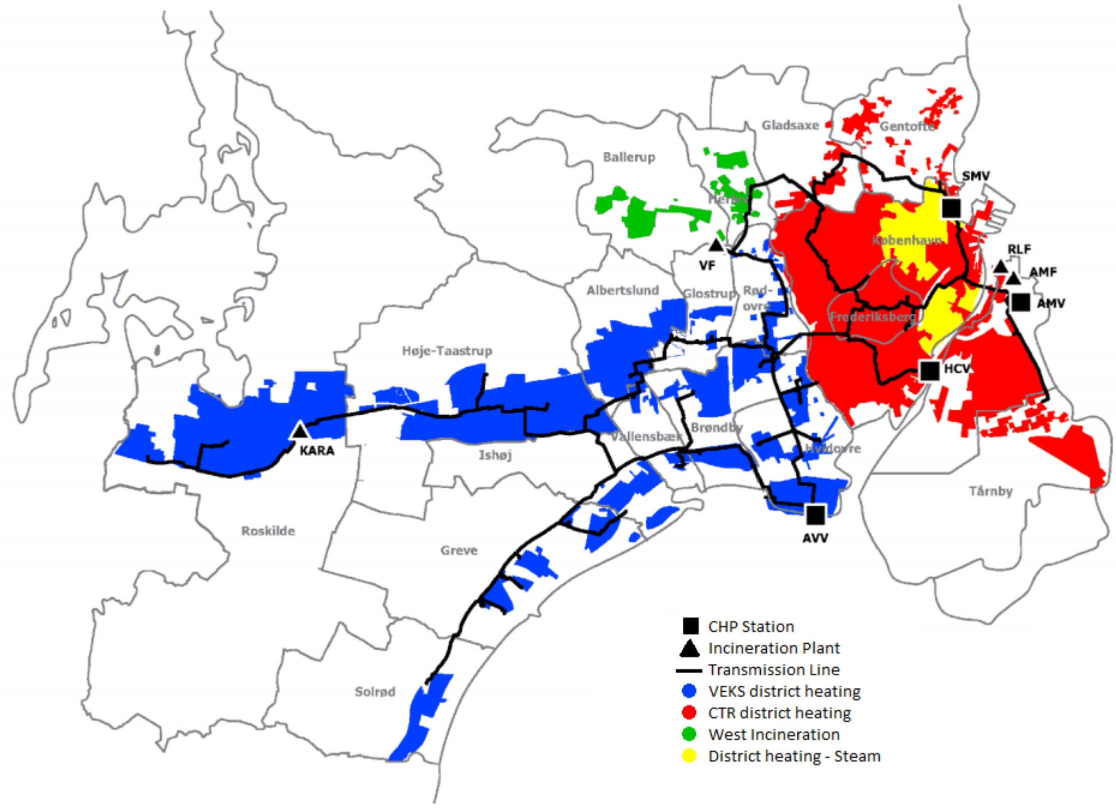

Figure 5.1: Map of DH areas in the Copenhagen region (CTR et al. 2011a).

The peak load boilers are used as back up during outage of the CHP plants and to cover the peak load at cold days with a very high heat demand. Table 5.1 on the facing page shows the major CHP plants and waste incineration plants in the area and their individual fuel types and capacities. Normally the capacity at the waste and CHP plants is sufficient and the peak load units are only used when the heat demand is unusual high and in case of technical issues. Bottlenecks in the system, can imply that the capacity is not adequately used, which results in surplus of CHP capacity. This is for instance seen in the western part of the grid, and the balance between demand and production capacity is strained in the center of Copenhagen (CTR et al. 2011b).

It can be seen in Table 5.1 on the next page that the CHP plants are using different fuels and most of them can use a combination of different fuels; biomass, coal and natural gas supplemented by fuel oil. The operation of the plants will be optimized according to the production costs and environmental aspects which means that the heat production are flexible to changes in fuel prices, electricity prices and fluctuations in heat demand (Varmelast.dk 2012). See more about this in Section 5.3.4.

CHP Plants		Fuel	Capacity (heat) MJ/s	Capacity (electricity) MW
Amagerværket (AMV)	Unit 1	Biomass, coal, fuel oil	250	80
	Unit 2	Biomass, fuel oil	166	95
	Unit 3	Coal, fuel oil	331	263
Avedøreværket (AVV)	Unit 1	Coal, fuel oil	330	250
	Unit 2	Gas, biomass, fuel oil	570	570
H.C. Ørsted Værket (HCV)		Gas	815	185
Svanemølleværket (SMV)		Gas, fuel oil	355	81
Waste Incineration Plants				
Amagerforbrændingen (AMF)		Waste	120	25
Vestforbrændingen (VF)		Waste	204	31
KARA/NOVEREN		Waste	69	12

Table 5.1: Fuel type and capacities at the main CHP plants and waste incineration plants in the Copenhagen region (Copenhagen Energy 2010a).

5.3 Actors in the District Heating Supply

There are several actors in the DH supply sector in the Copenhagen region. In this section the main actors in the sector are described with focus on CTR. In Figure 5.2 on the following page there is a schematic representation of the actors in the DH sector in Copenhagen with focus on CTR. The boxes in the figure are divided into three categories; production, transmission and consumption but this is a rough categorization because some of these could be located in more than one of the categories. In the following the main actors are presented and relation to this figure. The focus is on the heating flows and less on the economic flows. The payments between producers, transmission companies, municipal energy companies and other actor is a complicated matter and this is not included here.

5.3.1 Heat Producers

The heat producers are delivering the heat into the DH grid according to a daily heat plan made by Varmelast.dk. The CHP plants Svanemølleværket, H.C. Ørsted Værket and Avedøreværket are owned by DONG Energy and the fourth plant Amagerværket is owned by Vattenfall. Both DONG Energy and Vattenfall are large energy companies. The waste incineration plants and waste water treatment center on the other hand are all municipality owned. (CTR et al. 2009a) The peak load boiler located in the transmission category in the figure is in reality a production unit, but in this case it is illustrating the own production of CTR and therefore seen as a part of the transmission system.

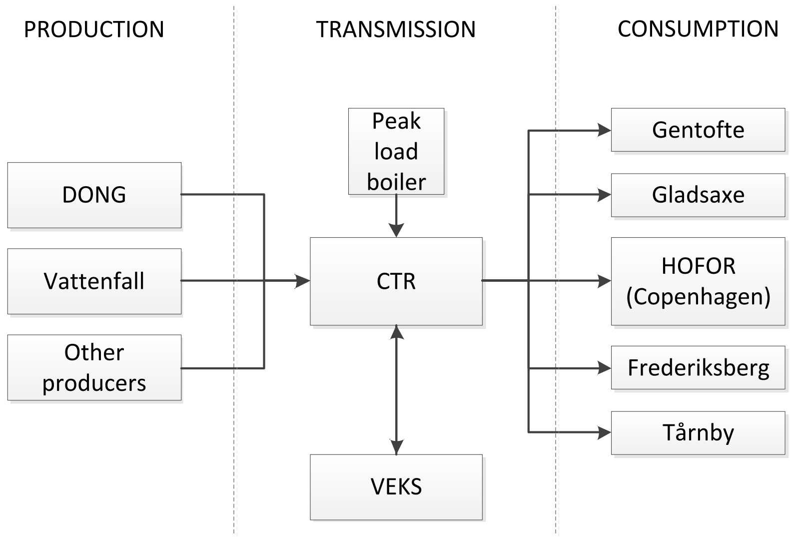

Figure 5.2: Schematic representation of the heat flow between the actors in the DH sector in the Copenhagen region, divided into Production, Transmission and Consumption.

5.3.2 Transmission Company (CTR)

Both CTR and VEKS are transmission companies established in 1984 when DH was rapidly expanded to cater for the inter-municipality transmission of heat production from the central CHP plants, and the companies are owned by the respective municipalities. Their purpose is to buy, transport and deliver DH as well as supplement the production of heat from own peak load boilers. CTR and VEKS own the transmission pipe systems and have the responsibility for the planning, operation, financing and development of the transmission grid (Copenhagen Energy 2010a).

In Figure 5.2 VEKS have neither production nor consumers connected, but this is just a limitation in the figure to focus on CTR. VEKS have the same producers connected as CTR and all of their owner municipalities as consumers. The double headed arrow between CTR and VEKS indicates that there is a transmission between the two systems.

CTR was established in 1984 and encompasses five ownership municipalities and the owner's share for each municipality is; Copenhagen 69%, Frederiksberg 16%, Gentofte 6.5%, Tårnby 5% and Gladsaxe 3.5%. CTR supplies around 250,000 households, corresponding to around 500,000 citizens in Copenhagen with DH. The bought heat for the transmission was in 2011 18,801 TJ, where 18,493 TJ was used to cover the heat demand within the CTR, 308 TJ was sold to VEKS and the heat loss was 81 TJ which corresponds to 0.4%. The reason for the relatively low heat loss is that the losses in the distribution systems not are included, but only CTR's own transmission system. The heat was produced from 21% waste incineration, 1% geothermal, 74% CHP and 4% peak load boilers, and in total 42% of the heat supplied from CTR is based on RES (CTR 2011).

An overview of the transmission system of CTR is shown in Figure 5.3, showing the transmission grid and the major energy plants. The transmission system includes a base load capacity of 918 MJ/s, a medium load capacity of 302 MJ/s and peak load capacity of 815 MJ/s divided into several units (CTR 2009), that are not shown in the figure. The transmission grid further includes 54 km transmission pipes, 27 heat exchange stations with a total capacity of 2,145 MJ/s and 3 booster pump stations with an installed power capacity of 6,200 kW. The maximum temperature is 120°C (CTR 2009).

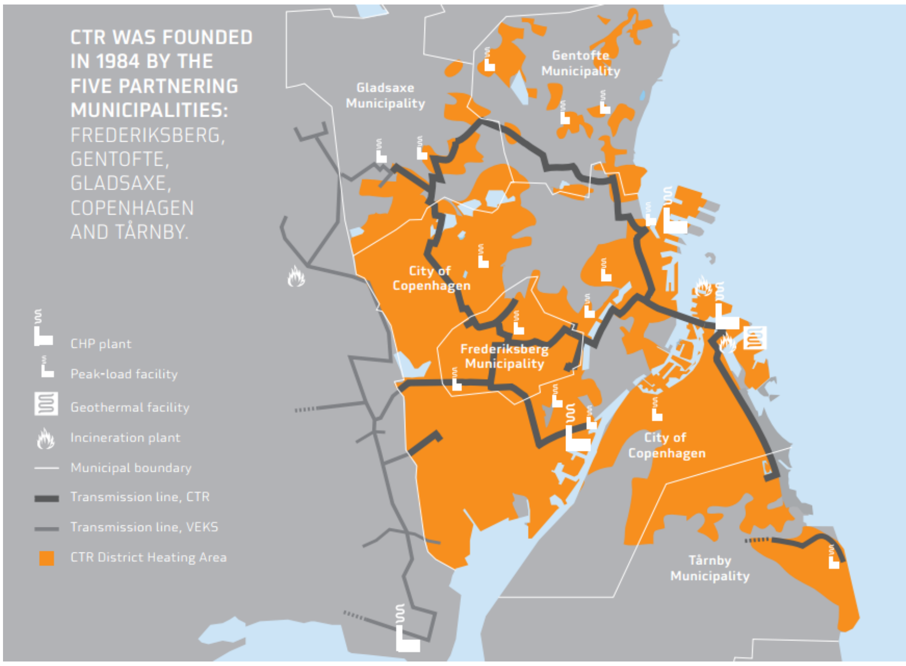

Figure 5.3: Overview of the CTR transmission grid (CTR 2009).

5.3.3 HOFOR

HOFOR (Hovedstadsområdets Forsyningsselskab, The Capital Area Supply Company) is a supply company in the Copenhagen region owned by the 16 municipalities of the supply area. The company is a merge of the former energy supply company in Copenhagen, Copenhagen Energy, and a number of water and waste water discharge companies in the Copenhagen region. HOFOR supplies DH, district cooling, city gas, water and waste water discharge. HOFOR only supplies DH, district cooling and city gas in the municipality of Copenhagen. (HOFOR 2012a)

HOFOR distributes DH in the municipality of Copenhagen including the steam and low temperature areas, see Figure 5.4 on the following page. The steam areas are gradually being converted to either DH or low temperature DH to save losses in production and distribution (HOFOR 2012c).

CTR delivers the heating to HOFOR through the transmission grid and HOFOR distributes it to the individual consumers. The steam supplied areas are not connected to the transmission system and HOFOR manages this supply outside CTR. In Figure 5.2 on the preceding page HOFOR is placed in the category of consumers even though it is a much larger company with some production as well, but HOFOR can be seen as the other municipalities from CTR's perspective.

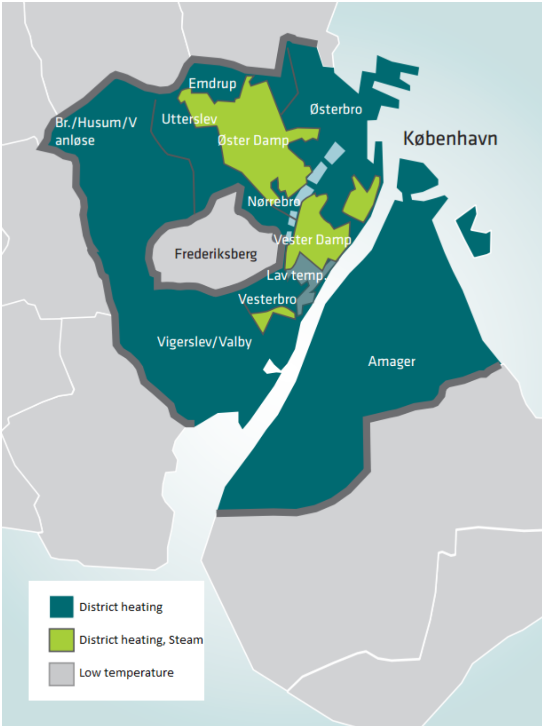

Figure 5.4: DH area of HOFOR (HOFOR 2012b).

5.3.4 Varmelast.dk

Varmelast.dk was established in January 2008 and is a cooperation between CTR, VEKS and HOFOR. The purpose is to ensure that the heat load of the plants in the Copenhagen area is distributed according to a collective economic optimization. Varmelast.dk is responsible for the planning of the heat production of the following day. This is done in cooperation with DONG Energy and Vattenfall. Their responsibility further lies in adjusting the heat plans according to demand and collecting the necessary data (VEKS 2011).

The major challenge in making the heat plans is to ensure the optimal production of both heat and electricity and still consider the priority of the heat production from waste incineration plants and geothermal production, and at the same time ensure the heat production follows the demand. The strategic planning of the plants still lies at the individual plants. The operation of the plants is based on the daily heat plan, which considers the heat demand, the economy of the producers, prices for the customers and the environment, and produces based on these aspects the optimal heat plan for the day. A sketch of how the daily heat plan is designed is seen in Figure 5.5 on the facing page.

The bidding round for next day's heat plan starts before 8 am and is based on the prognoses for next day's heat demand. The CHP plants then calculate the cheapest way to fulfill the demand with regard to electricity prices, fuel prices, CO_2 quotas and energy taxes. By the tax structures, the most environmental friendly fuels are prioritized. The initial heat plans from the producers are then adjusted according to hydraulic barriers in the grid and according to optimal use of the heat accumulators at the Amagerværk and Avedøreværk based on the marginal costs. The final heat plans are then sent to the producers which tell them what to produce on hourly basis. The final heat plan need to be sent by 10.30 am, so the producers know how much heat they need to produce and thereby how much electricity they can offer for sale on Nordpool spot market, see description in Section 4.2.1 on page 27. The daily heat plan is adjusted three times a day, at 8 am, 3 pm and 22 pm, according to the real heat demands, the official spot price on electricity and other unexpected events at the CHP plants (Varmelast.dk 2012).

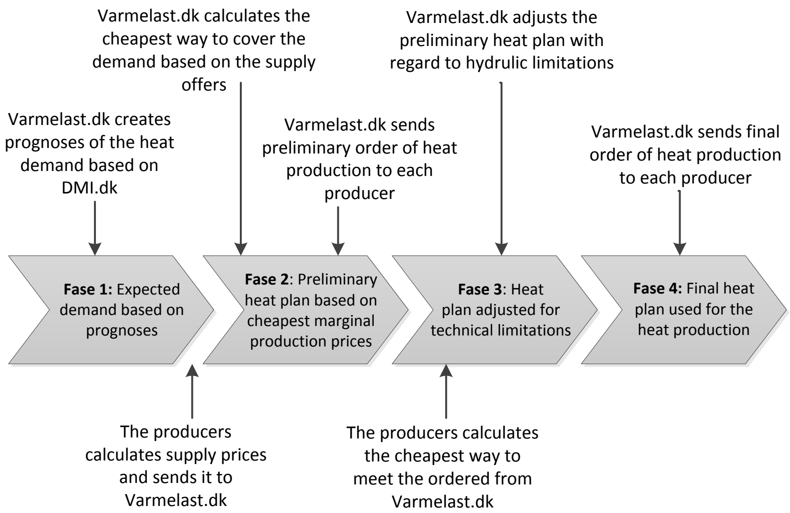

Figure 5.5: The process of making the daily heat plans at Varmelast.dk (Varmelast.dk 2012).

5.4 Development and Planning of District Heating in the Copenhagen Region

Copenhagen was the first city in Denmark to implement DH with the first systems built already in 1925. The first systems were based on steam supply and that is why there is still some steam systems left in the city today. Copenhagen has since been developing DH systems but most significantly after the national heat planning legislation was implemented in Denmark after the oil crisis in the 1970s (Copenhagen Energy 2010a).

In 1984 the municipality of Copenhagen presented the plan Heat Plan Copenhagen which included the implementation of mandatory connection to the DH grid. This lead to a substantial development of the DH grid and construction of CHP plants in the Copenhagen metropolitan area, for instance the CHP plants at Amagerværket and Avedøreværket. (Copenhagen Energy 2010a)

In 2009 the municipality of Copenhagen presented an ambitious plan called Copenhagen Climate Plan which set the goal of 20% reduction of CO_2-emissions in 2015 and presents a vision of making Copenhagen CO_2-neutral by 2025 (Municipality of Copenhagen 2009). With this plan a lot of work was started regarding the future CO_2-neutral energy supply in the Copenhagen Region and how it practically can be reached. Table 5.2 on the following page presents a time line over this process.

Time of presentation	Institution(s)	Reference	Abbreviation
2009	The municipality of Copenhagen	Københavns Klimaplan (Copenhagen Climate Plan)	CCP1
2009, September	Copenhagen Energy, CTR and VEKS	Varmeplan Hovedstaden (Heat Plan of the Capital Region)	HPC1
2010, January	Copenhagen Energy	Forsyningsvejen til et CO_2-neutrals København (The Supply Way to a CO_2-neutral Copenhagen)	-
2010, November	CTR and VEKS	CO_2-neutral Fjernvarme I Hovestadsområdet I 2025 (CO_2-neutral District Heating in the Capital Region in 2025)	-
2011, September	Copenhagen Energy, CTR and VEKS	Varmeplan Hovedstaden 2 (Heat Plan of the Capital Region 2)	HPC2
2012	The municipality of Copenhagen	KBH 2025 Klimaplan (CPH 2025 Climate Plan)	CCP2
Ongoing project	Copenhagen Energy, CTR and VEKS	Varmeplan Hovedstaden 3 (Heat Plan of the Capital Region 3)	HPC3

Table 5.2: Time line of documents related to the work of making the energy supply in Copenhagen CO_2-neutral.

Already before CCP1 was presented a dialogue with the important energy companies in the region, Copenhagen Energy (now HOFOR), CTR, VEKS, DONG Energy and Vattenfall was started about the possibilities regarding CO_2-neutrality. HPC1 is an important part of this and is an analysis project made in connection to the organization of Varmelast.dk by the three supply companies Copenhagen Energy, CTR and VEKS about how to develop the heat supply of the region in the future. The projects HPC are despite their names not regular plans, but analysis of the DH system in the region. The HPC1 project analyzes different scenarios with a target of 70% RE supply and one scenario with 100% and shows that it is possible and that it can be done in a feasible way (CTR et al. 2009a).

Hereafter, in 2010 the three supply companies announce that they will support the goals of CO_2-neutrality in 2025. First Copenhagen Energy (Copenhagen Energy 2010b), not surprisingly since they were 100% owned by the municipality of Copenhagen, and later CTR and VEKS announced their support as well (CTR and VEKS 2010). As a follow-up, HPC2 was presented with the purposes to create a common platform between the three supply companies for decisions towards CO_2-neutral DH supply regarding priority of projects and specific technologies (CTR et al. 2011b).

This development indicated that the biggest hurdle on the way to CO_2-neutrality; the energy production, was moving in the right direction, and in the municipal budget agreement in 2011 it was now decided to refine the vision from 2009 of CO_2-neutrality in the municipality by 2025 into a more specific plan. This plan was CCP2 and was presented in 2012 and gives some more specific goals and initiatives to make the municipality CO_2-neutral in 2025 (Municipality of Copenhagen 2012). The project of HPC3 has already been started with the purpose to analyze and coordinate large investments in the coming 10-15 years in the heat production and transmission systems and to quantify the potential of interplay between the DH and electricity systems with large amounts of wind integration (CTR et al. 2013).

The development shows that there are many actors involved in the plans for the CO_2-neutrality and it indicates that the different stakeholders are willing to act on the targets for CO_2-neutrality since it is shown to be an economic benefit. For that reason the development described in the HPC2 and CCP2 will be used to define the reference scenario for 2025 for the scenario analysis. In the following, key elements of these are presented. The specific values used in the analysis are presented later in Chapter 6.

5.4.1 Targets in CPH 2025 Climate Plan

The targets in the 2025 climate plan both include a description of how the energy system is expected to reach the goal in 2025 and how the energy system is expected to develop after.

Energy Production toward 2025: The electricity and heat production will be based on wind, biomass, geothermal and waste energy. The plan is to have an electricity production based on RE, that exceeds the local demand and therefore exporting electricity. This means that the electricity production based on coal is assumed to decrease outside the area of Copenhagen. The initiatives toward 2025 are done by the energy companies and require significant development in the infrastructure. (Municipality of Copenhagen 2012).

Energy Production after 2025: It is expected that the energy production will change after 2025, where there will be implemented even more wind in the energy system. Parts of the biomass based heat production will be replaced by geothermal heat and HPs. This means that after 2025 will geothermal energy together with biomass and supported by HPs and waste incineration be the base in the heat supply in the Copenhagen area. Depending on the technological as well as the economic development, the heat supply is expected to be supplemented by solar heat and use of TES to ensure a high level of flexibility in the overall energy system. The development of the technology will be crucial to the knowledge of the last period from 2025 – 2050, where technologies will be improved and tested. (Municipality of Copenhagen 2012)

5.4.2 Targets in Heat Plan of the Capital Region 2

The CCP2 and HPC2 have the same approach and solutions but HPC2 focuses on the heat supply and therefore has more details about this but from an overall perspective it fits well with the solutions presented in CCP2.

The reference scenario of HPC2 is also presented in HPC1. This is not CO_2-neutral, but none of the scenarios are 100% CO_2-neutral because of fossil fractions in the waste for the waste incineration and the electricity consumption. When export of electricity from biomass CHP is considered to reduce coal production elsewhere it can be seen as CO_2-neutral. The main changes towards 2025 are that all coal fired CHP will be replaced with biomass CHP, 65 MW geothermal capacity excl. drive steam will be implemented to reduce dependency on biomass the development of the heat demand will be a slight decrease from 35 TJ today to 34 TJ in 2025. This is caused by expansions of the DH-systems on the one hand and of heat savings and higher outdoor temperature on average on the other hand (CTR et al. 2011b). In CTR an increase of 5% in the demand is expected due to expansion in the grid (Magnusson 2013).

5.4.3 The Challenge of CO_2-Neutral Peak Load Heat Production

One of the big challenges in reaching a CO_2-neutral heat supply is to cover the peak load heat demands which are usually covered by natural gas or oil boilers (CTR et al. 2011b). There are technical options, but the problem is to find feasible options. Anders Brix, Climate and Energy Coordinator at the Municipality of Copenhagen, suggests in an interview that TES might be an option to cover peak loads by charging the TES with an EB or HP when the electricity price is low and discharging it to cover peak loads of the heat demand (Brix 2013).

There are currently no large amounts of TES in the area of Copenhagen, but at Amagerværket and Avedøreværket there are TES of respectively 750 MWh and 2,600 MWh (CTR et al. 2009b), which is used by varmelast.dk to produce as much heat as possible on the CHP plants, when it is cheap, and use the heat when the demand is high, usually in the morning time. A project idea has been presented by Copenhagen Energy to establish a large scale TES of 300,000 m^3 in an old harbor area in Copenhagen called Nordhavn (Harris 2011). Such storage would significantly increase to total TES capacity in the area.

5.5 Summary

The supply of DH in the Copenhagen area is rather complex with many actors involved. The heat is also being transmitted through different transmission companies and areas and thereby exchanged trough different systems. This makes an exact model of the chosen case study of CTR transmission company complex and a boundary of the modeled area is necessary, which is given in Chapter 8.

Due to the complexity of the overall DH system in Copenhagen, the development described in the HPC2 and CCP2 is used to define the reference scenario for 2025 for the scenario analysis, which is presented in Chapter 6. Here the expected situation in the energy production in 2025 is used as baseline. The fuel use in the modeled area is set according to the analyses of the CO_2-neutral scenario described in HPC2.

Based on the described plans for the Copenhagen area, it is assessed how the area of the CTR transmission company, can improve the flexibility and fuel use, when the technologies of HP/EB are installed in the transmission system in combination with increased capacities of TES.

Presentation of the Scenarios 6

In this chapter the structure and the content of scenarios in the analyses in the two following chapters are presented. The same scenarios are used in both of the parallel analyses using EnergyPLAN and EnergyPRO presented in Chapter 7 and 8 respectively where the EnergyPLAN analyses is handling the energy systems of East Denmark and the EnergyPRO analyses handles the CTR DH system in Copenhagen. First, the specific scenarios are presented followed by an explanation of the assumptions for the economic calculations. Lastly the two computer models are presented with an explanation of how they have been applied.

6.1 Scenarios

The Choice Awareness theory states that it is important always having a number of different technical alternatives and to compare and communicate these to increase the transparency of the decisions and the public awareness. This is here materialized in some technical alternatives which are presented, but these should only be seen as a contribution to the development towards a RE system and not a final solution. A detailed description of the technologies TES, HP and EB which are applied in the following chapters can be found in Chapter 3 on page 15. In Table 6.1 the scenarios handled in this project are presented.

Scenario	TES Capacity	HP Capacity	EB Capacity
Reference 2025	-	-	-
TES	Increased	-	-
TES + HP	Increased	Increased	-
TES + EB	Increased	-	Increased

Table 6.1: The four scenarios of the analyses with the changed parameters respectively. The "-" indicates the value of the reference scenario.

Reference 2025 is a scenario which is based on a baseline reference system for 2011. The input parameters have been projected using a number of sources describing the expected development in the systems towards 2025. This includes realization of the targets of Copenhagen Municipality of being CO_2-neutral by 2025, projection by DEA of the energy flows in Denmark and projections of the electricity demand by Energinet.dk. See all the specific data input and the references for the two models for both Reference 2011 and 2025 in Appendix A on page 105 and C on page 125. The scenario is seen as a representation of the expected development if no additional effort is done to implement TES. This scenario is used to compare the three following alternative scenarios to.

TES is the scenario where the capacity of TES is increased compared to Reference 2025 without any implementation of HP and EB. This is done to see what the potential of implementing TES alone will be. For each of the models the capacity of TES is varied in the relevant scale. As the two different systems are different in size different values of the capacity have to be applied, but various capacities are tested to see the development in the relevant indicators as the TES capacity is increased.

TES + HP is a scenario where increased TES capacity is combined with increased capacity of HP to analyze the potential synergy of combining these two technologies as described earlier. The idea of this scenario is to assess how well the HP capacity can utilize the excess electricity production from the increasing wind production capacity and store it in the TES to use it later in the DH systems. First, the HP capacity is increased without increasing the TES capacity to be able to compare if the change in the system is caused by the synergy or just from the HP alone. Hereafter different selected TES capacities are analyzed the same way where the HP capacity is varied in the same range as before. The synergy of implementing the two technologies together can now be assessed according to the relevant indicators.

TES + EB is the scenario where increased TES capacity is combined with increased capacity of EB to analyze the potential synergy of combining these two technologies as described earlier. The idea of this scenario is to assess how well the EB capacity can utilize the excess electricity production from the increasing wind production, like for the scenario TES + HP. The difference is that the EBs have much lower investment costs, but also a lower efficiency compared to the HP. The procedure of the analyses is the same as described for the TES + HP scenario.

6.2 Scenario Indicators

To assess the different scenarios and compare them to each other a number of indicators have been selected. The main indicator is the Socio Economic Costs (SEC) which will give the socio economic feasibility of a certain change. Other indicators used in the analyses are Primary Energy Supply (PES), CO_2-emissions, electricity balance and TES utilization. These indicators are presented in slightly different forms in the two analyses in EnergyPLAN and EnergyPRO. In EnergyPRO there are in addition to the mentioned indicators also indicators for the utilization of the HP and EB. Details of the indicators are presented in Section 7.1 on page 51 for the EnergyPlan analysis and 8.2 on page 73 for the EnergyPRO analysis.

6.3 Socio Economy

In this project socio economic calculations are made for the scenarios to compare the economic results from a societal perspective. According to Choice Awareness the socio economy is important because this shows how beneficial a particular project or strategy is to the society which can then be used to suggest a public regulation strategy. For the calculation of this project the socioeconomic perspective specifically means that taxes, levies, subsidies and other public economic regulations are not included in the calculations, but on the other hand a cost for the CO_2-emissions are included because this is seen as a cost for the society. The calculation includes investment costs, fuel costs and variable and fixed operation and maintenance costs. These are calculated by the models and added up to the total annual costs.

The discount rate in economic calculations is an important factor in the feasibility study of an investment. The purpose of the discount rate is account for the time perspective of future payments so that future payments are valued lower than payments today. The discount rate reflects the lost alternative income which the invested resources could have generated in a different investment. In Denmark The Ministry of Finance recommends using a discount rate of 5%, but are currently planning to reduce it for the calculation of green energy projects. In connection to this, the CEO of The Danish District Heating Association, Kim Mortensen, suggests a discount rate of 3% which will increase the incentive to make investments in such projects (DR 2013). Parallel to this, a discount rate of 3% is chosen for the calculations in this project.

6.4 The EnergyPLAN Model

The computer model EnergyPLAN is developed to simulate the operation of an energy system with high amounts of fluctuating RES integrated. EnergyPLAN is a deterministic model which means that with a certain input it will always generate the same output. The model balances production with demand for electricity, DH, gas and hydrogen on an hourly basis for a full year with a selected optimization strategy. EnergyPLAN can be used to analyze national energy systems, local energy system or integration of specific technologies in an energy system (Østergaard et al. 2010).

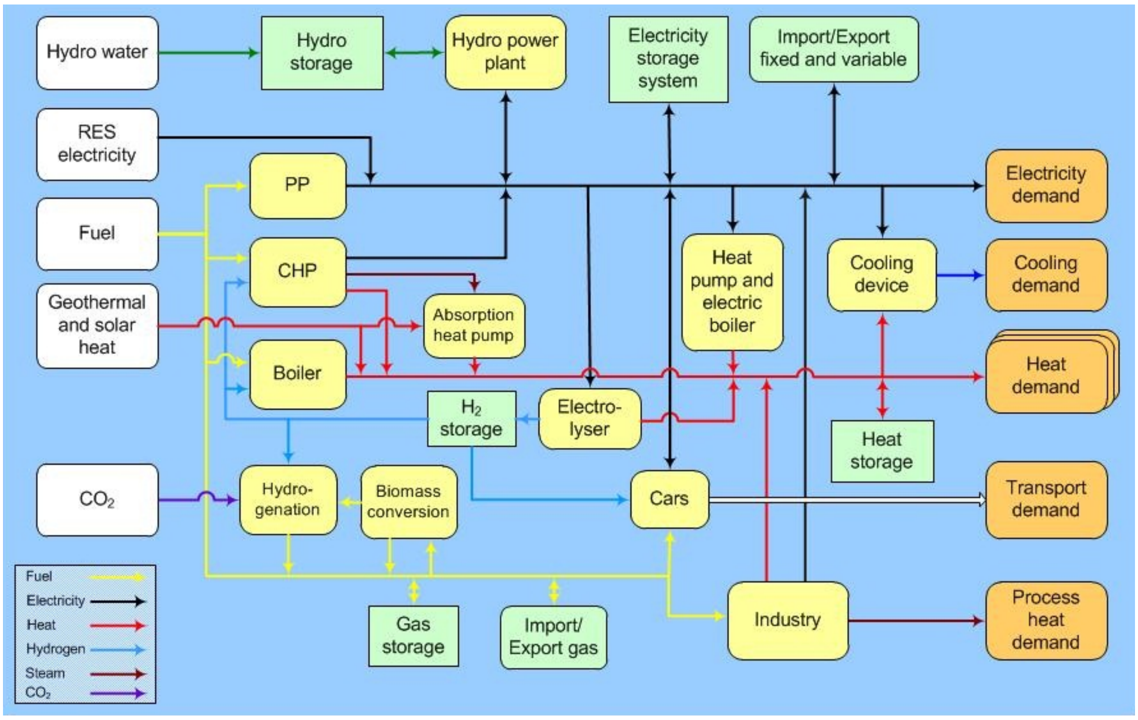

Figure 6.1: Schematic diagram of the relations between energy sources, conversion technologies, storage and demand for EnergyPLAN - Version 10.0 (Lund 2012).

The model works on an aggregated level and do not distinguish the operation of every individual energy conversion unit, never the less there is a focus on the interdependency between the electricity system and the heating systems to enable the model to balance the system between electricity and heating and utilize the energy sources beyond control, like wind, solar or wave energy. Especially the CHP and HP give flexibility to the energy system because they can work to balance both the electricity and the DH systems dynamically. Figure 6.1 on the preceding page shows a schematic diagram of the EnergyPLAN model where the left column is the energy sources for the system, the middle section is conversion technologies, storage and import/export connections and the right column shows the demands that have to be covered.

The extensive DH systems that exist in Denmark are an important factor in the flexibility of the system to utilize the fluctuating RES, mainly wind electricity as described in Chapter 4 on page 25. In EnergyPLAN the heat producing units connected to DH systems are divided into three groups according to their ability to balance the electricity system. DH group 1 is based solely on boilers and thereby do not interact with the electricity system directly. DH group 2 represents systems based on decentralized CHP which means that they are able to coproduce electricity and heat at a fixed ratio. DH group 3 is systems based on central CHP plants which are able to coproduce electricity and heat at a variable ratio or electricity alone. In DH groups 2 and 3 HP, TES and EB capacities can also be implemented.

The specific costs are from the integrated cost file called "2020DEACosts." This file is based on costs from DEA (2012d) and are costs projected for 2020. This is used even though the scenarios are for 2025, but the development of especially fuel prices are difficult to predict accurately so a projection for 2020 is seen as usable. This file also includes life time expectancies for the different investments which are also included in the model calculations. The costs are presented in Appendix A.4 on page 116. EnergyPLAN calculates the optimal way to meet the demand on the basis of a chosen regulation strategy. There are three different regulation strategies, two technical optimization strategies and one market economic optimization strategy.

Technical Regulation 1 seeks to optimize the supply for the heat demand in the system with a priority in the different production units to keep a high efficiency of the system.

Technical Regulation 2 seeks to meet both the heat and electricity demands to minimize the CEEP. E.g. the model can down regulate the electricity production by replacing CHP production with boiler or HP production and thereby keeping the same heat production.

Market Economic Regulation optimizes the production according the electricity prices on a predefined electricity market. Here the model gives the priority to the units with the lowest marginal electricity production cost and operates electricity consuming units when the electricity prince is low. For example if the electricity price is low the model may replace a CHP unit with a gas boiler or maybe even EB if the price is very low.

When making an analysis the model generates a number of different outputs. The four main outputs are the total primary energy supply (PES), the CO_2-emissions from the combustion of fossil fuels, the total annual costs and the critical excess electricity production (CEEP). The system indicators are used in the analyses and further elaborated in Section 6.2. The model also provides a large number of system parameters and values of how the different production groups have been operating during the modeled year in annual values as well as hourly values which can also be presented graphically.

6.4.1 Application of EnergyPLAN

The purpose of applying EnergyPLAN is to analyze the potential of implementing large capacities of TES combined with HP or EB in a system with a high share of wind production. EnergyPLAN is also used to analyze the integration of specific technologies by: (Salgi and Lund 2008), (Mathiesen et al. 2008) and (Lund 2005). The EnergyPLAN model is seen as good way to model a large energy system like East Denmark because it works on an aggregated level and the requirements for data collection are low compared to a model which models every production unit individually. Also the fact that the model works with an hourly time resolution is seen as an important aspect because the time dependent dynamics of implementing TES and HP or EB in a large energy system is very important.

In this project the regulation strategy Technical Regulation 2 is used. As this strategy seeks to balance both heat and electricity it will be using the resources in the best way when assuming the system to have no interconnections to neighbor regions. The interconnections have been disregarded because it is very uncertain to which extend the excess electricity in 2025 can be exported and at which price. For stabilization of the electricity grid a minimum share of 30% has been set, as recommended in (Lund 2012). In this project the grid stabilizing capacities are large CHP extraction plants, small CHP plants and waste incineration plants. HP capacity has been set to only being able to cover 50% of the DH demand in one hour because of the supply temperature limits to HPs.

To reduce the CEEP the EnergyPLAN model has a number of strategies for this purpose which can be selected and prioritized. These are reducing RES electricity production, replacing CHP with boiler and replacing CHP with EB. The strategy of reducing RES electricity, here the wind production, is not included because it is an interesting point to see how much CEEP is generated in a system with a certain amount of wind capacity and how it can be reduced by various technologies. Replacing CHP with boiler in DH group 2 is set as the first priority and replacing CHP with boiler in DH group 3 is the second priority. Replacing CHP with EBs is set as the third priority, but the capacity is set to 0 MW in all scenarios except the TES + EB scenario where this is increased.

The change in CEEP is seen as an indication of the effect of the different assessed initiatives in terms of systems flexibility. The absolute value of the CEEP is not very important here because in 2025 other technologies will probably be developed and other measures may be in place to increase the flexibility of the system, e.g. electric vehicles, individual HP, hydrogen production etc. The technologies assessed in this project will not stand alone and the rather large CEEP seen in some of the scenarios is not expected to be the case in reality. In the case of this project, the East Denmark region, there are no examples of a DH system based on large CHP extraction plants in which small CHP plants are also located (DEA 2011b). Therefore in the DH systems of group 3 all the CHP capacity is based on large CHP extraction capacity. See further details about data for the reference systems and the data sources in Appendix A on page 105.

6.5 The EnergyPRO Model

This section gives a description of the used software to analyze the CTR transmission system, EnergyPRO. The program is introduced with general information together with a description of operations strategies and the available external conditions in the program, which set the frame of the analysis. Finally, it is described how the program is applied to the analysis of CTR.

6.5.1 The EnergyPRO Software

EnergyPRO is a modeling software used for analysis of combined techno-economic systems and other types of complex energy projects. The model is capable of combining electricity and thermal energy from multiple types of different energy producing units and transmission of energy between two or more sites. The model can be used for specific projects of for instance a techno-economic analysis of a DH cogeneration plant where gas engines are combined with boilers and TES. Other types of plants such as geothermal units, solar collectors and wind farms as well as pumped hydro storage and other storage projects can also be modeled and detailed in the program. The optimization of a given project is allowed against fixed tariffs or the spot market prices for electricity, see Section 6.5.2 concerning the operation strategy.

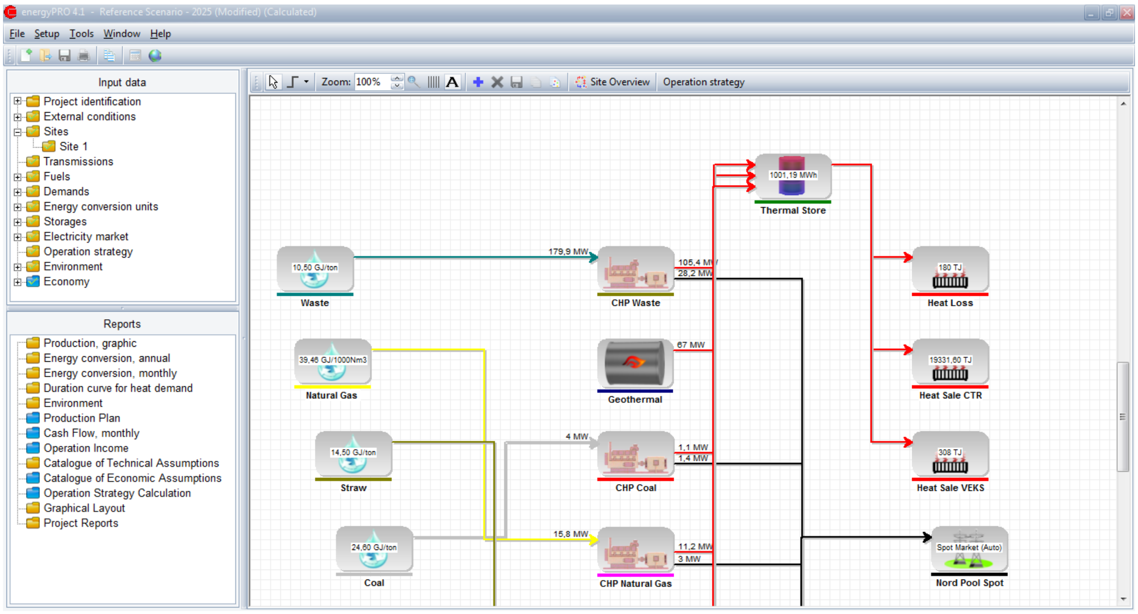

Figure 6.2: Snap shot of the EnergyPRO model

The desktop of the program is divided into three main areas shown in Figure 6.2; the Editing window, where all energy units, markets, demands, etc. are set in order to give an overview of the modeled energy project. The Input window in the upper left corner is where all inputs to the energy units in the editing window are defined. The reports and output data of the modeled projects can be printed from the Report window in the lower left corner. EnergyPRO provides the user with output sheets of energy conversion in the model, environmental data and financial statements.

6.5.2 Operation Strategy

Two operation strategies are available in the program; an automatic calculation of operation strategy "Minimizing Net Production Cost (NPC)" and user defined "User defined Operation Strategy". Both are closely connected to the prices on the electricity market.

Minimizing Net Production Costs: The basic methodology of the calculations in the operation strategy is an incremental approach. For instance for the heat producing units each unit is calculated as a stand-alone unit producing one MWh at the time, while other units such as cooling producing units produce one MWh-cooling. At the same time all economic values in revenues and operation expenditures are evaluated in the calculation. This method is repeated for each production units in each electricity tariff period, placing as much production in the cheapest units, according to what is most beneficial to the system. In this operation strategy the electricity market is automatically defined as the spot market.

User Defined Operation Strategy: The model optimizes through an iterative operation strategy according to fixed tariffs, user defined under "Electricity Market". There can be several tariff groups, but these are often grouped into periods of peak load, high load and low load or simply day and night tariffs. In this operation strategy the EnergyPRO model calculates the optimization period (tariff groups) several times, starting with the energy units with top priority. Hereafter it calculates the same period adding the energy units of second highest priority and so forth. This operation strategy thereby takes into account the priority set up in the operation strategy of the energy units.

Calculation Module: For both operation strategies it is possible to choose a calculation module. If the purpose is to evaluate a project over more years three options are available: The Design module is selected for one-year calculations, with the emphasis on energy conversion and operation costs. The Finance module is selected for investment analysis. This add Investments and Financing to the Design and includes calculations running over more than one year. At last, the Account module adds the calculation of income statements and balance sheets to the Finance module and further adds depreciation and taxation to the calculation input. For a daily optimization of the operation, the Operation module is selected. The content is close to the Design module, but with a few more settings. The operation module further makes the hour by hour energy conversion available in a spreadsheet format.

6.5.3 External Conditions

The external conditions set the frame of the model by projects period and time series. If Design or Operation is chosen in the calculation module, the planning period is always one year. The only information to set is the starting month and year. If Finance or Accounts is chosen it is possible to set "Years to be planned" determining how many years there will be incorporated in the calculation.

Time series can either be pasted in from spread sheets, loaded from the EnergyPRO data folder or from NCAR online data (The National Center for Atmospheric Research). In the EnergyPRO data there can be found temperature data from various countries as well as spot market prices, radiation data and wind data collected for different years. From the NCAR online data it is possible to collect data for a specific geographic location.

6.5.4 Application of EnergyPRO

The primary purpose of using EnergyPRO in the analysis of the CTR transmission system is to assess the potential of implementing large capacities of TES in combination with HP or EB, when high share of wind is present in the system, and how this will affect a smaller and more local energy system (compared to the EnergyPLAN model of East Denmark). EnergyPRO is considered as an appropriate tool to perform such analysis, where more energy units, TES, HP/EB are balanced and optimized against and the spot market. Since it is possible to make inputs to individual energy units, this tool is thought to be a good way to make a model of CTR as close to reality as possible, considering the given boundaries of the analysis in Chapter 8 on page 71. EnergyPRO allows the analysis of CTR to include more dynamics, as compared to the EnergyPLAN model, since it is possible to include the specific energy units.

Minimizing Net Production Costs is chosen for the analysis, where the incremental approach in the operation strategy takes each MWh produced by each unit into account, while optimizing the costs by hourly basis due to the defined external conditions. This gives a qualified model of how the system works and is being optimized. A central point is the possibility to implement TES, HP and EB on hourly time resolution. This is an important factor, since it reflects the dynamics of implementing large capacities of these technologies in the system, and how they influence the system when compared to the hourly spot market price on electricity.

The Minimizing NPC strategy is used to optimize the economic costs of the system, when implementing larger TES and HP/EB capacities, since the model hour by hour calculates which production units can cover the heat demand in the cheapest way. This is expected to make the investments in the new technologies beneficial, since there can be expected to be savings in the annual fuel use. The costs of the fuel is then compared to the spot market price of electricity and the model will hour by hour determine whether it is most beneficial in an economic perspective to run the HP/EB to cover some of the heat demand, or whether it is most beneficial to charge the TES or to let the CHP plants cover the heat demand.

When using one of the optimization strategies it is important to be aware of the complexity of the operation in reality and the dynamics this creates in the system. An example is that the demand for electricity normally is high in the morning and in the afternoon, lower during the rest of the day and lowest during night time. The prices of electricity may therefore vary significantly. Adding to the complexity is the CHP and the fact that the heat demand is normally low during summers and significantly higher during winter. Adding larger capacities of TES and HP/EB to the system is seen as one way to ease this mismatch.

The plants supplying to the DH grid in CTR are divided according to fuel type. This means that the capacity for the producing plants based on for instance wood pellets are collected in one plant, the plants based on coals are combined in one plant etc. This approach has been used in order to comply with the goals in the climate plans of being CO_2 neutral, as it is difficult to predict which plants exist in 2025.

7 Results of the East Denmark Analysis

In this chapter the results of the EnergyPLAN scenario analyses of implementation of TES combined with HP and EB in the East Denmark region is presented. First, each scenario for the modeled system and the varied parameters are presented. Hereafter the applicability of EnergyPLAN for this specific purpose is discussed with the results. Finally, a sub conclusion of the chapter is given based on the found results.

The initial expectation for the results of the analyses was that in a system with significantly increased wind electricity generation and increased TES and HP or EB, some part of the excess electricity would be converted to thermal energy through the HP or EB and stored in the TES for later use. That is not the result of this analysis though. It shows that large TES capacities combined with HP or EB will not give a great benefit, neither from an energy system perspective nor from a socioeconomic perspective.

7.1 Key Indicators

As mentioned in Chapter 6 the indicators used in the analyses are here presented.

Annual Socio Economic Costs (SEC) The total annual costs from a socioeconomic perspective. This is further elaborated in Section 6.3.

Primary Energy Supply (PES) The total amount of fuel used in the specified energy system, both for heat and electricity production, industrial use, transport, etc. This includes all fossil fuels and bio fuels.

The CO_2-emissions The total CO_2-emissions measured in tons from the fuel consumption in the energy system.

Critical Excess Electricity Production (CEEP) Shows the annual amount of electricity that cannot be utilized in the system.

Storage max use Refers to the maximum utilized storage capacity in any hour relative to the maximum storage capacity. Any capacity larger that this is not being utilized by the system.

The indicators are connected, but not completely. E.g. increased PES can lead to increased CO_2-emissions, but if the fuel distribution changes to a higher share of biomass it will not necessarily do so. The same with the annual costs; if the PES increases some expensive fuels might at the same time be replaced with cheaper ones and thereby reduce the costs. The dynamics between these three are complicated and they are all seen as important.

For the analysis purpose the systems has been set in "island mode" which means that there are no electricity interconnections to surrounding areas. In reality there are interconnections and it will to some extent be possible to export the surplus wind electricity this. The change in the CEEP is here seen as an indicator of how much system flexibility the specific technology/technologies can contribute with as a reduction in the CEEP means that the system is able to utilize more of the surplus electricity production.

7.2 Reference Scenario

As mentioned in the methodology in Chapter 6, the different scenarios are assessed using the key indicators PES, CO_2 and Annual Costs. These key indicators are used to assess the scenarios in the following sections. As mentioned, Reference 2011 is just the basis for Reference 2025 and not used further. The Reference 2025 on the other hand is used as a comparison to each system in the alternative scenarios. The alternative scenarios are all variations of the 2025 scenario where only TES capacity and HP capacity or EB capacity are varied. The details of the data input can be found in Appendix A on page 105 and the output data sheets can be found in Appendix B on page 119. The reference models for 2011 and 2025 used in the analyses are given on the CD attached to this report.

In Table 7.1 it is seen how the three indicators PES, CO_2 and Annual costs are expected to change from 2011 to 2025. The PES increases but at the same time the CO_2-emissions decrease. The increase in PES is caused by the general increase in energy consumption expected in the different sectors and the reduction in CO_2 emissions at the same time is caused by the reductions in the share of fossil fuels used. The total annual costs are also increased from 2011 to 2025. This increase is caused by the increase in fuel costs. The Storage max use is seen in Table 7.1 and shows that the storage capacities in both DH group 2 and 3 are fully utilized. This indicator is mainly interesting in the situation where the TES is increased and will show how large a storage capacity the specific system is able to utilize.

	PES [TWh]	**CO_2 [Mt]**	**Annual Costs [M DKK]**	**CEEP [TWh]**	**TES 2 max use [GWh]**	**TES 3 max use [GWh]**
Reference 2011	90.02	18.43	33,480	0	8.85	3
Reference 2025	93.63	12.15	35,972	2.29	8.85	3

Table 7.1: Key indicators for the reference systems, annual values.

The cost distribution between the fuels is seen in Figure 7.1. Here, the increase in biomass consumption is seen by the increase in the costs for biomass. The rest of the total costs, from 2011 to 2025, count for a small decrease. The CEEP is increasing from 0 TWh in 2011 to 2.29

TWh in 2025. This is caused by the increase of wind capacity in the system and because the system is set in island mode so the excess electricity cannot be exported. In a real situation it would be possible to export the excess electricity, but the electricity export would be in the wind peak hours and it is assumed that the wind production in 2025 in the neighboring regions will be significantly higher than today as well. This means that the price for the electricity export may be very low or even negative and therefore for analysis purpose the value of the potential electricity export is set to zero. The CEEP is here mainly used as an indication of how flexible the systems are, so the lower CEEP the better the system is to utilize the excess electricity when comparing systems with equivalent amounts of fluctuating RE.

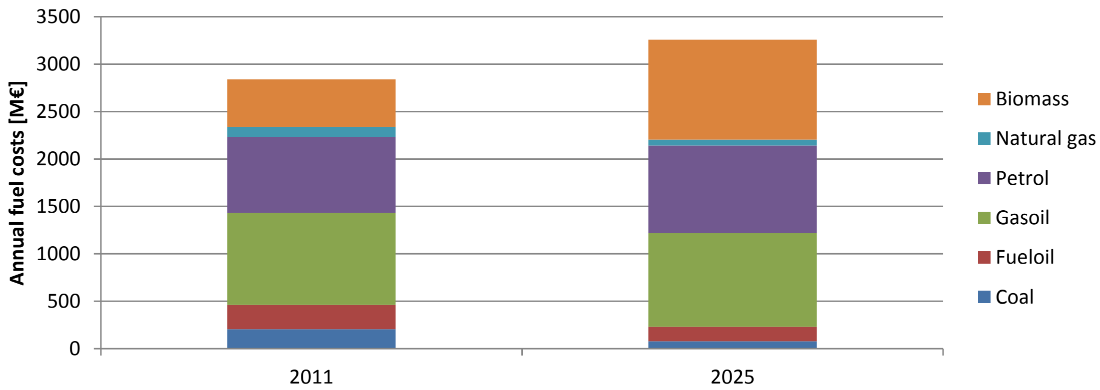

Figure 7.1: Distribution of fuel costs on the different fuel types in the reference systems.

The analysis of each of the scenarios is divided into two according to DH groups; 2 and 3. The focus is on these two groups because these groups are interlinked with the electricity system by the CHP, HP and EB capacities. HP capacities could be implemented in DH group 1 as well, but EnergyPLAN does not support this so the analysis of this is omitted.

Figure 7.2 on the next page shows the distribution of heat production between the different production units for DH group 2 and 3 respectively. This illustrates some of the differences between the two groups. In group 2 there is some HP capacity where there is none in group 3, but on the other hand there is no geothermal heat production in group 2 which there is in group 3. The boiler share is also significantly larger in group 2 than in group 3 which may be because of the higher overall efficiency of the CHP units in group 3 and because the CHP capacity in DH group 2 is not sufficient to cover the highest peaks in heat demand.

Another important difference is that the CHP in group 2 is back pressure units which produce heat and electricity in a fixed ratio, whereas the CHP in group 3 is extraction units which have a variable heat/electricity ratio. This creates a larger flexibility of production in group 3 than in group 2. Another factor that should be noticed is the total DH production which is 2.57 TWh in group 2 and 9.3 TWh in DH group 3 which indicates that there might be a larger potential for implementation of TES. The differences mentioned here are used to explain differences in the results in the following sections.

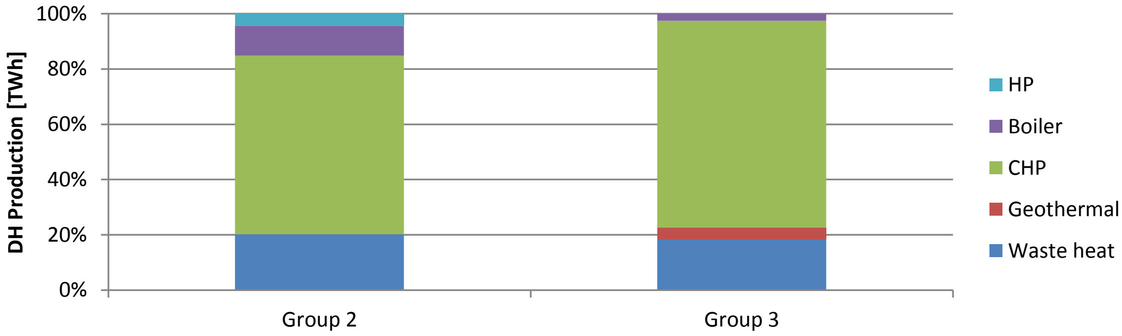

Figure 7.2: DH production share in DH group 2 and 3 divided on the type of production unit in the Reference 2025 scenario.

7.3 TES Scenario

In this scenario it is assessed how increased TES capacity implemented in the Reference 2025 scenario will influence the system. The detailed data input for the model can be found in Appendix A on page 105. The analysis is done in two steps; first the TES capacity is varied for DH group 2 and secondly the capacity is varied for DH group 3. The results of varying the TES capacity for the two DH groups is presented and discussed for each step.

7.3.1 DH group 2

When the TES capacity is increased the system has a larger capacity to use for optimization of the production and the operation of the system. In DH group 2 the full capacity of the storage is being utilized until 33.06 GWh, but for larger capacities the system still only uses 33.06 GWh of the storage capacity. Capacities larger than this cannot be utilized by this particular system.

To assess the, for this case, three important indicators PES, CO_2 and Annual costs, the values have been indexed according to the Reference 2025 values seen in Table 7.1 on page 52, to see the relative development of each indicator as the TES capacity is increased. Figure 7.3 on the facing page shows the three indexed indicators as a function of the TES capacity. It is seen that the PES is reduced towards 40 GWh and the CO_2-emissions are increased slightly. This is because the storage increases the flexibility of the CHP and thereby the number of hours it can operate because the CHP has a higher share of fossil fuel consumption than the alternative boilers have. The costs are increasing from 8.85 GWh and never come below index 1. This means that no increase of the TES capacity will be a socioeconomically feasible solution. The CEEP remains constant at 2.29 as the TES capacity is increased which means that the TES in this case cannot increase the system flexibility.

In Table 7.2 on the next page the absolute values for PES, CO_2 and Annual costs are seen for three different values of TES. These values are used in the coming sections as index 1 in the analyses of increased HP and EB capacities.

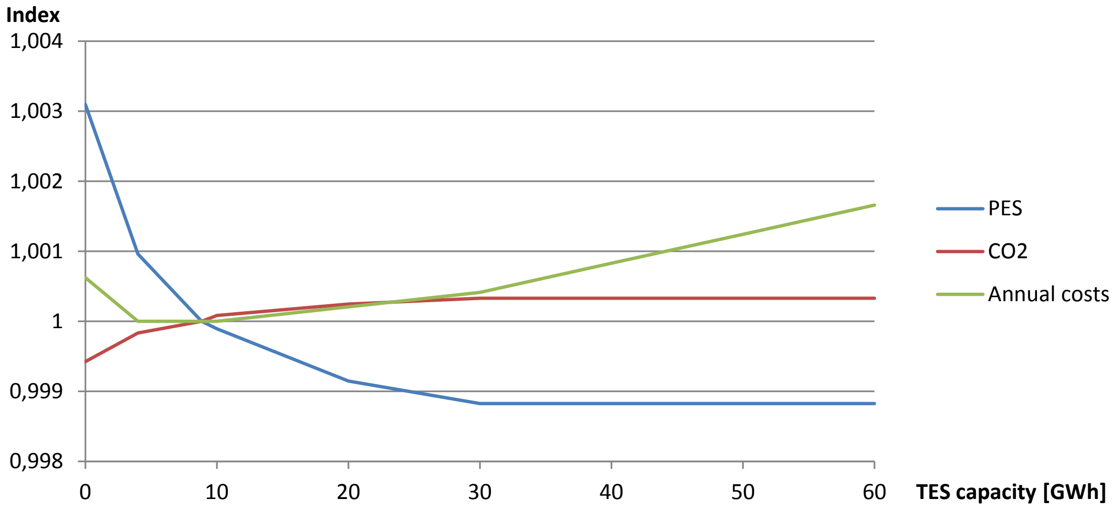

Figure 7.3: Indexed values of PES, CO_2 and Annual costs as functions of TES capacity in DH group 2. Index 1 is the values seen in Table 7.2 for Reference 2025.

	PES [TWh]	**CO_2 [Mt]**	**Annual costs [M DKK]**
Reference 2025 (8 GWh)	93.63	12.15	35,972
30 GWh	93.52	12.15	35,987
60 GWh	93.52	12.15	36,031

Table 7.2: Absolute values of PES, CO_2 and Annual costs of increasing values of TES in DH group 2.

7.3.2 DH group 3

In DH group 3 when the storage capacity is increased the full capacity of the storage is being utilized until 69.71 GWh and capacities larger than this cannot be utilized by this particular system. Figure 7.4 on the following page shows a graph parallel to Figure 7.3 showing the indexed values of PES, CO_2 and Annual costs but for DH group 3. The development here is simple compared to the one for group 2. Both PES and CO_2 are decreasing slightly and constant hereafter. Only the annual costs are increasing, but this is caused by the increased investment costs for the increasing capacity of TES. Like for the DH group 2 the CEEP remains constant at 2.29 TWh with the increased TES capacity.

In Table 7.3 on the next page the absolute values for PES, CO_2 and Annual costs are seen for three different values of TES. These values are used in the coming sections as index 1 in the analyses of increased HP and EB capacities.

The flexibility that increased TES 3 capacity can generate almost has no value to this system. The capacity of storage that can be utilized by the system Is larger than the one for DH group 2, but this may be caused by the fact that the total demand of DH group 3 is 3.6 times larger than in group 2. The effect of implementing the TES to the system is still lower than in group 2 though. This may be explained by the fact that the production system of group 3 is more flexible already because of the extraction plants' capacity to regulate the production.

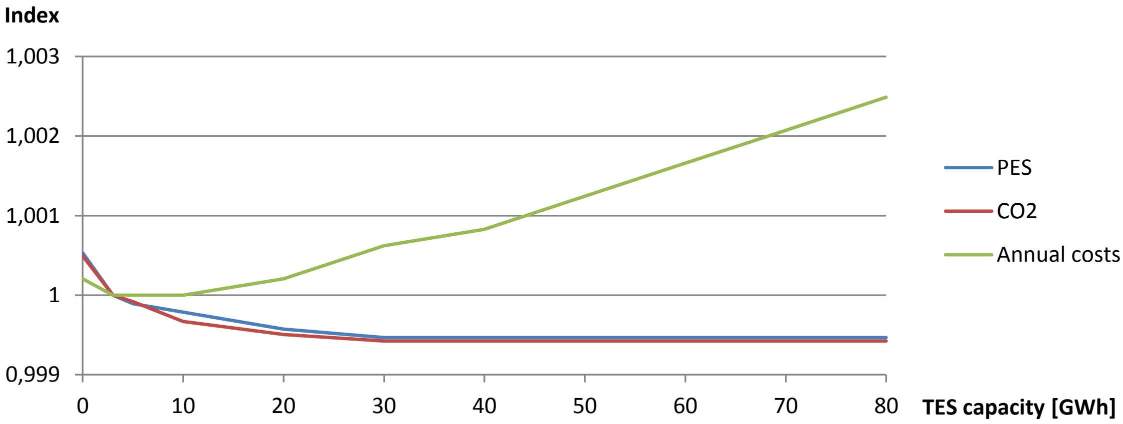

Figure 7.4: Indexed values of PES, CO_2 and Annual costs as functions of TES capacity in DH group 3. Index 1 is the values seen in Table 7.3 for Reference 2025.

	PES [TWh]	CO_2 [Mt]	Annual costs [M DKK]
Reference 2025 (8 GWh)	93.63	12.15	35,972
40 GWh	93.58	12.14	36,002
80 GWh	93.58	12.14	36,062

Table 7.3: Absolute values of PES, CO_2 and Annual costs of increasing values of TES in DH group 3.

7.4 TES + HP Scenario

In this scenario it is assessed how increased HP capacity combined with increased TES capacity implemented in the Reference 2025 scenario will influence the system. The detailed data input for the model can be found in Appendix A on page 105. The analysis is done in two steps; first the capacities are varied for DH group 2 and secondly the capacities are varied for DH group 3. The results of varying the HP capacity in a system with increased TES capacity for the two DH groups will be presented and discussed for each step.

7.4.1 DH group 2

Figure 7.5 on page 58 shows the impact of increasing the HP capacity in DH group 2 with the same TES capacity as the Reference 2025. This is interesting for comparison to the following two systems where the TES capacity is increased. Figure 7.5 is placed on the same page as 7.6 and 7.7 on page 58 to ease the comparison of the three. The full capacity of the storage is utilized for all HP capacities. In the figure it is seen that the PES and the CO_2-emissions are reduced as a consequence of the increased HP capacity. The annual scenario costs are constant until around 40 MW where it starts to increase which means that the capacity in DH group 2 can be increased to 40 MW without increasing the total socioeconomic costs.

The CEEP is being reduced from 2.29 TWh in the Reference 2025 at a HP capacity of 11.06 MW to 2.05 TWh at the HP capacity of 200 MW. See Table 7.4. This indicates that the larger HP capacity increases the flexibility of the system.

HP 2 capacity [MW]	**11.06**	**50**	**100**	**200**
CEEP [TWh]	2.29	2.21	2.13	2.05

Table 7.4: CEEP with increasing HP 2 capacity in the system.

Figure 7.6 shows the same system as in Figure 7.5 just with an increased TES capacity of 30 GWh. For this system it is known from previous section that the capacity of TES will be fully utilized without increased HP capacity. Here it could be expected that the increased HP capacity would increase the system's capacity to utilize the TES capacity by converting the present excess electricity production to thermal energy and charging it to the TES, but in this case the opposite is the result. As the graph shows the degree of storage utilization is decreasing as the HP capacity is increased. There is a peculiar increase in the storage max use from 50 MW to 100 MW which is hard to explain, but it might be because of the heat demand pattern and the level of the peaks. It can also be seen that the PES is increased compared to the situation in Figure 7.5 where no additional TES have been implemented, but the CO_2 emissions remain almost the same. The costs have been increased marginally as a result of the additional investment costs for the increased TES capacity. The CEEP remains exactly the same as shown in Table 7.4 with no additional TES capacity. This means that by having larger TES in the system with HPs the system gets higher fuel consumption and higher total costs without reducing the CEEP.

In Figure 7.7 the TES capacity is increased further to 60 GWh, which is more than the reference system is able to utilize, to see if the system with HPs implemented can utilize a larger capacity of TES than without the HPs. The analysis shows that the same tendency occurs here as for the system with 30 GWh of TES, but just more pronounced. As expected, the storage is not fully utilized without any HP capacity, but the TES utilization only decreases as the HP capacity is increased. Here the PES is also increased compared to the situation shown in Figure 7.5, the CO_2-emissions are slightly decreased and the costs are also increased. This shows that also in this system there are no real benefits of combining the TES and HP in DH group 2.

In this last case the exact same development of CEEP is present. See Table 7.4. As the development of CEEP with the increased HP capacity is identical for the three different TES capacities it indicates that the TES and HP capacities are not able to work together. It seems more like they are working against each other and reducing the potential flexibility they both can offer to the energy system. One explanation to this can be that the thermal energy produced by the HP may only be used to cover a present demand and not to produce for storage and later use. This explanation fits with the results showing that the increased HP alone reduces the fuel demand and the CEEP. By utilizing an increasing amount of the excess electricity to produce heat it thereby substitutes some fuel consumption for the alternative heat production.

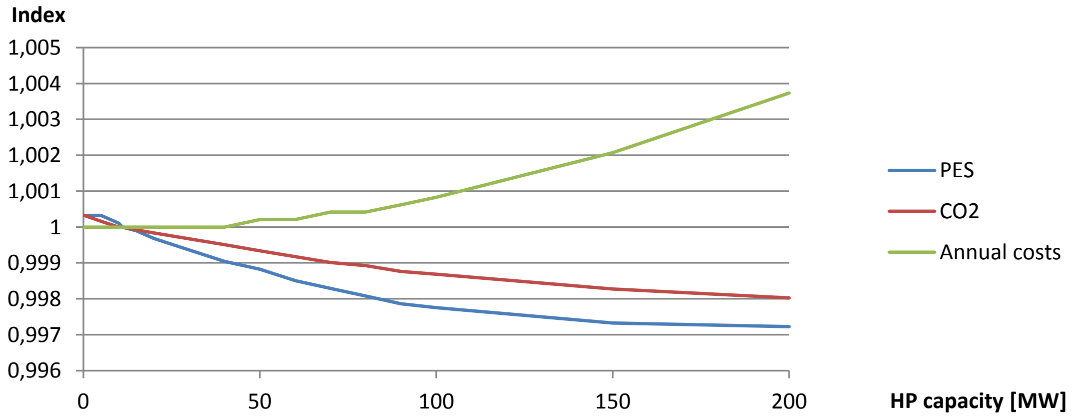

Figure 7.5: Indexed values of PES, CO_2 and Annual costs as a function of HP 2 capacity with TES capacity as reference. Index 1 is the values seen in Table 7.2 for Reference 2025.

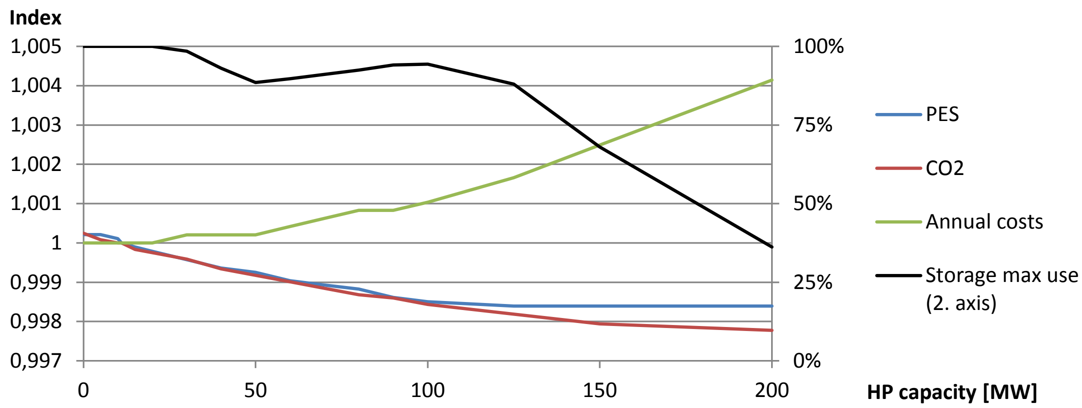

Figure 7.6: Indexed values of PES, CO_2 and Annual costs as a function of HP 2 capacity with TES capacity of 30 GWh. Index 1 is the values seen in Table 7.2 for 30 GWh.

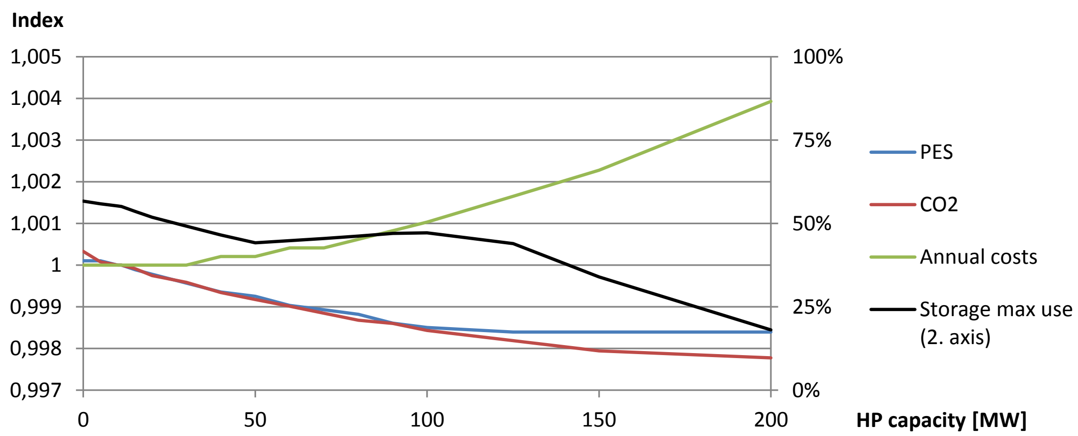

Figure 7.7: Indexed values of PES, CO_2 and Annual costs as a function of HP 2 capacity with TES capacity of 60 GWh. Index 1 is the values seen in Table 7.2 for 60 GWh.

7.4.2 DH group 3

In Figure 7.8 to 7.10 on the next page analyses are illustrated parallel to the previous analyses, but here for DH group 3. As mentioned, there are some differences between DH group 2 and 3 that makes it relevant to look at both groups individually to see how they respond to implementation of TES and HP.

Figure 7.8 shows the impact of increasing the HP capacity in DH group 3 keeping the same TES capacity as for the Reference 2025. This is mainly used for comparison to the following two systems where the TES capacity is increased. The full capacity of the storage is utilized for all HP capacities in this setup which is the reason that it is not shown in this first figure. It is seen that the CO_2-emissions remains almost constant as the HP capacity is increased and the PES is decreasing slightly. This means that the effect of increasing TES in group 3 is low. In Table 7.5 it is seen that the CEEP remains almost constant as well in this case, only slightly reduced. This indicates that the larger HP capacity does not increase the flexibility of this system. The analysis shows that there will be no significant benefit of increasing the HP capacity in this system.

HP 3 capacity [MW]	**11.06**	**50**	**100**	**200**
CEEP [TWh]	2.29	2.25	2.24	2.23

Table 7.5: CEEP with increasing HP 3 capacity in the system.

Figure 7.9 shows the same system as in Figure 7.8 just with an increased TES capacity of 40 GWh. For this system it is known from previous section that the capacity of TES of 3 GWh will be fully utilized without increased HP capacity. Like for the analysis of DH group 2 it could be expected that the increased HP capacity would increase the systems' capacity to utilize the TES capacity, but also in this case the opposite is the result. As the graph shows the degree of storage utilization is decreasing as the HP capacity is increased. The CEEP remains exactly as shown in Table 7.5 where there is no additional TES capacity. This means that there is no positive effect of increasing the TES to 40 GWh in the system with increased HP capacity.

In Figure 7.10 the TES capacity is increased further to 80 GWh, which is more than the 69.71 GWh the reference system is able to utilize, to see if the system with HPs implemented can utilize a larger capacity of TES than without the HPs. The analysis shows that the same tendency applies here as for the system with 40 GWh of TES. The storage is not fully utilized with no HP capacity, and the TES utilization only decreases as the HP capacity is increased. The development of PES, CO_2 and Annual costs are almost unchanged from the setting in Figure 7.9. This shows that also in this system there are no real benefits of combining the TES and HP in DH group 3.

In this last case the exact same development of CEEP is present as shown in Table 7.5. As the development of CEEP with the increased HP capacity is identical for the three different TES capacities it indicates that the TES and HP capacities are not able to work together. Generally the system in DH group 3 is affected very little by introducing increased capacities of HPs and TES. This may be because the system is flexible already and that TES and HPs do not contribute with any flexibility that can supplement what is already in place.

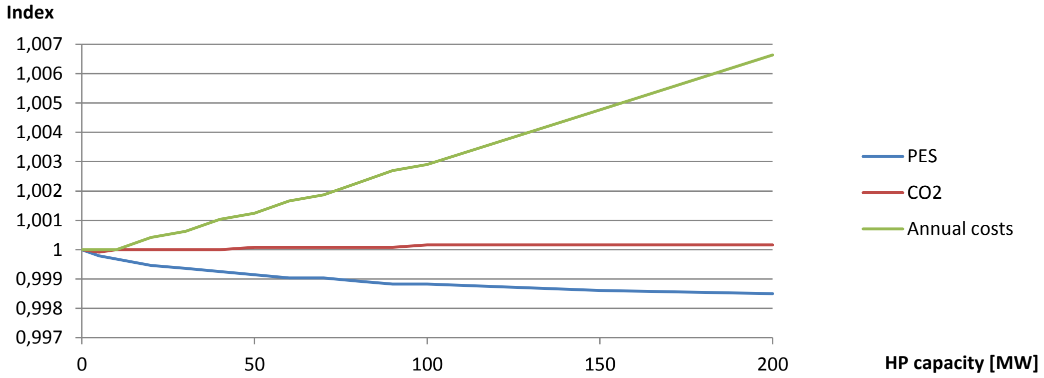

Figure 7.8: Indexed values of PES, CO_2 and Annual costs as a function of HP 3 capacity with TES capacity as reference. Index 1 is the values seen in Table 7.3 for Reference 2025.

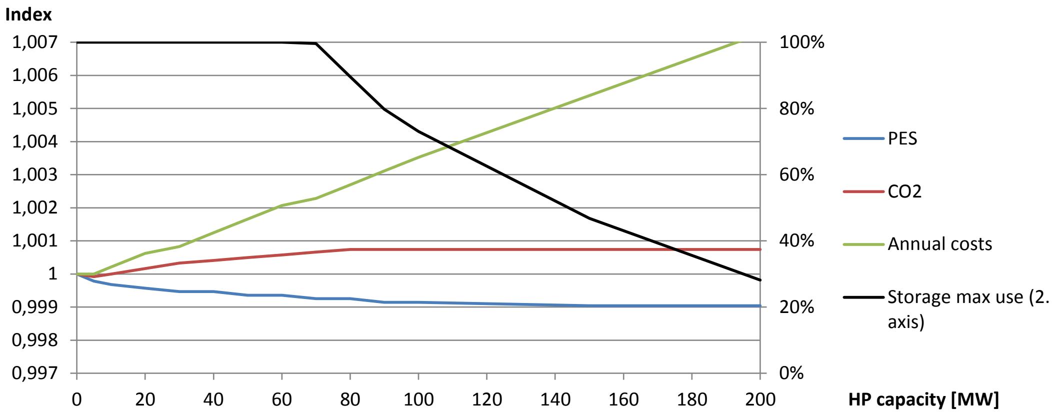

Figure 7.9: Indexed values of PES, CO_2 and Annual costs as a function of HP 3 capacity with TES capacity of 40 GWh. Index 1 is the values seen in Table 7.3 for 40 GWh.

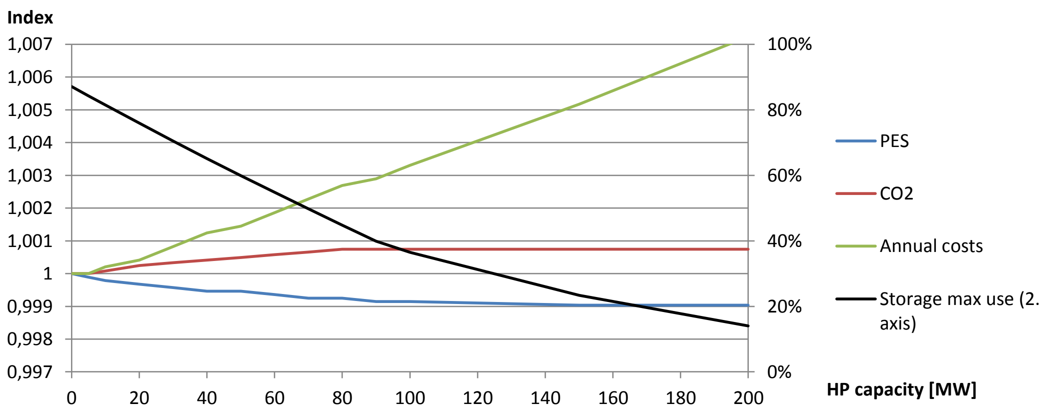

Figure 7.10: Indexed values of PES, CO_2 and Annual costs as a function of HP 3 capacity with TES capacity of 80 GWh. Index 1 is the values seen in Table 7.3 for 80 GWh.

7.5 TES + EB Scenario

In this scenario it is assessed how increased EB capacity combined with increased TES capacity implemented in the Reference 2025 scenario will influence the system. The analysis is done in two steps like the two preceding analyses; first the EB capacity is assessed for the DH group 2 and secondly for DH group 3. The results of varying the HP capacity in the systems with increased TES capacity for the two DH groups are presented and discussed for each step.

In the EnergyPLAN model EB capacity can be included in two different ways. The first way is to include it as a HP with a COP of 1 which then will work as an EB. The second way is in the regulation tab in the EnergyPLAN model to set up an EB capacity to utilize eventual CEEP for DH production in either DH group 2 or DH group 3. Here, like for the HP, DH group 1 is not an option. It is chosen to use the latter of the two ways because the results of the analyses presented in Section 7.4 on page 56 do not show any significant benefit of using HP and if the COP is just reduced to 1 to simulate an EB the benefit will be even lower. Therefore to reduce the possibility of an error in the model determining the results the alternative way to include EB is assessed in the analyses in this section.

When the EB is included in the regulation tab none of the costs related to the technology are included. These are added manually afterwards in a spreadsheet. In Table 3.2 on page 24 the costs used for this are seen.

7.5.1 DH group 2

Figure 7.11 on the following page shows the development of PES, CO_2 and Annual costs as the EB capacity in group 2 is increased. The storage is fully utilized and therefore not included in the graph. Instead the CEEP is included in the graph since the development of this is interesting in this case. It is seen that the PES is decreasing and the CO_2-emissions are increasing. The heat production from the EBs substitutes some heat production from the alternative production units which is the reason that the PES is reduced.

The fact that the CO_2-emissions are increasing at the same time may be because the CHP production in DH group 2 is reduced and the electricity produced here replaced with some condensation production in group 3 that has a higher share of fossil fuels. The annual costs are decreasing until about 400 MW and increasing hereafter. This means that increasing the EB capacity in the Reference 2025 is socioeconomically a good investment. It can also be seen that the CEEP is decreasing in this scenario like the case of the TES + HP scenario in DH group 2 which means that also increasing EB capacity is able to utilize a share of the CEEP.

Figure 7.12 on page 63 shows the development of the same four indicators as Figure 7.11, but in this case with an increased TES capacity of 30 GWh. The picture here is almost the same as the case with no additional TES capacity, but the PES is decreasing slower and the CO_2 is increasing slower with the increase of the EB capacity than in the other case. This means that the system with increased TES capacity is being affected less by the larger EB capacity. The annual costs now reach optimum at about 300 MW which means that the investment here is less beneficial than without the increased TES capacity. This is underlined by the CEEP which is also decreasing slower with the larger TES. In total this means that increased EB and TES capacities in DH group 2 do not work well together and do not supplement each other.

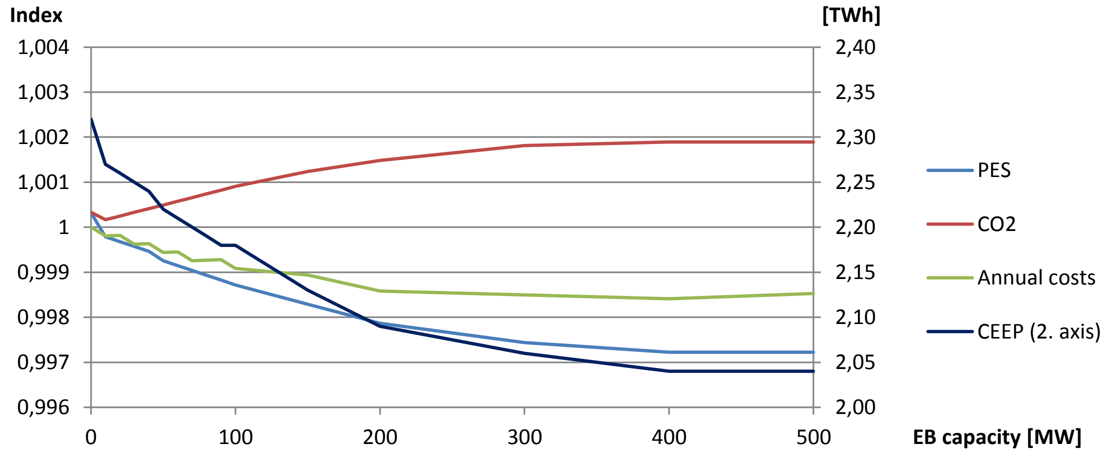

Figure 7.11: Indexed values of PES, CO_2 and Annual costs and CEEP as functions of EB 2 capacity for a TES 2 capacity as the reference. Index 1 is the values seen in Table 7.2 for Reference 2025.

7.5.2 DH group 3

Figure 7.13 and 7.14 on the facing page shows the same four indicators with 3 GWh and 40 GWh of TES respectively with the changes of EB capacity implemented in DH group 3. The two figures show almost identical pictures of the effect of implementing EB capacity in group 3 for both the reference capacity and the increased capacity of TES. In both cases the PES is reduced a bit towards 10 MW of EB and the CO_2-emission is increased a bit at the same time. Hereafter they are both constant with the increasing EB capacity. The annual costs are about constant, but start to increase slightly towards 200 MW. The CEEP is also decreasing much less here that in group 2.

This means that implementation of EB capacity in DH group 3 neither with nor without increased TES capacity. Like the result of the TES + HP analyses this also means that the effect of implementing EB capacity in DH group 3 is lower than in group 2 because of the different system composition.

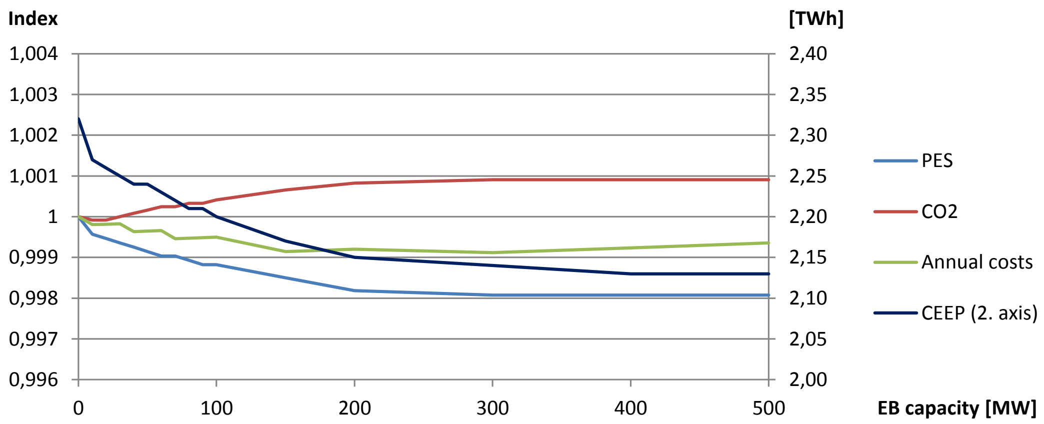

Figure 7.12: Indexed values of PES, CO_2 and Annual costs and CEEP as functions of EB 2 capacity for a TES 2 capacity of 30 GWh. Index 1 is the values seen in Table 7.2 for 30 GWh.

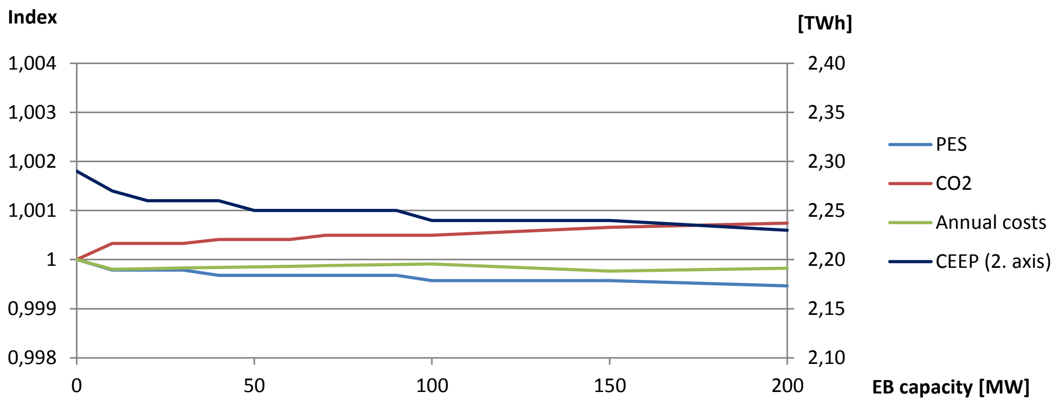

Figure 7.13: Indexed values of PES, CO_2 and Annual costs and CEEP as functions of EB 3 capacity for a TES 3 capacity as the reference. Index 1 is the values seen in Table 7.3 for Reference 2025.

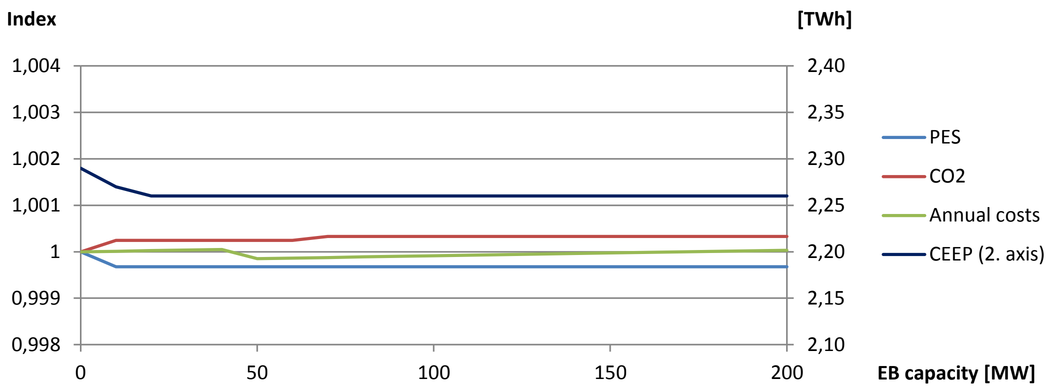

Figure 7.14: Indexed values of PES, CO_2 and Annual costs and CEEP as functions of EB 3 capacity for a TES 3 capacity of 40 GWh. Index 1 is the values seen in Table 7.3 for 40 GWh.

7.6 Sensitivity Analysis

In this section the sensitivity of the results will be analyzed for variations in the fuel price level and for the COP of HP.

7.6.1 Fuel Prices

The fuel prices are very volatile and it is hard to predict the development of the fuel prices in the future. The fuel costs is an important factor in the calculation of the socioeconomic feasibility of implementation of TES and possibly combined with HP or EB as the fuel costs makes up three quarters of the total scenario costs and therefore it is important to analyze the sensitivity of the calculation of changes in fuel prices. To assess the sensitivity to fuel prices of the results two alternative sets of fuel prices have been used. One is a higher price level and the other is a lower price level than the set used in the main analyses. The set of fuel prices used in the analyses is here called the medium prices. The specific used values are included in the same cost data file, which is included in the EnergyPLAN model, as used in the scenario analyses. In the model the medium prices is called "Basic", the low price set is called "Alternative 1" and the high price set is called "Alternative 2".

Figure 7.15 shows the annual costs for the Reference 2025 scenario for the three different sets of fuel prices. The high prices make the total costs increase with 17.9% compared to the medium prices and the low prices make the costs decrease with 11.4% compared to the medium prices.

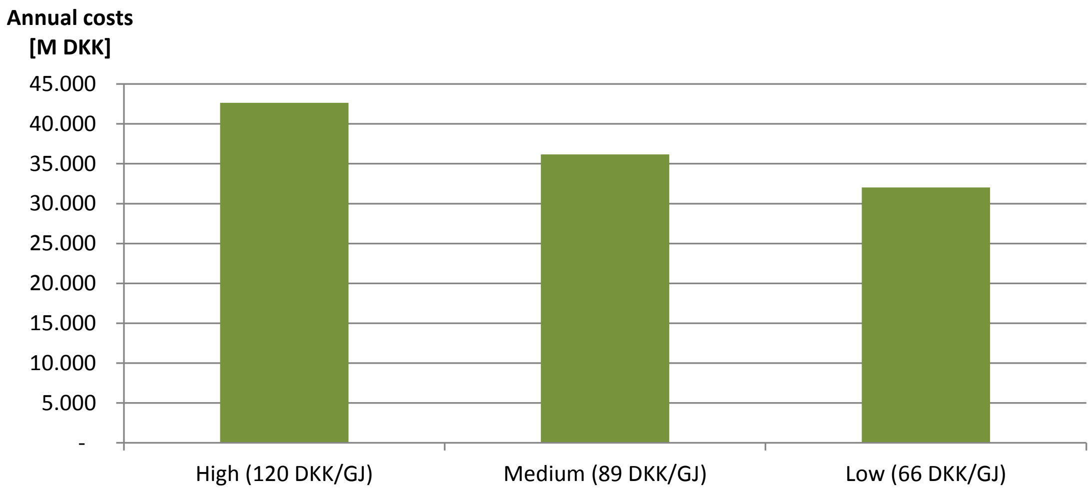

Figure 7.15: Annual costs for the Reference 2025 scenario for high, medium and low fuel price labled with the corresponding oil price.

In Figure 7.16 the relative development of the fuel prices in the TES scenario for DH group 2 is seen. The values are indexed according to the reference for each fuel price set respectively so they can be compared. In Figure 7.3 on page 55 the same graph for the annual costs in the TES scenario is shown only with the medium prices. Figure 7.16 shows that the development of the annual cost in the TES scenario is very similar between the three sets of fuel prices, but for the high prices the annual costs are marginally less affected than the low and medium.

That means that the change in fuel prices will not affect the result of the analyses, but it will change the magnitude of the total annual costs.

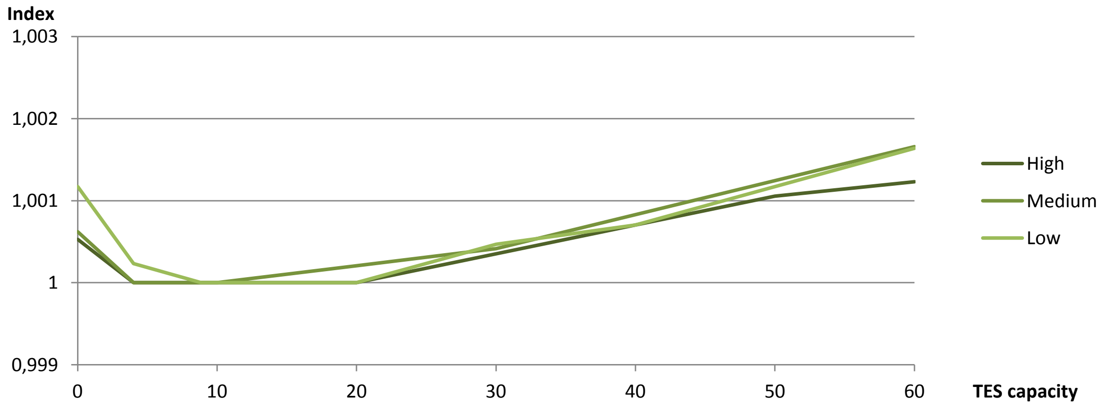

Figure 7.16: Indexed values of the annual costs of the TES scenario in DH group 2 for high, medium and low fuel prices.

In this sensitivity analysis only the TES scenarios for DH group 2 is presented as an example of the effect of changing the fuel prices, but the same tendency, that the relative difference is low, applies to DH group 3 and the other scenarios as well, so they are not all presented here.

7.6.2 COP of Heat Pump

The COP of a HP is very dependent on the temperature level of its heat source. This is further discussed in Section 7.7. The heat source can be geothermal energy or from a waste water treatment facility. It can also be through an aquifer possibly combined with ATES, as described in Chapter 3 on page 15. If there is no good heat sources the COP of the HP will decrease and it might be less feasible to implement the technology.

In the analyses in this chapter a COP of 1.95 is used for DH group 2 and a COP of 3.0 is used for DH group 3. See the references in Appendix A on page 105. The reason for this difference is that the units in DH group 3 is large CHP extraction plants which are typically located near cities and near the sea which is assumed to make a better potential for a heat source. The small CHP in DH group 2 is usually located in smaller towns with a less good potential for good heat sources.

To assess the impact of having a different COP than assumed in the calculations two alternative COP values for DH group 2 have been analyzed. As an example the TES + HP scenario in the case of 30 GWh of TES has been used. The one alternative value analyzed is 1.5 which is lower than the 1.95 assumed in the reference scenario. The other alternative is 3.0 which is higher than the reference and equivalent to the COP used in DH group 3.

Figure 7.17 shows the relative development of the annual costs with the three different values of COP. This figure can be compared to Figure 7.6 on page 58. It is seen that with lower COP the annual costs are higher. This is because when the HP has a higher COP it utilizes the energy more efficiently and thereby saves fuel. Generally the difference between the graphs is very small which means that in this particular system changes in the COP does not have a large impact on the feasibility of TES and HP.

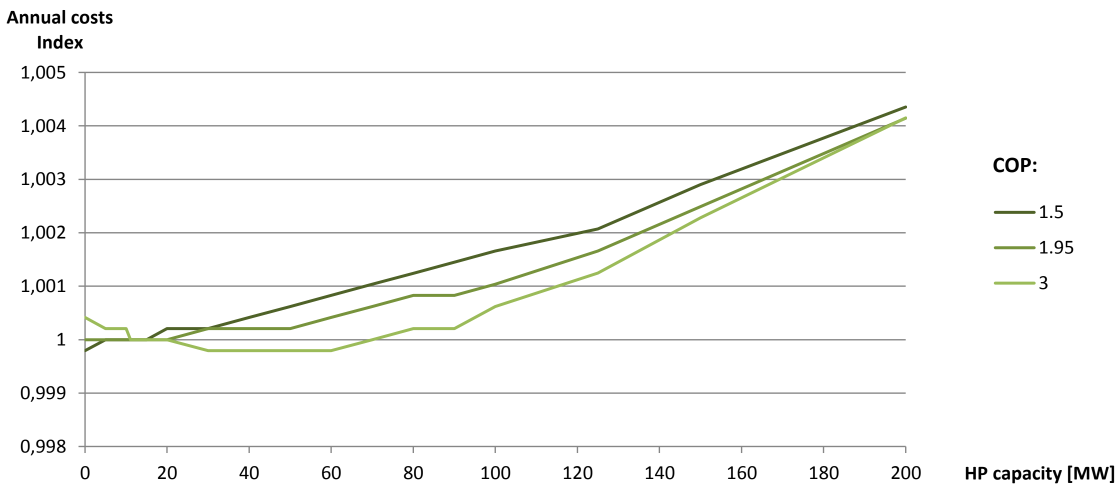

Figure 7.17: Indexed values of annual costs for COPs of 1.5, 1.95 and 3.0 in the TES + HP scenario in the case of 30 GWh of TES.

To see the impact of different COP for different TES capacities a system with 100 MW HP capacity in DH group 2 has been assessed for three values of TES and the two alternative COP values. The results of this is shown in Figure 7.18. The figure shows that the values for the higher TES capacity have higher costs and the higher COP gives lower annual costs.

It is seen that the difference caused by the COP is very similar for each of the TES capacities and this means that the COP affects the level of the annual costs, but it does not affect how large a TES capacity that will be feasible.

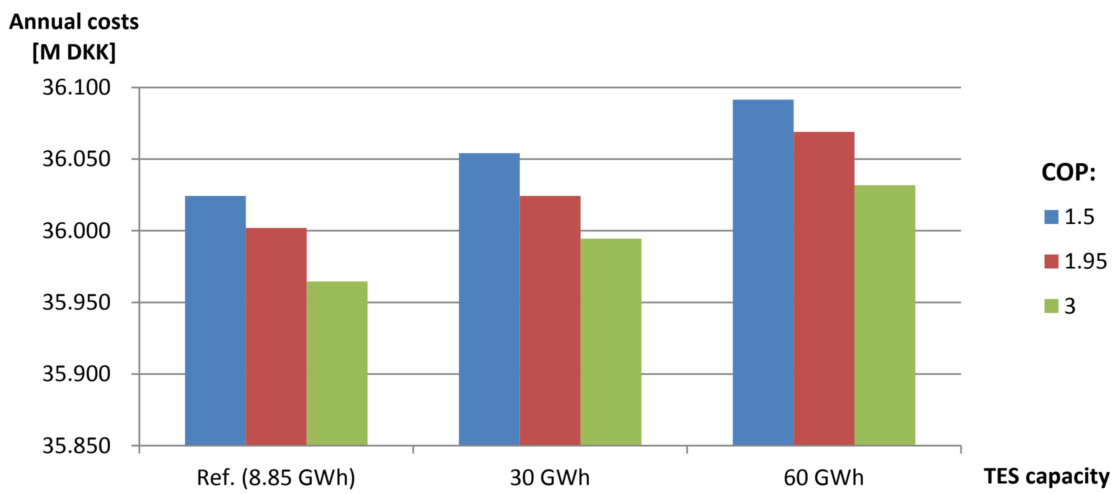

Figure 7.18: Annual costs for different TES capacities and three different values of COP.

Figure 7.19 shows the CEEP in the system for the three values of COP. It is seen that with the COP of 3 the CEEP is reduced less than in the case of lower COP. This may seem strange because more efficient HP capacity should be able to use the excess electricity more effectively. The reason is that the full heating load which can be covered by HP is already covered in some hours and when the COP then is increased it just uses less electricity to cover the same demand which increases the CEEP. This does not mean that the lower COP is a better solution as it was seen in Figure 7.17 that the higher COP is still more socio economically feasible. A part of the reason for this is also the fact that the model is not able the charge the TES with the HP. The tendencies shown in the figures 7.17 and 7.19 and described above also generally apply to DH group 3.

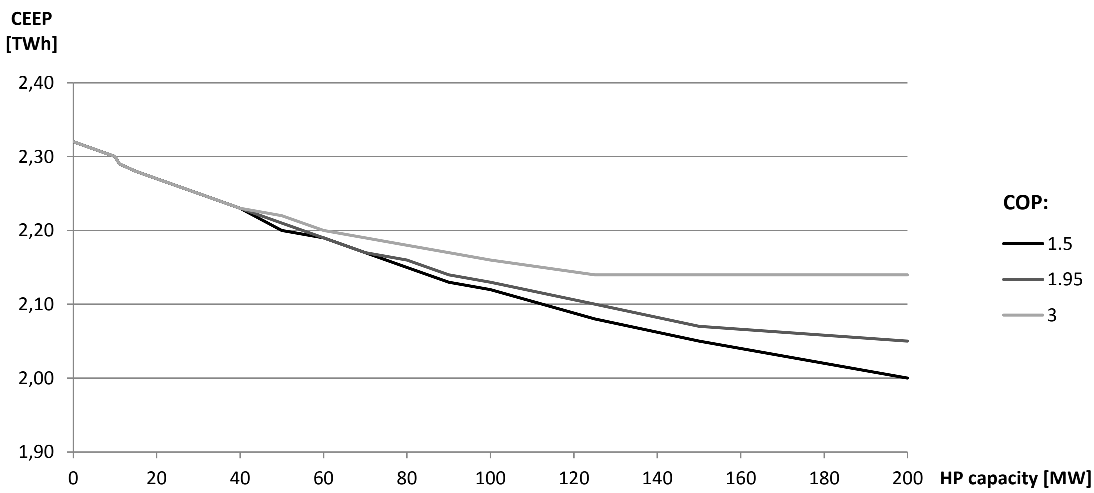

Figure 7.19: CEEP for COPs of 1.5, 1.95 and 3.0 in the TES + HP scenario in the case of 30 GWh of TES.

7.7 Discussion of EnergyPLAN Applicability

During the analyses using the EnergyPLAN model some issues in relation to the specific analyses of this project have been realized which will be discussed in this section. Three issues are discussed where the last of the three is far the most critical one.

7.7.1 TES, HP and EB in DH Group 1

The DH group 1 in the model only contains fuel based boilers and solar thermal capacities to cover the demand. This means that DH plants without CHP capacity, but with HP or EB capacity do not really fit in the model. Generally the EBs will be located at CHP plants because they often have a TES that they can use as a buffer, but there is no technical problem in having an HP or EB at a non-CHP DH plant.

The issue related to the analyses performed in this chapter is that the demand in DH group 1 cannot be included as a potential for TES and HP or EB in the future scenario for 2025 because these capacities simply cannot be implemented in group 1. The demand in group 1 is equivalent to 17% of the total demand in Reference 2025 and there might be a potential benefit of implementing TES, HP and EB here as well to cover a part of the heat demand as in the other DH groups.

7.7.2 Constant Heat Pump COP

In the model the COP for the HPs is a constant factor which means that it cannot take in account seasonal changes. The COP will in many situations be sensitive to the ambient temperatures and the general weather conditions because the HP is depending on a heat source. This means that the COP in the winter would be lower than the average and in the summer it would be higher than average.

The constant COP can be a problem to the analyses because this will give an inaccurate picture of how the heat demand will be covered. It is especially in the case of large capacities of HPs it is a problem because there might be some heat sources locally with a rather constant temperature throughout the year, but these are limited and in larger scale ambient temperature sources must be used. For example if the sea water is used as the heat source the COP will vary a lot over the year. As the model is working with an hourly time resolution it would give a more accurate simulation to have a variable COP.

7.7.3 Inability to Charge TES with Heat Production from HP and EB

This issue is experience through the analyses and the problem is that is seems like the model is not able to charge the TES with heat production from HP and EB. To quantify the problem a case from the analyses in this chapter has been chosen.

The case is the system with 30 GWh of TES and 100 MW of HP in DH group 2. See Figure 7.6. In this case it was expected that the combination of TES and HP would increase the performance of the system, but the analysis showed that the opposite was the case. It is seen that the full storage capacity is not utilized and at the same time there is a large CEEP which could be converted to thermal energy and charged to the unused capacity at the TES.

To assess this in detail the hourly values of the output of the system has been exported to a spreadsheet and analyzed further. If there exists an hour in this system where there is a CEEP > 0 and the HP capacity is not fully utilized it means that there is an error in the model because the CEEP could then be utilized by the HP to charge the TES. To assess if such an hour or several hours exist the hours in the spreadsheet have been counted where the following applies:

TES utilization < TES capacity **AND** HP load < HP max load **AND** CEEP > 0

The sum is 1,298 which means that in 1,298 hours of the year in the particular chosen case system there is CEEP, unused HP capacity and unused TES capacity at the same time. This is a very critical point because this basically means that EnergyPLAN is not able to properly model the main area of study in this project; the potential of combining TES and HP or EB.

7.8 Conclusions from the East Denmark Analysis

In this section the results of the analyses in this chapter is presented and seen in the light of the discussion of Section 7.5 it is afterwards concluded how the results are seen.

In the TES scenario it is assessed how an increase of the TES capacity to the Reference 2025 scenario will affect the system. The results show that the effect will be very small especially in DH group 2 where the reduction in PES and CO_2 is less than 0.1%. The annual socioeconomic costs are not reduced compared to the reference for any capacity of TES and the CEEP is constant for any capacity of TES. This means that there is not a good potential in increasing alone the TES capacity in the Reference 2025.

In the TES + HP it is assessed if an increased TES capacity will be more socioeconomically feasible in combination with HP. The results shows that without increased TES the increase of HP alone will improve PES and CO_2, but no reductions in the annual costs can be gained. When the HP capacity is increased in a system with also increased TES the results show that the effect of the HP and the performance of the system is slightly lower than without increased TES and neither the annual costs nor the CEEP are reduced. This means that there is also no potential in increasing TES combined with HP.

The analysis of the scenario TES + EB show generally the same results as the TES + HP. It shows that increasing EB capacity in a system with increased TES does not improve the system. Here, the CEEP is larger in the system with larger TES capacity compared to the reference. The results also show that a socioeconomic benefit may be gained from increasing the EB capacity alone, but with larger TES capacity at the same time the costs are increased.

As shown in Section 7.7 there might be an error in the EnergyPLAN model since the model does not seem to utilize the excess electricity optimally for this given system. This means that there might be a potential of combing TES with HP and EB even though the results of the analyses do not show it at this stage. If there is an error in the model these analyses may be performed again to show the right results.

Results of the CTR Analysis 8

This chapter describes the modeling of the transmission system of CTR including a system description, the main assumptions and limitations together with calculations and presentation of the results. A detailed description of the assumptions, inputs and calculations in the EnergyPRO model is found in Appendix C on page 125. The reference models used in the analyses are given on the CD attached to this report.

Before presenting the analysis, it should be noticed that the expectation of implementing larger capacities of TES, HP and EB in the system, is that these technologies use electricity and replace some of the fuel use, by charging the increased capacity of the TES from the HP or EB, or that those are able to supply some of the heat produced from electricity. The analysis frame in which the modeling of the system has been made and the most important assumptions to perform the analysis are presented in the following section.

8.1 Analysis Frame

The analyses of the CTR system are complex and the results depend on the system boundaries to a high extent. Therefore, the chosen boundaries used in these analyses are presented here. The modeling of the system is seen in two different frames; one for the heat perspective and a different frame for the economic perspective.

Heat Perspective: The boundary of the system from a heat perspective is the transmission grid of CTR. The frame of the modeling is shown in Figure 8.1 on the following page, where the square marked by the dotted line represents the system of the CTR transmission grid; i.e. the model includes all energy producing units within the area of CTR, the heat sale to VEKS, and the heat losses in the transmissions system. The model thereby indirectly includes the demand from the end users in which the distribution losses are included. The houses and the radiator placed on the right side of the exchange station represent the end-users.

Economic Perspective: To analyze the potential of implementation of TES, HP and EB from a socioeconomic perspective a boundary of the analyzed economic system is defined. The frame of modeling here goes outside the physical boundaries of the heat perspective and is set by economic reasons. In the economic calculations, the aim is to calculate the socioeconomic potential of the different alternative scenarios. In Figure 8.2 is the modeling frame of the economic calculations shown.

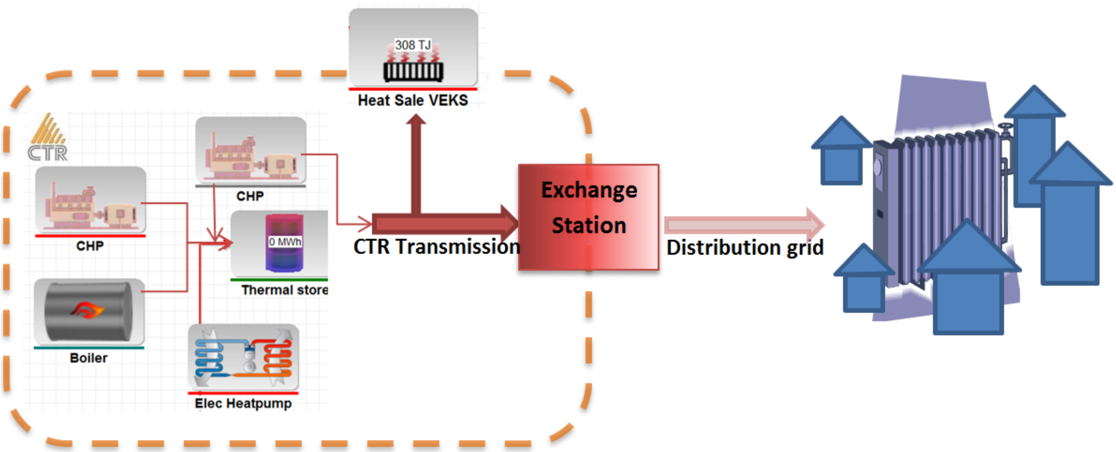

Figure 8.1: Heat perspective modeling frame of the CTR transmission system.

In the economic perspective, the model of the CTR system takes external elements outside the heat model into account; fuel costs, electricity sale and purchase, additional electricity purchase for HP and EB, and revenues from the heat sale to VEKS. Included in the economic calculations are the costs of annual investments, annual operation and maintenance, and annual electricity purchase to the hydraulic pumps in the system. Further the electricity sale from the CHP plants in the system is included in the calculations. The electricity market is seen as an external condition and the electricity price at the market is assumed to reflect the socioeconomic costs of the production of the electricity. Since the additional electricity used in the HP and EB is sold and bought at the same time, i.e. at the same price, this is balanced in the economic calculations.

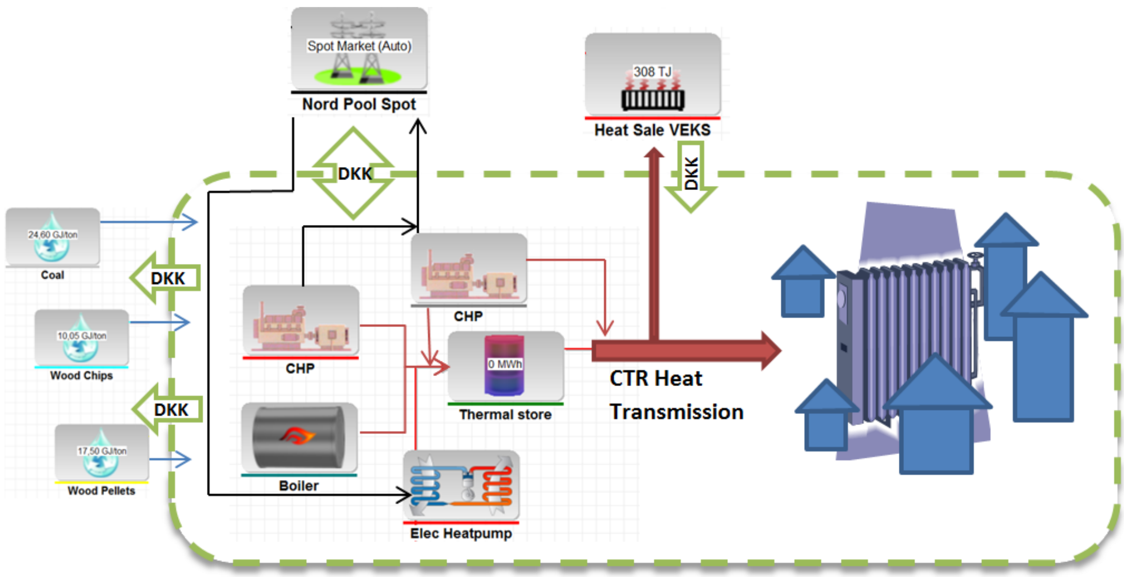

Figure 8.2: Economic perspective modeling frame of the CTR transmission system.

What is not taken into account in the economic calculation frame is the annual heat purchase CTR buys from the heat producing plants, since this is thought to be included in the fuel costs. With reference to Figure 8.1 and 8.2 and the described frame in the previous section, the model of the CTR transmission grid includes:

- All energy producing units with postal code within the area of CTR, i.e. postal codes in Copenhagen municipality and the municipalities of Tårnby, Frederiksberg, Gentofte and Gladsaxe. This includes: CHP plants, boilers, EB/HP and geothermal units with fuel inputs and fuel costs. CTR has some production capacity available at Avedøreværket (Magnusson 2013), which is not taken into account in the model
- The demand of the transmission system includes heat sale to VEKS, heat loss of the transmission system and demand from the end users in CTR area. The demand from the end users in CTR includes the losses from the distribution grid. Normally there is an overall heat loss of 7% (Magnusson 2013)
- The electricity market is only included by use of the spot market prices on hourly basis in 2011 and 2025 for sale of electricity, since the system includes electricity producing units; CHP plants, and wind consuming units in terms of the modeled HP and EB
- The costs of annual electricity purchase, investment, and O&M have the same values in 2011 and 2025 as the economic calculations in 2025 is represented in 2011 values.
- Investments in the conversion of the CHP plants to a biomass based production is assumed to be covered by other parties and is therefore not included in the economic calculations for CTR.

8.2 Key Indicators

In the following a short description of the indicators is presented, which the scenarios are compared according to:

Annual SEC: This is the result of the economic calculation by the EnergyPRO model, including fuel costs, revenues from electricity and fixet annual investments and O&M costs. This parameter is included, since it is through these economic calculations, the model optimize the system according to the set operation strategy by minimizing net production costs.

Annual SEC incl. Investments: In this parameter **additional** investments are included together with O&M costs for larger TES, HP and EB capacities. By making this calculation it is possible to see, if and when the additional investments exceed the benefits from the changed system by implementing higher capacities of TES, HP and EB.

PES: This is the annual fuel use from the system. This parameter indicates if the changes of the system impact the annual fuel use.

Net electricity production: This indicator shows the amount of electricity exported from the system with the additional electricity consumption from HP and EB subtracted.

TES utilization: Expresses of how many MWh on annual basis, the TES has been filled hour by hour compared to the maximum MWh. A smaller percentage in the TES utilization is not necessary indicating, that the store is used less. This can also be an expression of that the larger the store, the longer it takes to load and unload, which gives a lower average use.

TES load: The TES load indicates how much energy that has been charged to the TES. This parameter is calculated in a spreadsheet based on the load on the TES hour by hour by the following criterion:

IF $\text{load}_i > \text{load}_{i-1}$ then load_i - load_{i-1} otherwise 0

The parameter thereby shows how many GWh there has been charged to the TES throughout a year, and is thereby another parameter that shows how the TES help increase the flexibility of the system. The charge of the TES end at the same level as it starts.

HP/EB utilization: This is similar to the TES utilization parameter. The parameter shows the percentage of how much the HP or EB have been running throughout a year. This percentage is calculated based on the used GWh on the units given by the EnergyPRO model compared to the maximum possible, calculated by multiplying the power capacity (MW) by the number of operating hours over the year (h).

In this analysis CO_2-emissions are not included as an indicator because the amounts of CO_2-emissions from the scenario are not influence by the assessed parameters and the CO_2-emissions will therefore remain constant in all scenarios. The total CO_2-emissions from the reference scenarios are presented in Table 8.2 on page 77.

8.3 Reference Scenario

The 2011 Reference scenario serves as base for the Reference scenario of 2025 and is not used further. The 2025 Reference scenario then serves as base in the alternative scenarios including larger TES, and increased capacities of HP and EB. The distribution of fuels in reference year 2011 and the fuel use according to the CO_2-neutral scenario in the climate plan used in the 2025 Reference scenario is shown in Figure 8.3. For 2025 fuel oil, gas oil and LPG are not used in the system, while bio oil is used as fuel in the boiler for peak load. The use of fossil fuels is in general decreasing, while the use of fuels based on biomass is increasing.

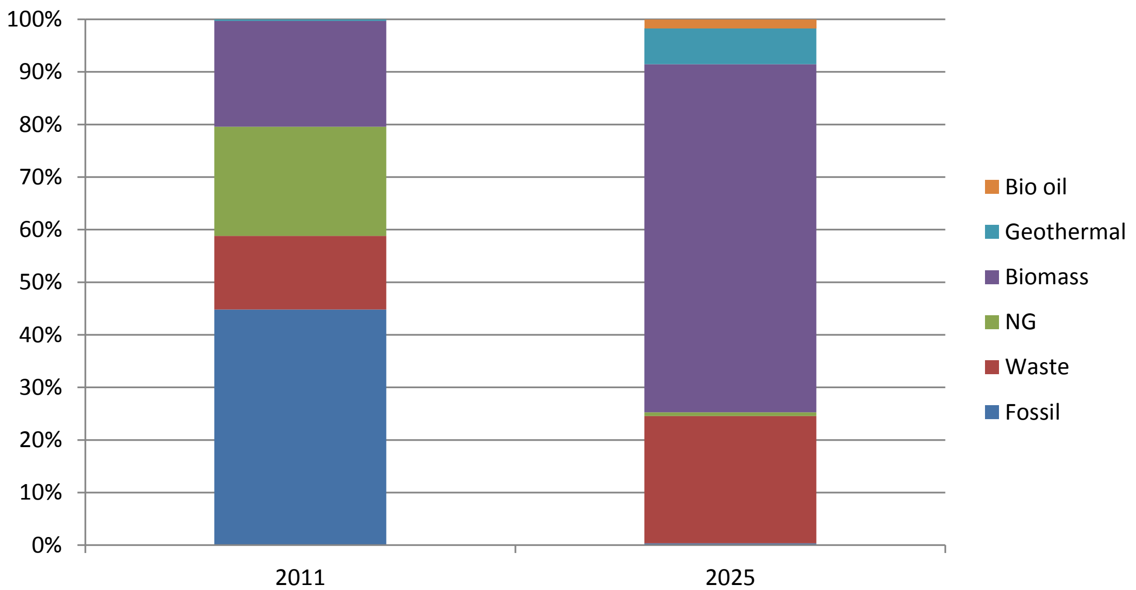

Figure 8.3: Share of fuel use in 2011 and 2025.

It should be noticed, that it was not possible for the calculated fuel values to cover the heat demand, neither in 2011 nor in 2025. This is due to the assumption of only including plants in the postal code area of CTR, where the capacity available at Avedøreværket it not included. Instead the uncovered heat demand has been covered in both 2011 and 2025 by adding additional capacity to the boiler; in 2011 covered by gas oil and in 2025 by bio oil. The calorific value for rapeseed oil is used. The fuel capacity has been found to be 1,000 MW on annual basis in both years, comparable is the peak load capacity in the CTR area in 2011 841 MW according to (CTR 2011).

8.3.1 Calculating Spot Market Price 2025

It is not possible to predict how much the higher share of wind and other fluctuating RE resources will influence the electricity price. The share of implemented RE in 2011 is already reflected in the 2011 spot market prices, but for 2025 where higher share of RE is expected in the system a price needs to be calculated. A calculation based on a projected average spot market price in 2025 from the Danish Energy Agency expected to be 616 DKK/MWh (DEA 2011e) and the relative fluctuation pattern from 2011 is applied to this. To simulate a system with a higher share of wind electricity the fluctuations are up scaled. It is here assessed how different degrees of fluctuation in the electricity prices impact the system. To do this analysis, a correlation of how much the price will vary compared to the price hour by hour in 2025 is found by Equation 8.1 for the New Electricity Price (NEP):

$$\text{NEP} = (\text{g(h) - M}) \cdot \text{f} + \text{M} \tag{8.1}$$

Where, g(h) is the function of the electricity price calculated every hour (h) in 2025 based on a correlation between the average price in 2011 and the expected average price in 2025. M is the average price in 2025 of 616 DKK/MWh and f is the fluctuation factor that indicates how much the price will vary. Figure 8.4 shows the tendency when f = 1.5.

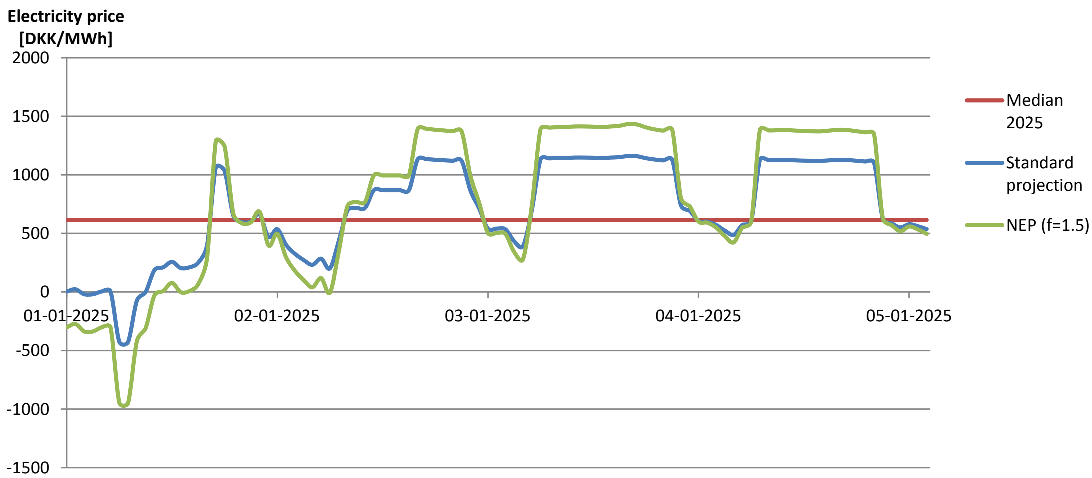

Figure 8.4: Fluctuations in the prices with a standard projection and with the NEP with f = 1.5 for four days in 2025.

On short term, the increased RE capacity in the system may reduce the electricity price, as wind production, for instance, is not a marginal electricity producer and therefore does not determine the electricity price. On long term, however, is the average spot market price expected to increase. Table 8.1 shows the influence on the Annual SEC, TES utilization and PES in the 2025 Reference scenario for different values of the fluctuation factor.

F-factor	Annual SEC [M DKK]	Storage utilization [%]	PES [GWh]
0.5	-268	61	7,451
1.0	-232	63	7,301
1.5	-184	64	7,219
2.0	-130	65	7,106
3.0	-13	67	6,985

Table 8.1: Annual SEC, TES utilization and PES compared to varied fluctuation factor.

The value of the fluctuation factor can be discussed and as seen from the values of the Annual SEC, the costs decreases when f increases. This means that in this scenario it gives a better socioeconomic result for the chosen area, when a higher degree of RE is implemented in the system. The higher degree of fluctuation in electricity prices also influences TES utilization and PES positively by a higher degree of TES utilization and a lower fuel use. With more fluctuating prices it is more beneficial in the CTR system to use the TES, reflected in the lower use of fuel and thereby a better economy due to lower fuel costs and higher electricity revenues.

In the following scenarios an electricity price with a fluctuation factor of 1.5 is used, when larger capacity of TES, HP and EB is implemented in the system as well. It is thereby the values of the 2025 Reference scenario with f = 1.5 that will be used as comparison, when varying the capacities of TES, HP and EB. This scenario is from here referred to as 2025 Reference scenario.

8.3.2 Presentation of the Reference Scenarios

In Table 8.2 on the next page the baseline values of the reference scenarios are shown, where it is seen that the PES decreases from 2011 to 2025. This is a consequence of the changes in the reference models; more CHP plants have been connected to the thermal store, as this is seen as a natural development in the system, resulting in a higher use of the TES where the TES utilization increases from 30% in 2011 to 64% in 2025. The much lower SEC seen in the Reference 2025 scenario is caused by the higher electricity revenues, since more CHP plants are connected to the TES and can thereby produce more electricity when high prices are high. See output prints from the EnergyPRO model in Section D on page 133 that shows a print from the economic calculations in 2025 Reference scenario.

In the Annual SEC of -184 M DKK in 2025 no additional investments are included. In the alternative scenarios including larger TES capacity, HP and EB, the investment price and the annual O&M of the chosen capacities is taken into account in the economic calculations. The CO_2-emissions are significantly lower in 2025 than in 2011 which is caused by the implementation of the suggestions from the HPC2 for the CO_2-neutral scenario. The CO_2-

emissions in 2025 are 94% from waste incineration and the remaining 6% is from a small amount of coal and natural gas.

	2011	2025
Total annual fuel use (PES) [GWh]	10,123	7,149
Annual CO_2 emission [Mt]	2.27	0.19
Annual SEC [M DKK]	-634	-184
Revenues [M DKK]		
Annual heat sale, VEKS	31	31
Annual el. sale	906	1,183
Expenditures [M DKK]		
Fuel costs	1,375	1,200
Annual investments	62	62
Annual O&M	72	72
Annual el. purchase	63	63
Storage capacity	1 GWh 24,000 m^3	1 GWh 24,000 m^3
Annual storage capacity [GWh/year]	8,770	8,770
Annual used storage capacity [GWh]	2,671	6,065
Used storage capacity [%]	30	64

Table 8.2: Baseline values of the Reference Scenario in 2011 and 2025.

8.4 TES Scenario

In the TES scenario it is assessed how increased TES capacity affects the modeled CTR system, when implemented in the 2025 Reference scenario. Only the TES capacity is varied in this scenario, meaning that all other inputs are kept the same as in the 2025 Reference scenario, see details in Appendix C on page 125. The influence of implementing a larger TES capacity is analyzed by increasing the TES capacity from 1 GWh in the 2025 Reference scenario to 83 GWh as the highest TES capacity. The economic results of this analysis is seen by the graph in Figure 8.5 on the following page, where the Annual SEC and Annual SEC including investments are showed as functions of the increased TES capacity. Table 8.3 shows the corresponding TES capacities in m^3 and GWh.

The economic calculation in this scenario includes the costs of the 2025 Reference system with additional expenditures to investment in larger TES capacity. The result shows that both the Annual SEC and the Annual SEC incl. investment costs are beneficial to the system, meaning that it is economically feasible to invest in larger capacities. The best economic result, when including investment costs, is when 21 GWh TES is implemented in the system.

m^3	72,000	120,000	216,000	300,000	500,000	1,000,000	1,500,000	2,000,000
GWh	1	5	9	13	21	42	63	83

Table 8.3: Corresponding TES capacities.

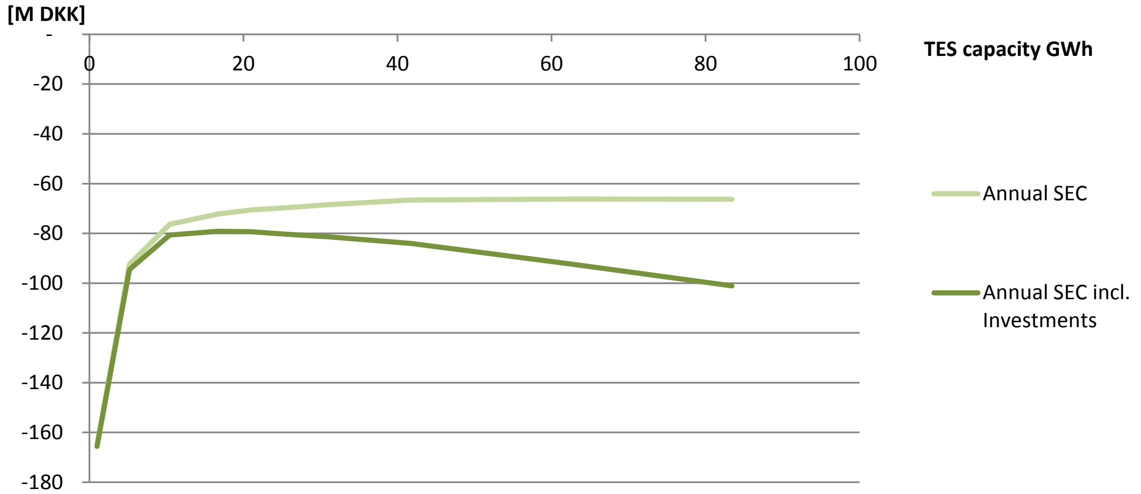

Figure 8.5: Annual SEC and Annual SEC incl. investments as functions of the TES capacity in TES Scenario 2025.

The reason for the better economy in the Annual SEC incl. investment can be explained by a better utilization of the fuels, when operating the system due to the chosen strategy of minimizing net production costs. The larger TES capacity allows the CHP plants in the system to produce more, when there are high electricity prices. This is seen by the fact that the electricity revenue in the 2025 Scenario was 1,183 M DKK, while it is 1,409 M DKK with a TES capacity of 21 GWh. As the TES capacity increases, the more additional electricity is the CHP plants capable of producing, seen from the increasing value of the Annual SEC incl. investments in the figure.

Due to the higher co-production at the CHP plants, the fuel use is slightly increasing in the system. This is seen in Figure 8.6, where the annual fuel use as well as the calculated TES utilization is shown. In Table 8.4 the different values of the TES parameters that are available from EnergyPRO are given. These values shows, that even though the TES utilization decreases as larger capacities are used, the load increases, meaning that the system is charging and utilizing the TES to a bigger extent, resulting in higher electricity revenues and fuel use.

TES capacity [GWh]	Average used TES capacity [MWh/h]	TES utilization [%]	TES load [GWh]
1	642	64	459
3	1,732	58	830
5	2,814	568	941
7	3,807	548	979
9	4,656	52	1,013
13	6,366	51	1,068
21	9,591	46	1,097

Table 8.4: Values of TES capacities, TES Scenario 2025.

Analyzing the absolute maximum capacity of TES, the modeled system is capable of using a capacity of 5,084,000 m^3, corresponding to 212.1 GWh. The Annual SEC of this system is -75.1 M DKK indicating, that the potential of additional electricity production due to larger

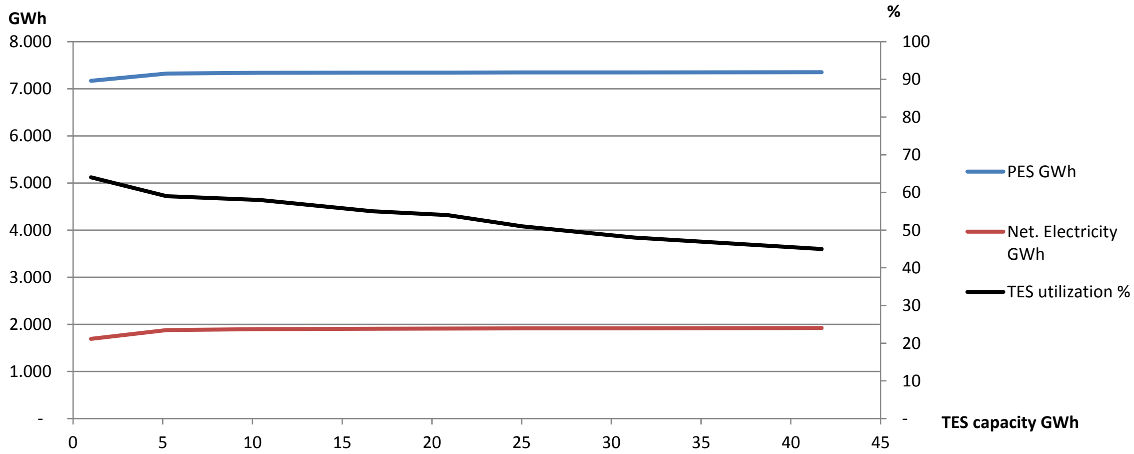

Figure 8.6: Values of PES, netto electricity and TES utilization as functions of the TES capacity in TES Scenario 2025.

TES capacities stabilizes at one point, and the investment costs will eventually exceed the economic benefits. The TES utilization here is only 11%.

8.5 TES + HP Scenario

This scenario has the purpose to investigate the influence on the 2025 Reference scenario when the capacity of the TES and HP is varied. In the first analysis, only the capacity of the HP is increased gradually, while the capacity of the TES is kept constant at 1 GWh. The results is shown in Figure 8.7 for the Annual SEC and Annual SEC incl. investments as functions of the varied HP capacity.

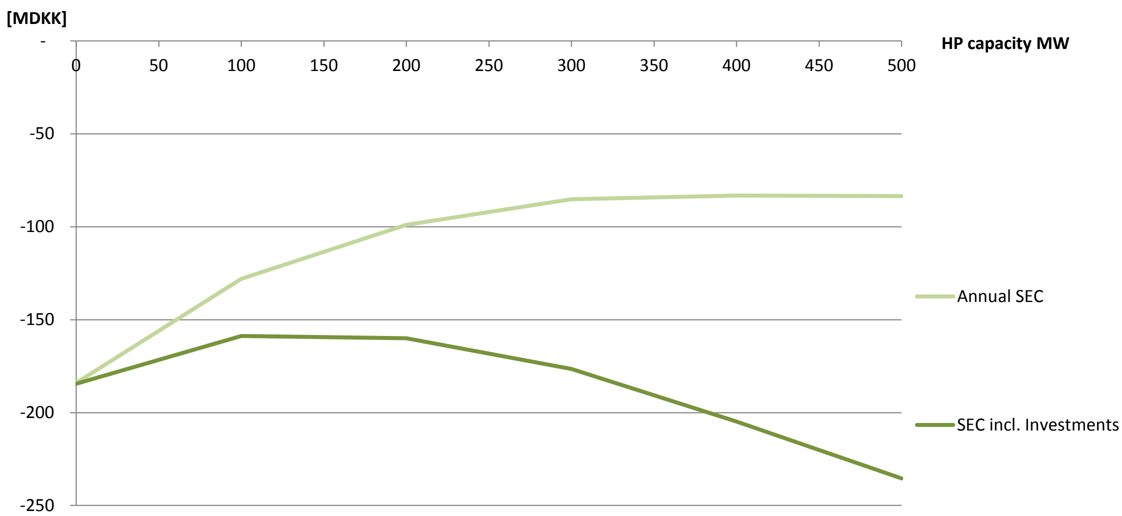

Figure 8.7: Annual SEC and Annual SEC incl. investsment as functions of the varied HP capacity.

According to the results, shown in Figure 8.7, it is still beneficial to invest in a HP capacity of up to around 300 MW for the system, while still having the TES of 1 GWh, since the Annual SEC including investments is higher than the reference, meaning that at this point the investments costs do not exceed the saved costs in the system. The HP capacity that gives the best SEC incl. investments is only 100 MW though. Due to the operation strategy of minimizing net production costs, the model places the production where it is cheapest, i.e. using electricity in the HP in the cheap electricity hours, but still produces electricity in the hours where the electricity price is high. This has resulted in a lower fuel use in this scenario, see Figure 8.8, where the PES, TES utilization and HP utilization is shown as functions of increased HP capacity. When higher HP capacities are available in the system, it is cheaper to let these run on electricity, than burning fuel in CHP plants, seen by the lower fuel use. Despite this, the HP utilization is only just above 20%, indicating that there might be a fine balance of what is cheapest to the system. Further under the operation strategy the HP is set to be of calculated priority, which means that they are not given high priority in the system as the base load producers of waste and geothermal.

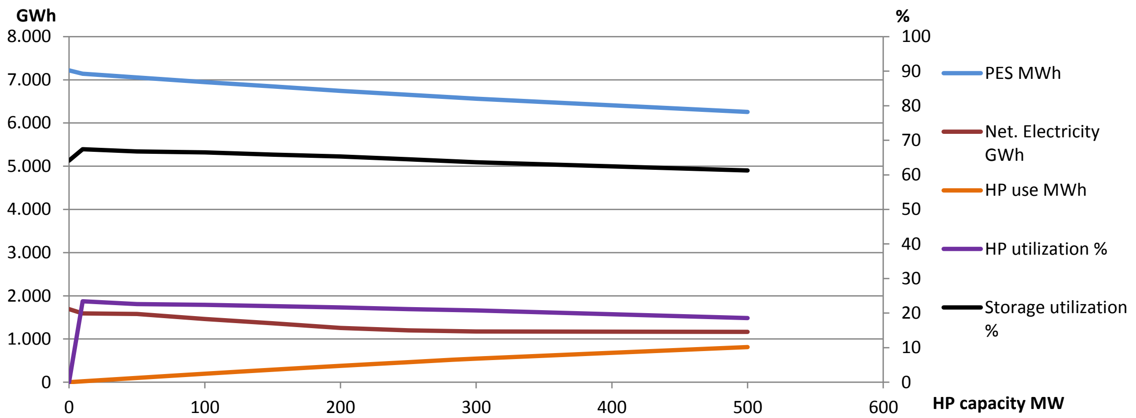

Figure 8.8: Values of PES, TES utilization and HP utilization as functions of the HP capacity in TES + HP Scenario 2025.

In Figure 8.9 it is seen that the increased HP capacity is replacing some of the heat production from primarily the boiler, but also from the CHP plants to a smaller extent, as the HP capacity increases. This is reflected in the lower fuel use shown in Figure 8.8. The TES load in this scenario is rather constant, varying from 459 GWh in the 2025 Reference scenario to 482 GWh in the scenario with 500 MW HP installed, but is still considered to contribute to the lower fuel use in the system.

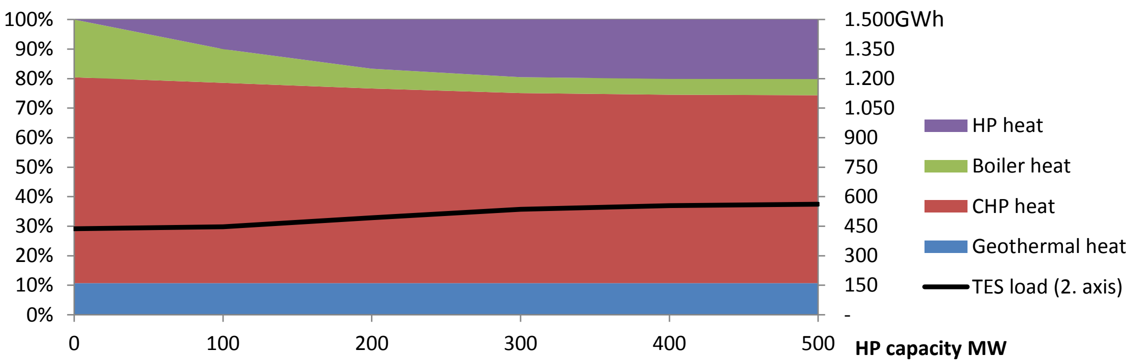

Figure 8.9: HP, boiler, geothermal and CHP heat production, and TES load as function of HP capacity in TES + HP Scenario 2025 for with reference TES capacity.

8.5.1 TES Capacity of 21 GWh and Varied HP Capacity

In this analysis a larger constant TES capacity is compared to an increasing HP capacity. The capacity of the TES is in this case kept constant at 21 GWh, since it is around this point in the TES scenario, that the Annual SEC is lowest. This is also here the best value of SEC incl. investments is found, which is at 0 MW HP capacity. Figure 8.10 shows values of the Annual SEC and Annual SEC incl. investments as functions of the varied HP capacity. The green dot represents the value of the 2025 Reference scenario.

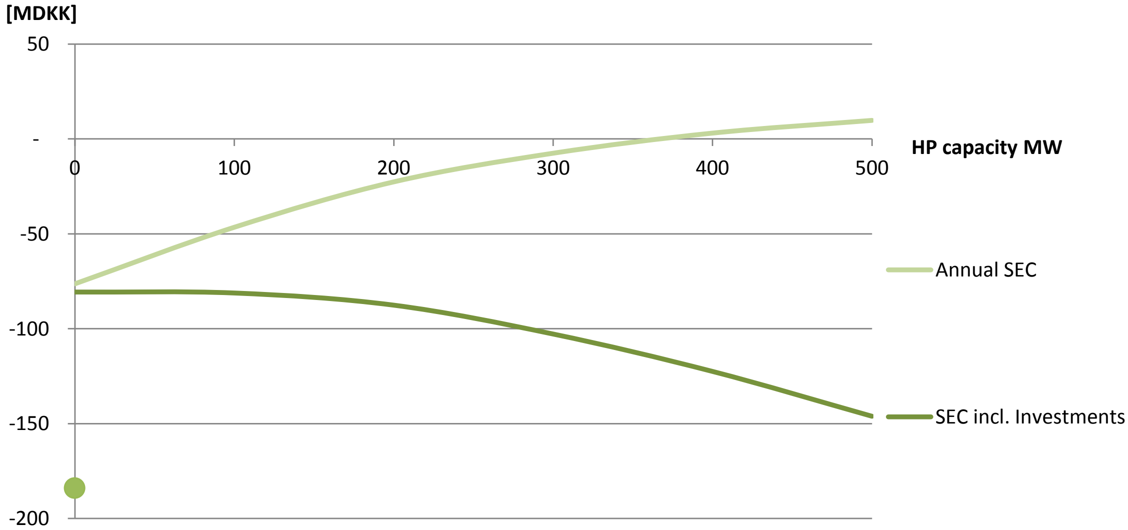

Figure 8.10: Annual SEC and Annual SEC incl. investments as functions of HP capacity.

The system seems to be able to utilize the high electricity prices and run the CHP plants in order to get higher revenues, since the spot market revenue at the point with 200 MW HP is 1,354 M DKK compared to the 2025 Reference revenue of 1,183 M DKK. The better Annual SEC is partially caused by the additional revenues and the decreasing PES, see Figure 8.11, where PES, HP use, HP and TES utilization, and net electricity produced, are shown.

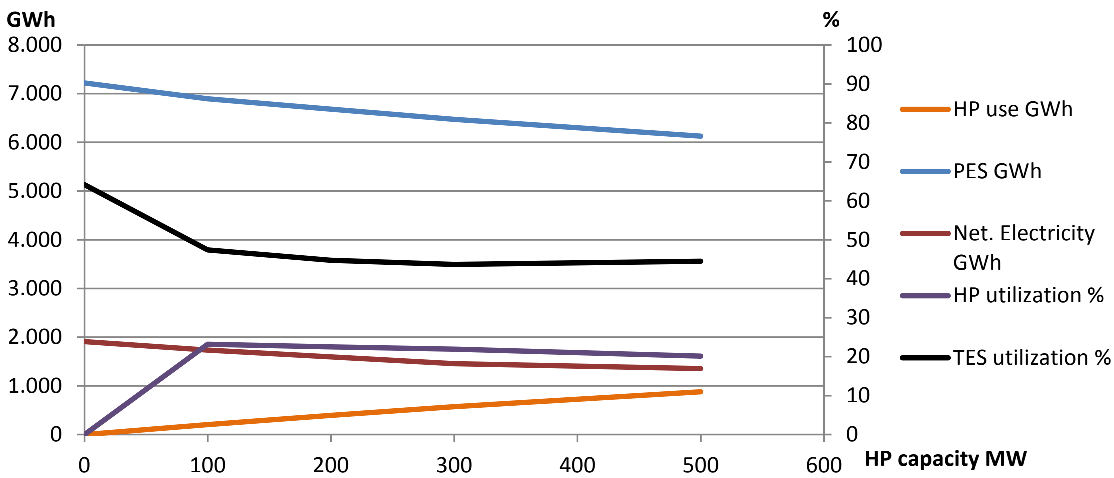

Figure 8.11: Values of PES, HP use, TES and HP utilization and net electricity production as functions of the TES capacity in TES + HP Scenario 2025.

The TES utilization is lower at each value of the HP capacity, compared to the sub analysis with TES of 1 GWh. This might be due to the much higher TES capacity and the balance of cheap electricity and fuel prices. In this scenario the HP capacity is capable of replacing some of the heat produced at the CHP plants to a greater extent than with only a small TES capacity. The heat production from the boiler is almost fully replaced at a HP capacity of 500 MW. This is seen in Figure 8.12, where the HP heat production is presented by the purple color. This also explains the lower use of fuel seen in Figure 8.11.

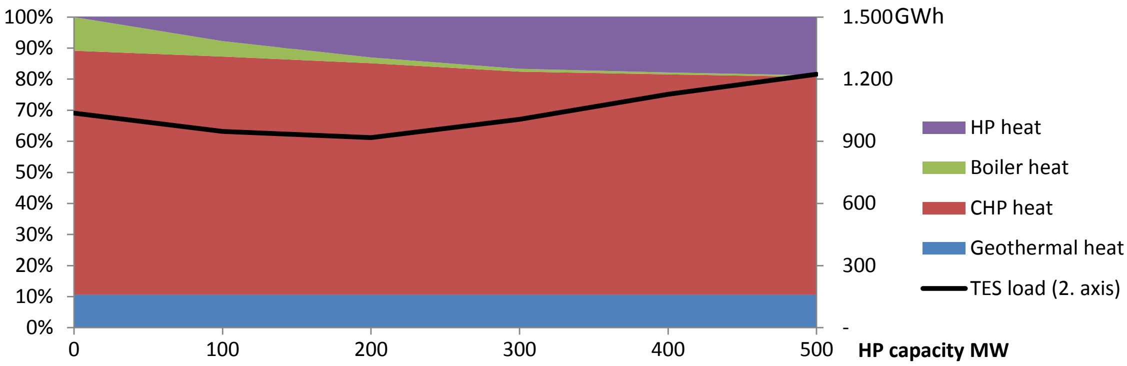

Figure 8.12: HP, boiler, geothermal and CHP heat production, and TES load as function of HP capacity in TES + HP Scenario 2025 with 21 GWh TES capacity.

The tendencies with higher production by the HP capacity is also reflected in the use of the TES capacity, where both the TES utilization and the TES load increases slightly as higher capacities of HP is implemented, see Figure 8.11 and 8.12.

In Figure 8.13 on the next page an example is given, where it is seen how the system is capable of using the low electricity prices to charge the TES from the HP capacity. At this point is used a TES of 21 GWh and 200 MW HP. In the graph there are three sections on top of each other. The first section shows the electricity price, the second one shows the heat production divided on the different production units in the system and the last section in the figure shows the charge level of the TES.

It can be seen that the HP is activated four times during the four days of the example. The three of the times the TES is being charged which is seen by the fact that the charge level is increasing at the same time. The last of the four times the HP is activated it is covering the present heat demand instead of the wood pellet CHP. At all the four times where the HP is activated the electricity price is low compared to the rest of the period which is the reason that the HP is activated.

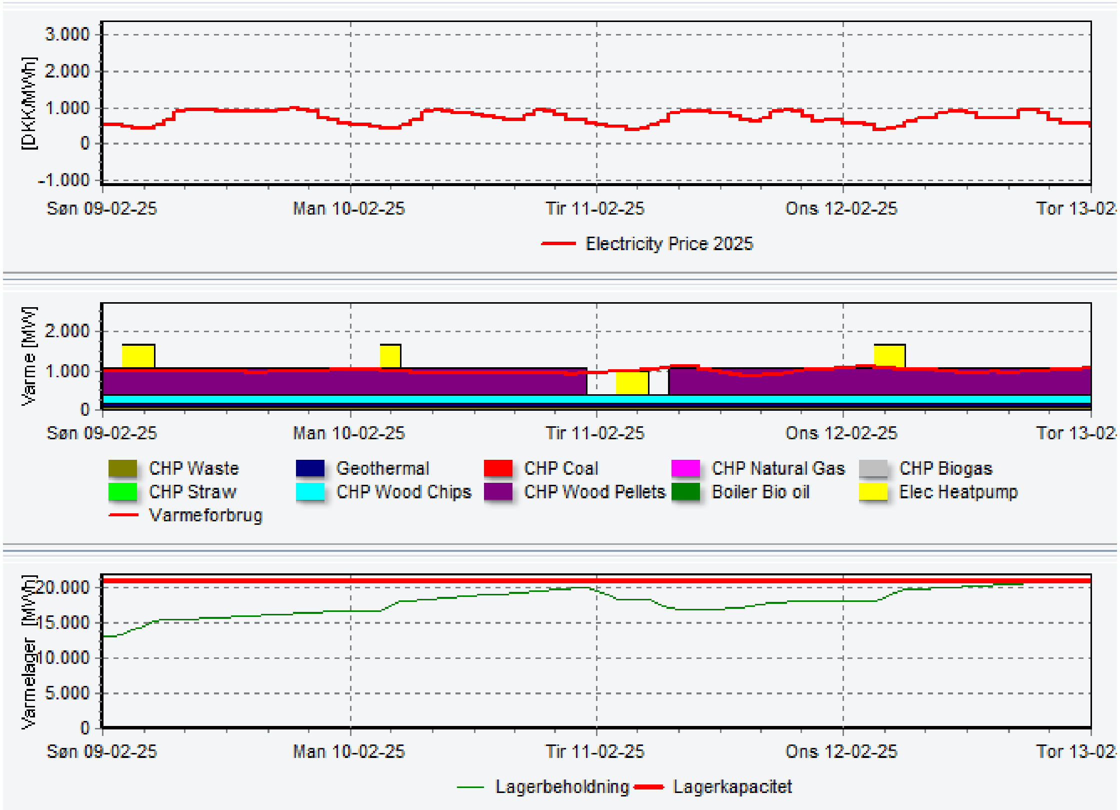

Figure 8.13: System graphic at 21 GWh and 200 MW HP.

8.6 TES + EB Scenario

In this analysis it is assessed how a higher implemented capacity of EB combined with TES influence the system. The EB is modeled as an electric HP with a COP = 1, cf. Chapter 3. The used investment costs for EB in the Annual SEC calculations are the same as in the EnergyPLAN model. In Figure 8.14 on the following page the Annual SEC and Annual SEC incl. investments are shown as functions of higher installed EB capacity, with a TES capacity of 1 GWh. From an economic point of view, it is cheaper to invest in EB rather than HP. In this scenario, even with the additional costs included, all analyzed capacities of EB will give the modeled CTR system savings compared to the 2025 Reference scenario. The implementation of EB is not capable of replacing as much fuel as the implementation of HP, which probably can be explained by the higher COP in the HP. In Figure 8.15 on the next page it is shown how the increased EB capacity influences the system with regard to PES, TES utilization and utilization of the installed EB capacity.

The system is only capable of utilization small amounts of the installed EB capacity, around 4%, but uses the TES to a greater extent, with a higher TES utilization in %, compared to the 2025 Reference. This may be explained by the optimizing strategy of minimizing net production costs in combination with a lower COP. In Figure 8.16 on the following page it is seen that the EB in the system is capable of replacing some of the heat production on the boiler, but not as much as in the HP scenarios. Also the TES load is increasing slightly, which indicates the use of low electricity prices to minimize the production costs in the system according to optimization strategy.

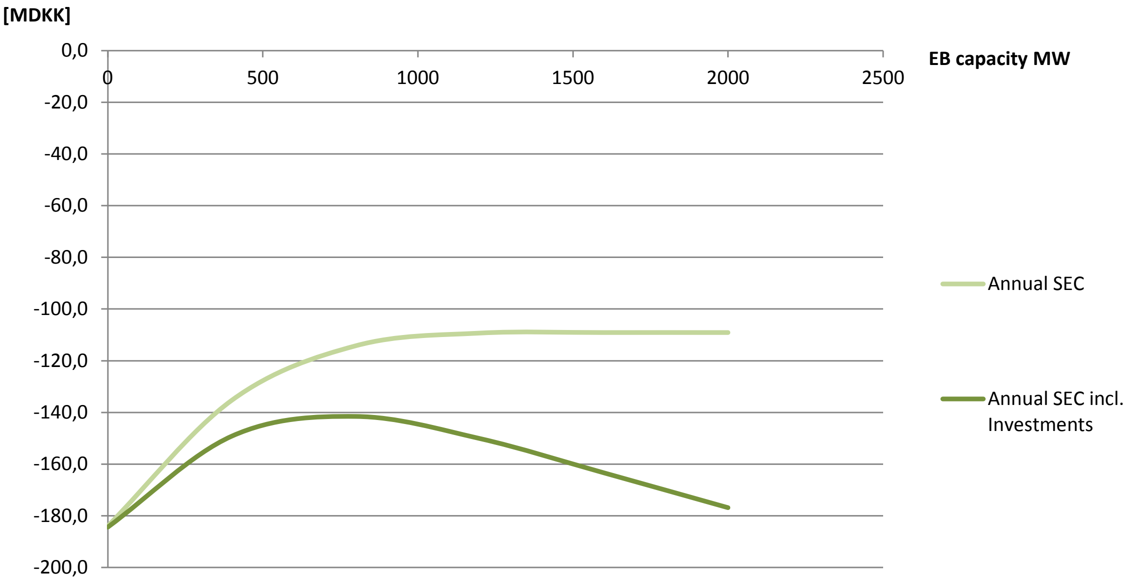

Figure 8.14: Annual SEC and Annual SEC incl. investments as functions of varied EB capacity.

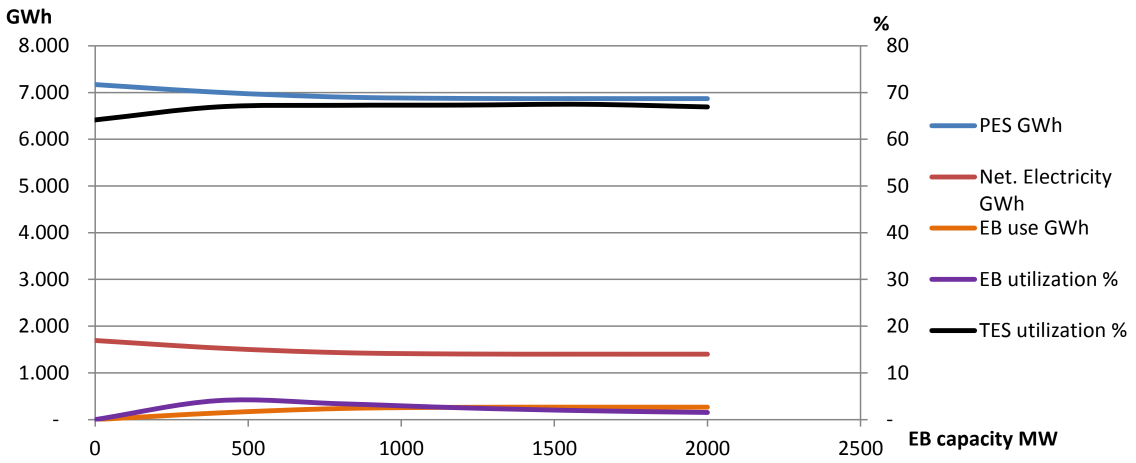

Figure 8.15: Values of PES, TES utilization and EB utilization as functions of the EB capacity in TES + EB Scenario 2025.

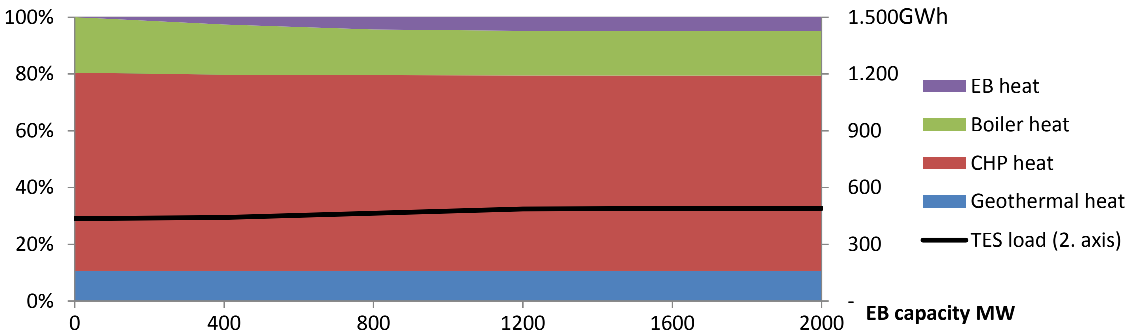

Figure 8.16: EB, boiler, geothermal and CHP heat production, and TES load as function of EB capacity in TES + EB Scenario 2025.

8.6.1 TES Capacity of 21 GWh and Varied EB Capacity

In this scenario it is investigated if the system is capable of using the EB capacity to a larger extent, when a larger TES capacity is implemented. The EB capacity is varied in a system with a TES capacity of 21 GWh. The system is more economic beneficial with regard to Annual SEC, with higher share of EB installed compared to the 2025 Reference scenario with no EB capacity and no additional TES capacity, see Figure 8.17, where the green dot represents the 2025 Annual SEC value.

All implemented capacities of EB in this system lower the SEC of the modeled CTR system. This is explained by a lower use of fuel, see Figure 8.18, and the higher electricity revenue the larger TES allows, due to more production on the CHP plants when there are high electricity prices. The spot market revenue, with an installed capacity of 1,200 MW EB is 1,450 M DKK, and thereby higher than the 2025 Reference.

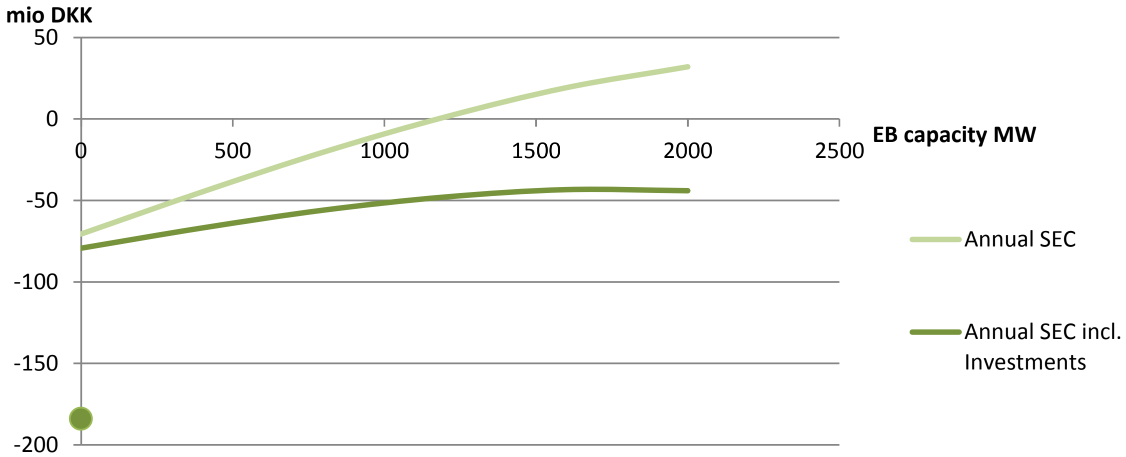

Figure 8.17: Annual SEC and Annual SEC incl. investments as functions of varied EB capacity.

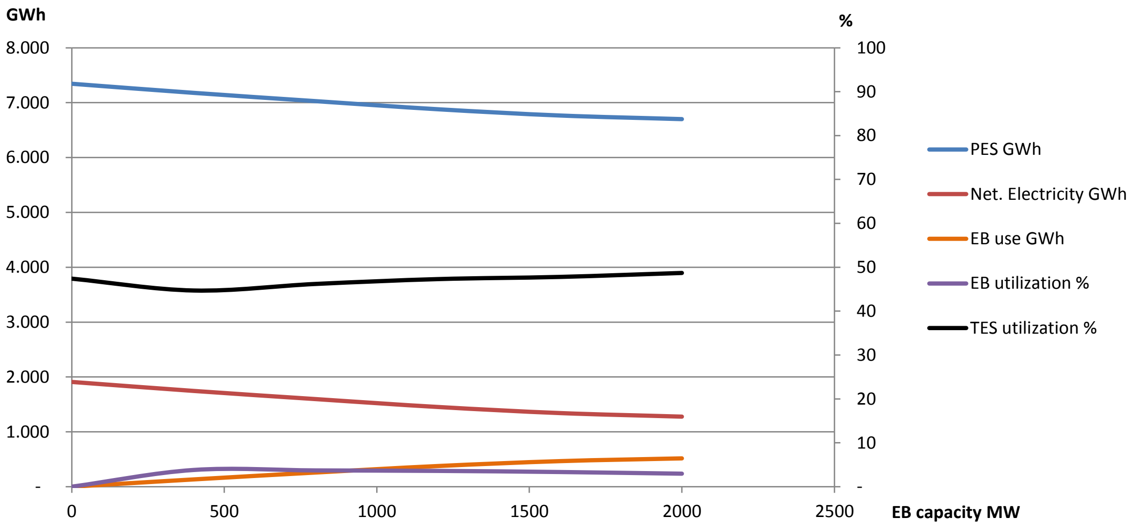

Figure 8.18: Values of PES, TES utilization and EB utilization as functions of the EB capacity in TES + EB Scenario 2025.

The values of the fuel is, as well as the TES and EB utilization, showed in Figure 8.18. In this scenario with EB the utilization is also low, around 4%. The higher TES capacity does therefore not affect the utilization, and is lower than in the previous analysis with a TES utilization of just above 50%. The TES load starts to increase after a Eb capacity of around 800 MW, see Figure 8.19, which is also where the TES utilization starts to increase.

Also seen in Figure 8.19 is how the EB capacities in this scenario with a higher TES capacity is capable of replacing more heat production from the boiler and the CHP plants, resulting in the lower fuel use. In the scenarios with HP combined with TES is where most fuel is replaced and taken over by heat production from HP. This is mainly thought to be due to the difference in COP and the interaction with the optimization strategy in the model. The difference in an economic perspective lies in the investments, where the investments costs and the annual O&M costs of HP are much higher than the costs of EB.

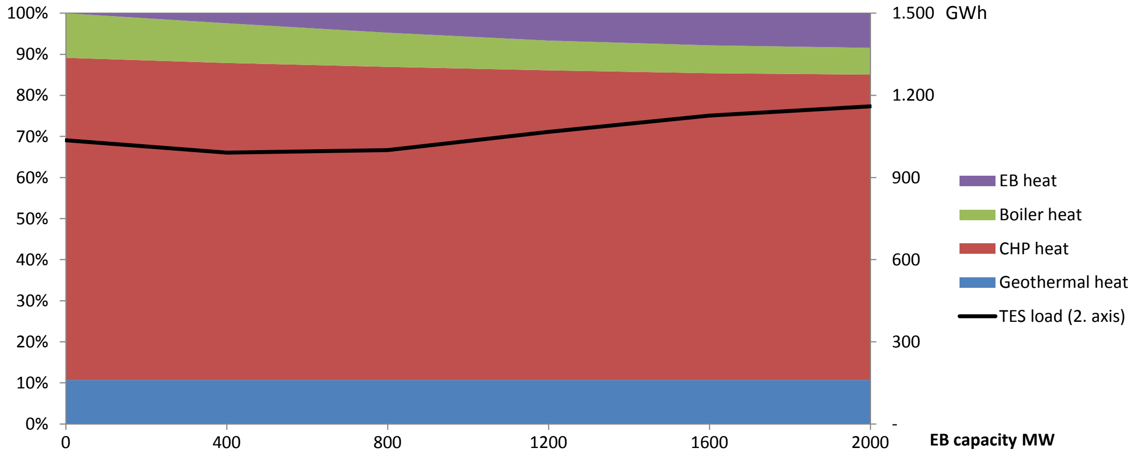

Figure 8.19: EB, boiler, geothermal and CHP heat production, and TES load as function of EB capacity in TES + EB Scenario 2025.

Analyzing various TES capacities against varied EB capacities give the following economic results of the Annual SEC including investments, shown in Figure 8.20 on the next page. From here it is seen that the TES capacity of 21 GWh is the most beneficial to the CTR system until an EB capacity of around 2,000 MW, with the best result at 1,600 MW. After 2,000 MW EB a much higher TES capacity is needed to give the best economic results, which is at maximum at 3,000 MW EB and 63 GWh TES capacity, corresponding to 1,500,000 m^3. Increasing the TES capacity further, leads to less beneficial results, as also seen in the figure, where a TES capacity of 83 GWh is below the TES capacity of 63 GWh.

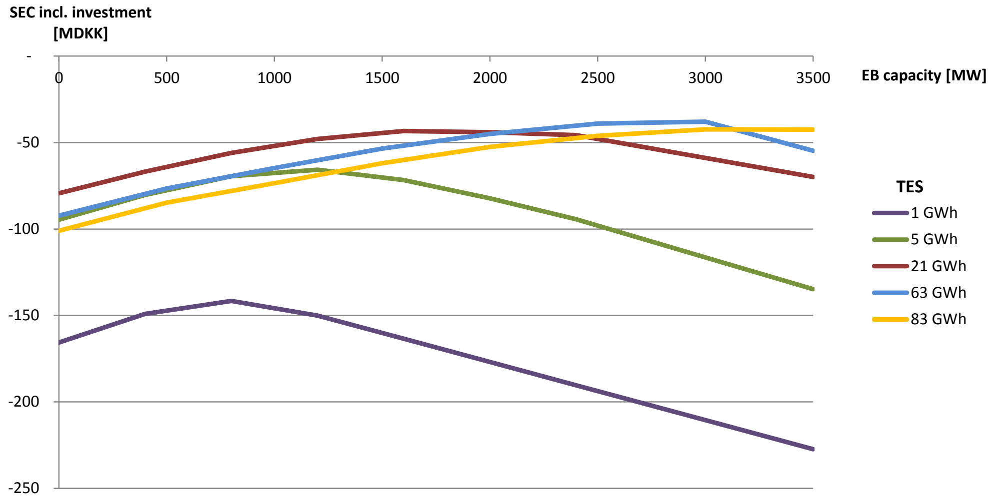

Figure 8.20: Annual SEC incl. investments for different TES capacities in the TES + EB Scenario 2025.

8.7 Sensitivity Analysis

In the sensitivity analysis one parameter will be changed at a time and compared to the found result in the main analysis presented previously in this chapter. The changed parameters are the fluctuation in the electricity price and the fuel costs. The sensitivity analysis is only presented for one chosen model setting, which is the scenario with a TES capacity of 21 GWh and a varied HP capacity, because the results for the other scenarios show the same tendencies.

8.7.1 Variable Electricity Price Fluctuations

The development of the electricity price is difficult to predict, as also mentioned in Section 8.3.1, where a fluctuation factor has been added to the predicted average spot market price in order to count for the higher share of RE in the system in 2025. With reference to Table 8.1 on page 76, the fluctuation factor has an influence on the Reference system, where a higher fluctuation factor gives lower SEC in the CTR system. In this analysis, it is assessed how the system is influenced by a high and low degree of fluctuation, when 21 GWh TES and varied HP capacity is implemented in the system. For this purpose fluctuation factors of f = 0.5 and f = 3.0 are chosen.

The factor of f = 0.5 means that the price fluctuates half as much as the baseline price, that is calculated based on the average spot market price of 616 DKK/MWh. When f = 3.0 means that the price fluctuates three times as much as the baseline price. In Figure 8.21 on the next page the economic results from this analysis are shown for both values of f compared to the same scenario with f = 1.5 from the main analysis, for both Annual SEC and Annual SEC including investments. It is clear that the higher fluctuation factor gives the best economic results via the revenues from electricity sales. The large storage of 21 GWh allows the CHP plants to produce electricity at the hours where the electricity prices are high, which gives a high additional revenue from sale of electricity from the scenario with f = 3.0. When the fluctuating factor is low, the investments are less feasible.

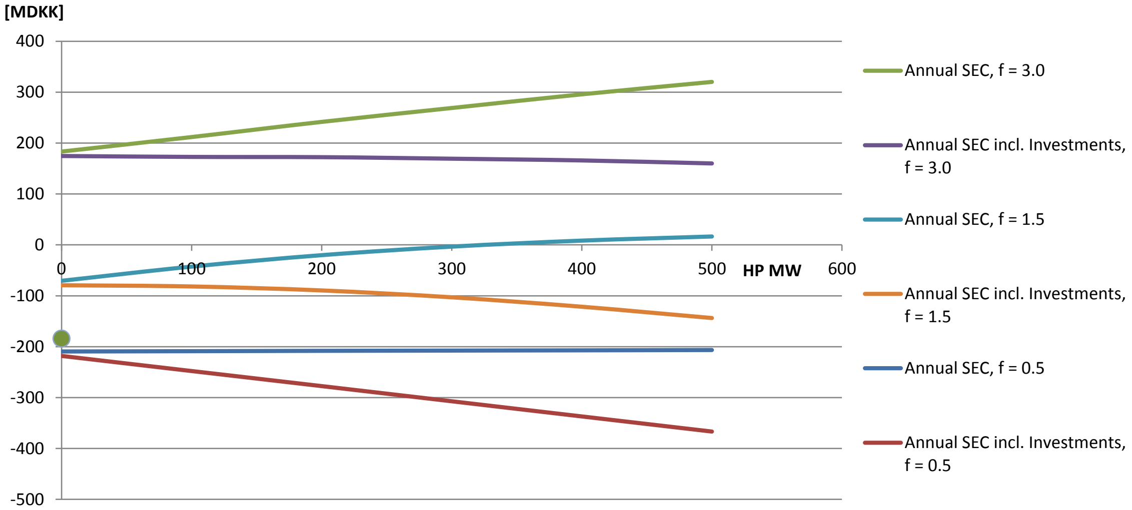

Figure 8.21: Annual SEC and Annual SEC inclusive investments for f = 0.5, f = 1.5 and f = 3.0 as functions of HP capacity.

What adds to the better economy of the system with a fluctuation factor of 3 is the lower use of fuel, which is seen compared to the use of fuel with a fluctuation factor of 0.5 in Figure 8.22. The figure also shows results of HP utilization and TES utilization for both values of f.

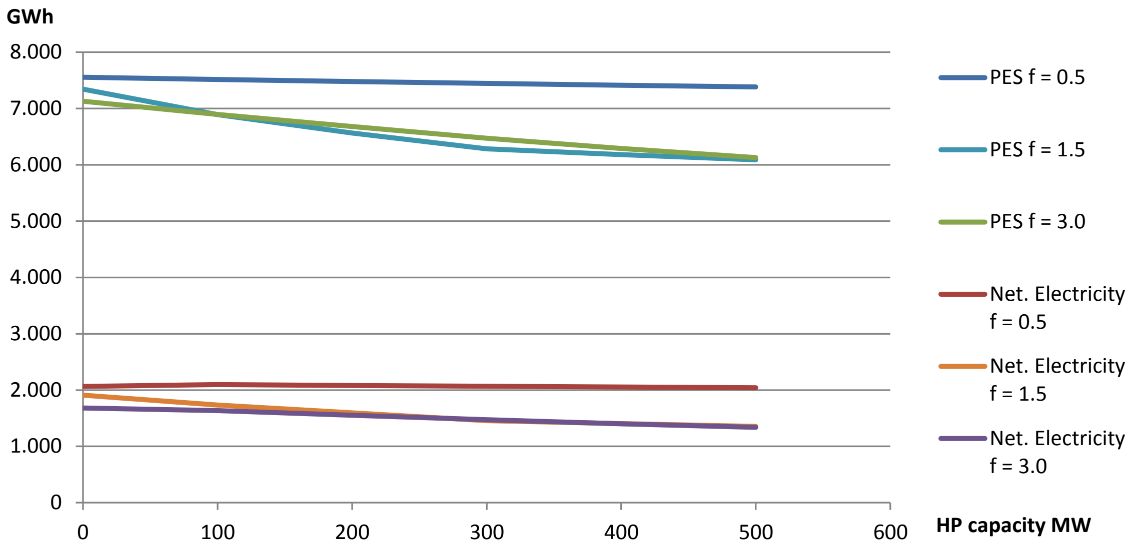

Figure 8.22: PES and net electricity production for f = 0.5, f = 1.5 and f = 3.0 as functions of HP capacity.

The declining use of fuel with f = 3.0 with increasing HP capacity may be because it is more beneficial to the system to use the HP more which is also seen in the declining net electricity production in this case. The tendencies are almost the same as for f = 1.5. The system with f = 3.0 has a higher net electricity production, which declines from 1,682 GWh at 0 MW HP to 1,339 GWh at 500 MW HP, compared to the scenario with f = 1.5 where the net electricity production declines from 1,410 GWh at 0 MW HP to 1,355 GWh at 500 MW HP. At the fluctuation factor of 0.5 it is seen that the PES remains almost constant and the same with the net electricity production. This means that by increasing f the energy system is only affected slightly, but by reduced f the system is using the HP capacity less.

From this analysis it is concluded that the fluctuation of the electricity prices has significant influence on the economy of the modeled CTR transmission system, where a higher factor gives lower costs. This is mainly due to the economic frame, where the revenues from electricity to the spot market sale are taken into account in the calculations. The electricity prices also influence where the production of heat is cheapest in the system and thereby how much fuel the system is capable of replacing by the HP capacity.

8.7.2 Variable Fuel Costs

As seen in the previous analysis, the electricity price has substantial influence on the economy of the modeled CTR system. In this analysis it is assessed how much the fuel costs influence the economy with the operation strategy in mind. As with the electricity prices, it is difficult to predict how the costs of biomass and other fuels will develop through the years. The fuel costs is in general thought to be an important parameter concerning the conversion in the Danish society of converting the energy system from being fossil fuel based to being based on RE resources.

Again, the TES capacity is kept constant at 21 GWh while the HP capacity is varied and the fluctuation factor is 1.5 as in the main analysis. The influence of the fuel costs is evaluated by making an analysis with high and low fuel costs according to the values of the high and low fuel costs, see Table A.18 on page 116. The economic influence of both analyses is represented in Figure 8.23 showing the Annual SEC and Annual SEC inclusive investments, where FC is an abbreviation of fuel costs and 'basic' is the costs used in the main analysis.

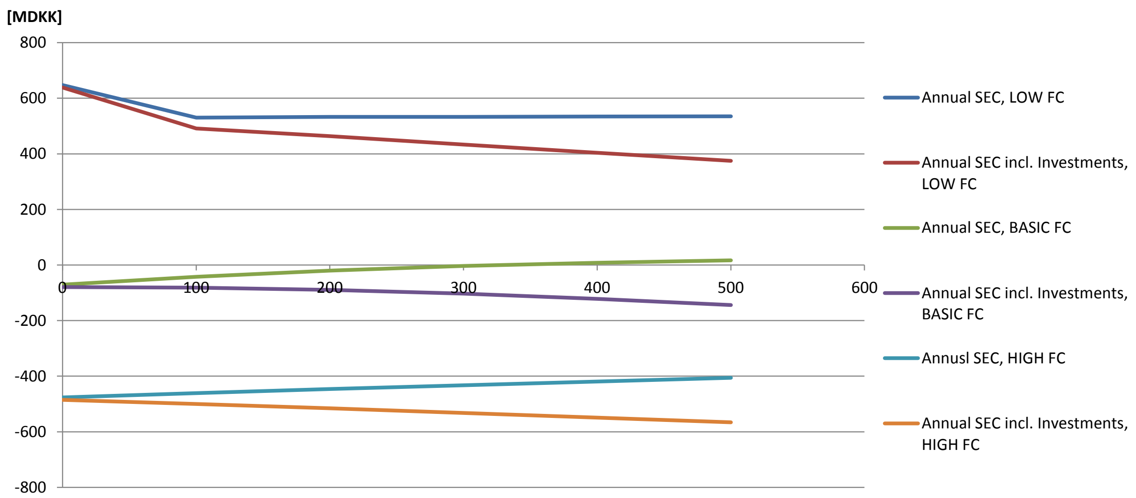

Figure 8.23: Annual SEC and Annual SEC inclusive investments.

The high fuel costs results in a lower fuel use, as it is seen in Figure 8.24, compared to the basic fuel costs and the low fuel costs. Using low fuel costs does not give the system economic incentive to utilize the installed HP capacities, which is seen from the almost constant fuel use and the significantly use of the HP, less than 1%.

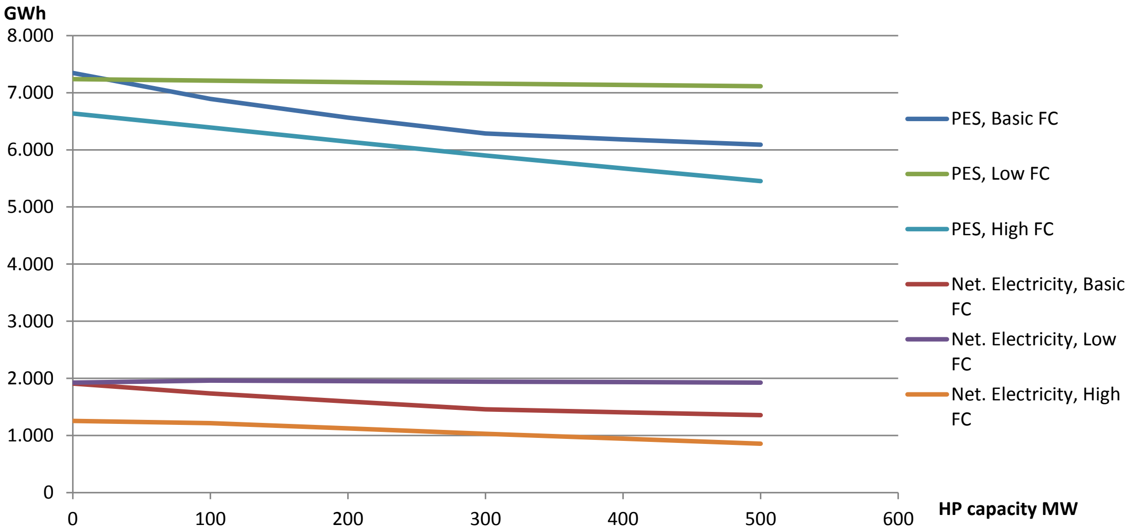

Figure 8.24: PES and netto electricity production for basic, low and high fuel costs as functions of HP capacity.

The varied fuel prices also have impacts on the produced electricity in the system, which is a part of the explanation of the economic results shown in Figure 8.23. When there are high fuel prices, it is expensive to run the CHP plants, resulting in less electricity production, hence less revenues from the spot market. On the other hand, when the fuel prices are low, it is cheap to operate the CHP plants which results in a high electricity production and high revenues.

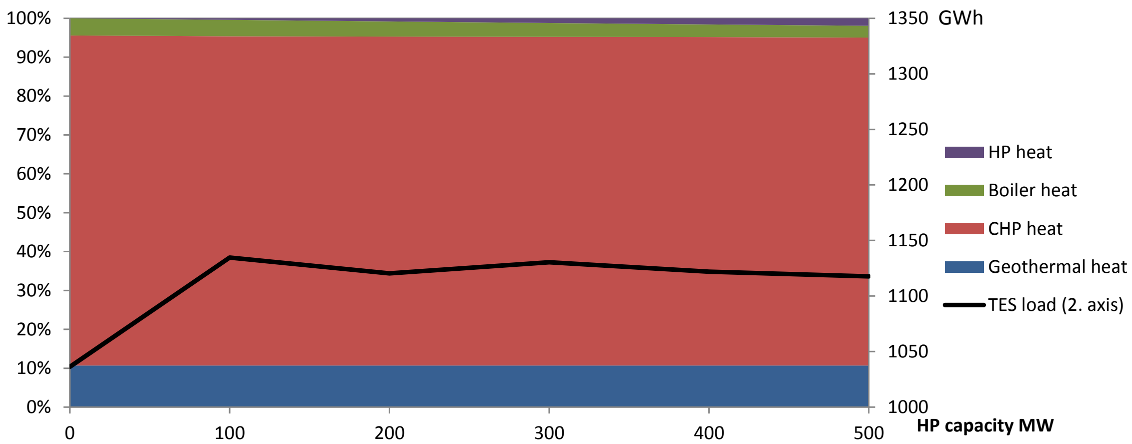

Figure 8.25: HP, boiler, geothermal and CHP heat production, and TES load as function of HP capacity with low fuel costs.

In Figure 8.25 and 8.26 on the next page is shown how the heat production is distributed on the units, with low and high fuel costs respectively. In the system with low fuel costs, there is a smaller fuel use, which is mainly placed in the CHP plants. Only very little of the heat production is placed in the boiler and at the HP capacity. In the system with high fuel costs, much more heat production is placed on the boiler and as the HP capacities increase, more heat production is replaced from the boiler and the CHP plants and placed at the HP capacity. This is due to the high costs of fuel, whereby the system uses the optimization strategy and uses more electricity to run the HP, when the electricity is cheap.

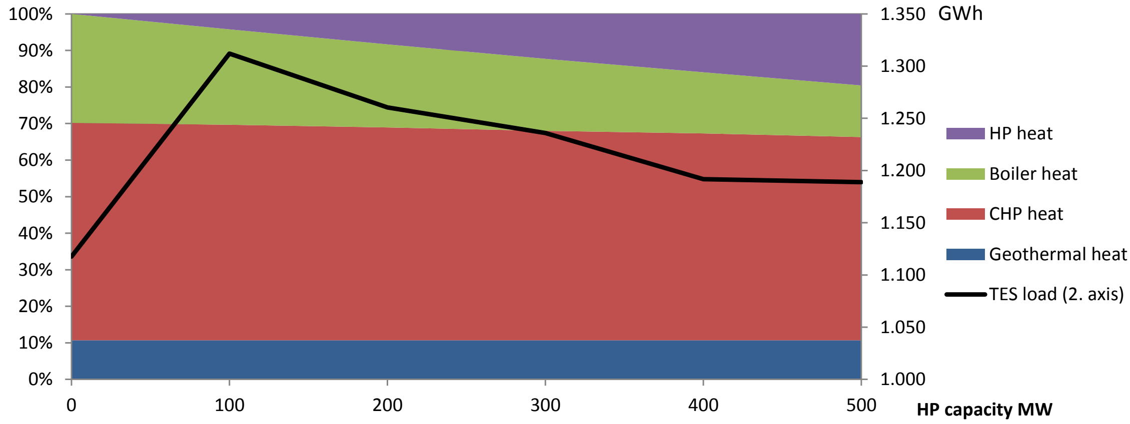

Figure 8.26: HP, boiler, geothermal and CHP heat production, and TES load as function of HP capacity with high fuel costs.

As with the fluctuation of electricity prices, variation of the fuel costs has significant influence on the economy of the modeled CTR transmission system, where low fuel costs give the best economy in the modeled CTR system. The fuel costs also influence, where the production of heat is placed in the system and thereby how much fuel the system is capable of replacing by the HP capacity; low fuel costs do not give the system any incentive to save fuel by using the HP capacity to produce heat and the fuel use is rather high compared to the basic fuel costs and the low fuel costs. This is again, due to the optimization strategy of minimizing net production costs in the system.

8.8 Discussion of EnergyPRO Applicability

In this section it is discussed how the use of EnergyPRO and how it has been applied can have influenced the results from the modeling of the CTR transmission system. One of the assumptions is the assumed COP = 3 on the HP. The influence of vary the COP in the HP is assessed in and explained in Section 7.6 on page 64.

8.8.1 Merging Plants

All heat producing units have been merged according to the expected use of fuel in the CO_2 neutral scenario in the Climate Plan. This assumption was done since it is impossible to predict which plants there will exist in 2025. One of the complications is the fact that it is not possible to have more than one fuel at each plant, which often is the case in reality. Also, the plants in the postal area of CTR have been merged, lessen some flexibility of the heat production. This problem has been tried to minimize by allowing down to partial load on the CHP plants, but there is still thought to be less flexibility in the modeled system as there are fewer plants and the plants can only run on one type of fuel. This also influence the economic aspects of the optimization strategy, since the model is forced to run a certain fuel, instead of mixing fuels, which in some situations might be more economic.

The HP and EB have also been modeled as one unit, regarding the capacity. This is again thought to lessen the flexibility, by forcing the model to use the entire unit of HP/EB and not only parts of it. In the model, the unit of the HP/EB is capable of using different shares of the total capacity, but in some cases, it might be more beneficial to have HP/EB connected to the different CHP plants and let them run either to supply heat of fill the TES, when it is most beneficial to the specific plant.

8.8.2 Optimization Strategy

Based on the sensitivity analysis on the EnergyPRO model, it is clear that the varied parameters have rather significant influence on the results, since these gave significant differences in which units in the system that was used to cover the heat demand. The high difference is thought to be caused by the chosen optimization strategy of minimizing net heat production costs.

It is therefore complicated to optimize such a system, and using only this operation strategy may not reflect how the system is operated in reality. This probably takes a lot of knowledge and experience to optimize both with regard to economy and at the same time minimize the annual use of fuel. An example that can be drawn out is when the fuel costs are low, which is good for the economy and an incentive to use biomass in the heat and electricity production. But this resulted in a higher fuel use, in this modeled system, which is not desirable seen in the light of preserving resources.

8.9 Conclusions from the CTR Analysis

The TES scenario show beneficial economic results, where the system will achieve savings in the Annual SEC up to a capacity of 21 GWh which gives the best economic result. With the increasing TES capacity, the annual fuel use increased due to a higher production at the CHP plants.

The analysis of combining TES and HP shows that it gives a small economic benefit to implement HP with the reference capacity of TES, but with an increased TES capacity, increasing the HP capacity do not give any benefit of the SEC. In both analyzed situations with TES and HP in combination showed a decline in annual fuel use, and the fuel use on the boiler can almost be completely reduced.

The analysis of combining TES and EB shows that with regard to economy, the system will have more savings by implementing EB compered to HP due to the much lower investments costs. The best combination found in the analysis is of 63 GWh of TES and 3,500 MW of EBs. With a TES capacity of 21 GWh of TES the optimal EB capacity is 1,600 MW EB capacity. Using EB in the system does not give the benefit of reducing the annual fuel use as much as it is possible by the increased capacity of HP. This is an important parameter when it comes to having a sustainable system and using biomass in combination with for instance wind power in the most effective way.

It therefore comes down to a validation of the operation in the system between a tradeoff of lowering the annual fuel use and the investments costs. This is also why the optimization strategy may give some optimistic results in an economic perspective, since this is set to minimize the net heat production costs. From the sensitivity analysis it is seen that a high fluctuation in electricity prices, gives a better economy and a higher use of the potentially installed HP in the system. The same tendency is seen when the fuel costs were varied between low and high costs.

Discussion of Results 9

In this chapter the results of the analyses are discussed. The results of the two different parts of the analysis are discussed against each other and reasons for the differences in the results are given. The technology, size and location of a potential TES is also discussed and lastly some issues connected to the implementation is discussed in connection the Choice Awareness theory.

9.1 Differences in Results of the Two Analyses

The scenarios and the structure of the analyses are built in the same way to make it possible to compare the results of the two analyses and discuss the differences. The results of the two analyses shows to be similar in points and different at others, but an important point is that this may caused by an error in the EnergyPLAN model, which is described in Section 7.7 on page 67. This makes the comparison difficult at some points, but a brief comparison is here presented.

The analyses of increased capacity of TES without increased HP or EB show that in East Denmark the PES will be reduced, but the annual costs will increase. This analysis should not be highly affected by the error in the model because it does not involve increased capacities of HP or EB. In CTR on the other hand the analysis shows that it will be feasible to have a larger TES capacity up to about 20 GWh which is equivalent to 21 GWh. This difference may be explained by the larger share of CHP production compared to boiler production in 2025, but also by the higher aggregation level in EnergyPLAN and lower level of detail. This means that the current level of TES integration generally may be good, but at certain places including CTR there may be a potential for increasing the TES capacity.

The analysis of increased TES combined with HP for East Denmark clearly show that it is not a feasible solution to combine TES with HP, but these results may not be valid because of the error in the EnergyPLAN model. For the CTR system the analysis also show that it is not necessarily feasible to combine TES and HP as the best solution in terms of SEC is 21 GWh of TES without any HP capacity. In the EnergyPRO model it is shown that the HP is able to charge the TES, opposite the EnergyPLAN model, but it is still not feasible here.

The last section of the analysis for East Denmark shows that an increased capacity of EB can give a socioeconomic benefit, but if it is combined with TES the benefit will be significantly reduced. This is also seen as a consequence of the error in the EnergyPLAN model since the

EB is not able to charge the TES. In the CTR system the EB capacity will also generate a socio economic benefit, both with and without increased TES capacity, but the best combination found in the analysis is 63 GWh of TES and 3,000 MW EB capacity reducing the costs with 128 M DKK annually compared to the reference.

In Chapter 5 it is mentioned that one of the biggest challenges in reaching a CO_2 neutral energy supply in the Copenhagen region is the peak load boiler production. In the analyses of the CTR system it is found that the TES combined with HP can reduce the boiler production share to 0.5% of the boiler production in the reference. See Figure 8.12 on page 82. With increased HP without increased TES the boiler production share is reduced to 28%. The TES capacity alone is only able to reduce the boiler share to 50% of the values in the reference. The TES and EB can in the best case reduce the boiler share to 16% compared to the reference. This means that there is another benefit to the TES + HP scenario in the CTR system which does not show in the economic calculations in this project. This is nevertheless an important point because the political goal as mentioned is to get a CO_2 neutral energy supply, where the only solution to the peak load production in the current plans is biooil boilers. According to Choice Awareness these two alternatives for supplying the peak load demand should be assessed equally and a detailed feasibility study of the two should be carried out to show which of the two is most feasible for society.

9.2 Size and Location of Storage

Before choosing a TES technology for a specific facility it is important to know the demand and the requirements for the specific situation, mainly the capacity, the charge and discharge capacities and the costs limitations. The results of the analyses of the CTR system show that rather large capacities of TES can be relevant, up to 63 GWh, and that the charge and discharge capacities have to be high because the storage is charged and discharged several times weekly independent of the season of the year. According to the characteristics summarized in Table 3.1 on page 22 this means that PTES and ATES are relevant options. The underground geological properties in Copenhagen might be assessed more thoroughly to find out if ATES is an option in reality. For large storage capacities the solution might be a combination of two different technologies for example if the capacity is split on more than one location.

CTR is responsible for the transmission and the transmission grid, and a potential implementation of a TES is expected to be connected to this transmission grid to balance the system at transmission level. David Magnusson, planning engineer at CTR, questions if this is possible though because the transmission system is operated at a higher temperature level than what TES can supply its stored energy at. According to Magnusson the TES must be located in the distribution grid instead. In this case the capacities assessed in the analyses will have to be split into a number of smaller storages each connected to one of the distribution grids. This probably means that the TES will be less flexible, but from the analyses in this project it cannot be said how much. Even though CTR currently do not consider a TES connected to the transmission grid as a feasible solution it is technically possible, but the storage then have to be discharged by a HP to boost the temperature to the required level in the transmission system which will require some additional investment and operation costs. Magnusson also mentions that hydraulic issues in the transmission system will have a large impact on where a TES can be located. The problem is that several of the production units are located close to each other and the pressure in the pipes that is necessary limits how large a share of the production that can be transported to the other end of the transmission system through the pipes.

An example of a specific location, as mentioned in Chapter 5, is the old dry dock in Nordhavn in Copenhagen which have been assessed previously for its potential for conversion to a PTES facility. This dry dock is approximately 13 GWh which is a rather large storage, larger than any existing or planned facilities in Denmark currently. The capacity is of a size where it might be suitable for connection to a distribution grid in the city. The details of how it technically and practically can be connected to one or more distribution grids are not assessed further here. This location is good because it is located relatively close to the city center, where the heat demand density is high, and it might be difficult to find other large suitable location for a TES close to the center.

9.3 Implementation

The implementations of the capacities suggested in the analyses, which are rather large, will probably be done gradually towards 2025 as the share of wind power generation is increasing. Some locations are better suited for the integration of a TES than others in terms of demand in the DH system, CHP share of the DH supply and other physical properties as described in the previous section. As mentioned, up to 20 GWh can be implemented with a socioeconomic benefit in CTR without investing in HP or EB which can be integrated at a later point if it is found to be feasible.

An important point in the implementation is that the incentive to invest in the analyzed technologies is strong enough and if such project is not business economically feasible it will probably not be made unless there is other important incentives, e.g. to have an energy supply free from fossil fuels. But the business case for the actors that will have to make the investment is important anyway. The important interests in the case of this project will, more than CTR, be VEKS, HOFOR, Varmelast.dk and Copenhagen Municipality. The actors are described in Section 5.3 on page 35.

Assuming CTR will be the owner of the project their interest will be potentially to save fuel and operation costs, but also the possibility of reducing their CO_2 emissions as they have set a goal to be CO_2 neutral by 2025. VEKS and HOFOR may have an interest in the project because they are both working in close cooperation with CTR and might have a benefit of the higher system flexibility in the increased TES capacity. They might also be interested in the results and experience with a large TES and HP or EB capacity and its potential for similar implementation in their own systems. Varmelast.dk will not be economically affected directly because they just have to distribute the production on the different production units in the system, but an increased TES capacity will enable them to distribute the production in a cheaper way. Copenhagen Municipality has an interest because the project will support their goals of being CO_2 neutral by 2025 and they may be interested in supporting the project by allocating the needed physical space for the TES.

If there is no feasible business case in investing in a TES in CTR under the given circumstances the investment will probably not be made. In this case it should be considered to implement a public regulation to ensure a foundation for a business case for the project. According to Choice Awareness a public regulation should be implemented to make sure that what is socioeconomically feasible also will be business economically feasible. In this case it should be feasible for CTR to invest in a TES capacity and if it isn't public regulation should be implemented. The public regulation could be in the form of a support for the investment costs or a cheap loan to cover the investment. In this way the business economic feasibility of the investment will be better and possibly it can be implemented. Regarding HPs, the analyses showed that it is not socioeconomically feasible to implement these until 2025 under the given assumptions. This means that a public regulation to better the business economic feasibility shouldn't be implemented here. If it is business economically feasible to implement HP it could be relevant to implement regulation that makes these investments less feasible. If it shows in another study under other assumptions that HP will be socioeconomically feasible, it might be relevant to support the investment in these by investment subsidies or for example an adjustment of the taxation like it was done from January 1st 2013 (Ingeniøren 2012).

10 Conclusion

The purpose of the project is to assess and find a solution to the research question given in Chapter 1.3 on page 4. The research question is repeated here:

What is the potential of implementing thermal energy storage in combination with heat pumps and electric boilers in the Danish energy system for DH to increase the flexibility for the inclusion of renewable energy sources?

To answer the research question, first an assessment of the relevant technologies for the specific purpose is made. Hereafter, two different computer models, EnergyPLAN and EnergyPRO, are applied to analyze the integration of TES in combination with HP and EB in a regional energy system and a local energy system respectively.

The Choice Awareness theory is applied as a framework for the analyses. Specifically, the importance of the socioeconomic feasibility is taken into account in the analyses as the socioeconomic costs in the analyses are seen as an important parameter. Also the emphasis on the alternatives assessment in is implemented in the analyses materialized as three different alternative scenarios to compare with the reference scenario. These three alternative scenarios are analyzed in parallel in both of the two computer models. The three alternative scenarios are: 1. Increased TES capacity, 2. Increased TES and HP capacities and 3. Increased TES and EB capacities.

The analyses of the regional energy system of East Denmark show that integration of TES is not a socio economically feasible investment and when HP is included the investment is even less feasible. The analysis of integration of TES and EB shows some positive results, but this is because of the positive effect of the EB capacity and the TES capacity only reduces the benefit. An assessment of how the EnergyPLAN model handles TES combined with HP and EB indicates that there is an error in the model so the results cannot be valid in that case though.

The results of the analyses of the local energy system of the transmission system of CTR show that there might be a potential in increasing the TES capacity up to 21 GWh from a socioeconomic point of view. The combination with HP shows not to be feasible, but the combination with EB can be feasible up to a TES capacity of 63 GWh and 3,000 MW of EB capacity. The results also show that the share of heat production from boilers can be significantly reduced with the implementation TES combined with HP or EB.

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EnergyPLAN Data Input A

In this chapter the data input and the sources are presented for the EnergyPLAN model. Each of the sources used are first described and it is explained how the data is treated. Hereafter the specific input values are presented in tables with references to the described sources for both of the reference years; 2011 and 2025. The reference models for 2011 and 2025 used in EnergyPLAN are found on the CD attached to this report.

A.1 Data Sources for the EnergyPLAN Modeling

This section describes the data sources on which the reference scenario is based and how the data have been treated to fit into the EnergyPLAN model. The two first handled sources, Count of Energy Producers 2011 and Annual Energy Statistic 2011 are described in greater detail than the others because these are central sources for the model and of greater importance of the others. Other sources are just used for one or a few numbers.

A.1.1 Count of Energy Producers 2011, Danish Energy Agency

The data source Count of Energy producers 2011 is a spreadsheet containing data from 2011 for all electricity and DH producers connected to public grids. These energy producers have to report data about their production units and fuel consumption every year. There is a lot of information about each unit in the spreadsheet but in this study only the columns presented in Table A.1 are used. This source is confidential and no data for specific plants or production units are presented in this report. The values presented are summaries of values from several plants and production units.

Data column	Type/Unit	Notes
DH grid ID	Integer	Each DH grid has a unique ID and every production unit is connected to the specific DH grid by this value. Each unit is only connected to one DH grid.

Continued on next page

Data column	Type/Unit	Notes
Plant type	Central CHP, Decentralized CHP, DHP, Local plant, Industry	This column is merged for each plant from an earlier version of the document from 2004 since the one from 2011 does not contain this information.
Postal code	Integer	The postal code of the address of where the production unit is located.
Electric capacity	MW	The maximum electricity production capacity.
Thermal capacity	MW	The maximum heat production capacity.
Annual electricity delivered to the grid	TJ	The production of electricity from the unit that is delivered to the grid. Own consumption of electricity at the plant is not included.
Annual heat delivered to the grid	TJ	The production of heat from the unit that is delivered to the grid. Own consumption of heat at the plant is not included.
Fuel use: (Separate columns)Coal, fuel oil, waste oil, gas oil, LPG, Natural gas, Waste, Biogas, Straw, Wood chips, Wood and biomass waste, Wood pellets, Bio oil	TJ	For each production unit the total fuel consumption is registered here. Some production units use more than one type of fuel.

Table A.1: The used data columns in the Count of Energy Producers 2011.

Firstly, all production units with postal code from 5000 and above or between 3700 and 3799 are removed since these are outside the geographical area of East Denmark. The remaining production units are in the region called East Denmark but except the island of Bornholm.

The second step is to divide the units into three groups according to the three DH groups. See the definition of these presented in Section 6.4.1 on page 47.

To get the input values for the DH section in the EnergyPLAN model, the industrial plants according to the Plant type column and the units with a consumption of waste according to the Fuel use column are sorted out to be used later in the sections Industrial and Waste in the EnergyPLAN model to avoid counting these twice. See Table A.3 on page 110. The demand is reached by summarizing the values in the column of Heat delivered to the grid.

The efficiencies are reached by dividing the total fuel input by the delivered energy. Capacities electricity and heat production are reached by summarizing the electric and thermal capacities of the units respectively.

The distribution of fuels in Table A.4 on page 111 is also summarized with the same setup and in the same way without the industrial and waste incineration plants. The categories of fuel; fuel oil, waste oil and gas oil are summarized as Oil in Table A.4 and LPG and Natural gas both as Natural gas. Biogas, Straw, Wood chips, Wood and biomass waste, Wood pellets, Bio oil are all counted as Biomass in the fuel distribution.

In the Industry section in the EnergyPLAN model this source is used for the electricity and heat production delivered from the industries divided into the three DH groups as described above. The values are summarized from the columns of delivered electricity/heat for the industrial plants. The fuel use in the industries is not taken from this source since this is not a complete list of the fuel use in the industries, but only the fuel use in the industries that deliver energy to public grids. In Section A.1.2 the source of the fuel use in the industries is described.

In the Waste section in the EnergyPLAN model this source is used for the waste input and energy production divided into the three DH groups as described above. The waste input is summarized from the table and the efficiencies are calculated as the delivered electricity or heat divided by the waste input for the specific production unit in the spreadsheet.

A.1.2 Annual Statistics 2011, Danish Energy Agency

DEA publishes every year an annual statistic of the energy flows in Denmark. The data is available online on the website of the DEA. The spreadsheet contains data about energy production, conversion and consumption for different sectors like transport, industry, commercial, households and the energy sector. The source provides total values for Denmark so to get specific values for the East Denmark region the values from this source are multiplied by the share of the Danish population living in the region which is 44.58%. See Section A.1.4 on the following page for further explanation. For this EnergyPLAN model the source have been used in three sections; Individual, Industry and Transport.

Individual: This source is used for energy consumption for individual coal, oil, natural gas and biomass boilers. The values are found in the section called Consumption sector under the topics One-family houses and Apartments. All the values under these topics are summarized except solar energy, HPs, electricity and DH because these does not have a direct fuel consumption at the individual level. The fuel consumption is already counted in the District Heating section in EnergyPLAN.

Industry: This source is used for the consumption of coal, oil, natural gas and biomass. The values are found in the section called Consumption sector under the topics Farming and forestry, Gardening, Fishing industry, Manufacturing industry, Building and construction industry, Wholesale, Retail, Private service and Public service. All the values under these topics are summarized except solar energy, HPs, electricity and DH because these do not have direct fuel consumption. The fuel consumption is already counted in the District Heating section in EnergyPLAN.

Transport: This source is used for the consumption of different fuels for transport. The values are found in the section called Consumption sector under the topic Transport. All the values under these topics are summarized into the groups Jet petrol, Diesel, Petrol, Natural gas and LPG. Electricity is omitted here this does not have a direct fuel consumption. The fuel consumption is already counted in the District Heating section in EnergyPLAN

A.1.3 CEESA Reference 2010

The CEESA Reference 2010 is an EnergyPLAN model which is made for the CEESA (Coherent Energy and Environmental Systems Analysis) project. The document is not published but given to this project group by Brian Vad Mathiesen, associate professor at AAU and co-author at the CEESA project. This source is used for the data input for the 2011 Reference scenario. This source is used where no applicable data for 2011 have been found. Specifically it is used for data regarding HPs, heat storages and fixed boiler shares.

A.1.4 Population Statistics 2011, Statistics Denmark

The purpose using this population statistics is to be able to adapt values that are given for the whole of Denmark to fit with the model of East Denmark. The source is a spreadsheet extracted from an online database on the website of Statistics Denmark. The extracted spreadsheet contains population figures for each municipality in East Denmark in 2011, except Bornholm, and the total population in Denmark. The population in the studied area is divided by the total population to get the share of the population that lives in the studied area which is 44.58

A.1.5 Market Data 2011, Energinet.dk

This source is a spreadsheet extracted from Energinet.dk online database with data about the electricity market. The extracted spreadsheet contains hourly values for gross electricity consumption and wind electricity production for East Denmark in 2011. The electricity consumption is used to calculate to total electricity consumption in that year and to provide a distribution of the electricity demand. The wind production is used to provide a wind production distribution. This is the only distribution for wind production even though there are both onshore and offshore production. This is because it has not been possible to find separate hourly data for the distributions of on and offshore.

A.1.6 Master Data Register for Wind Turbines 2011, Danish Energy Agency

This data source is a spreadsheet published by DEA with the capacity and annual production of all wind turbines in Denmark. It includes information about the location of the wind turbine as well and if it is onshore or offshore.

In the spreadsheet all units that are located outside the area of East Denmark are removed and all the units that did not produce any electricity in 2011 are removed as well. The remaining units are sorted according to if they are onshore or offshore and then the capacities onshore are summarized and the offshore capacities are summarized too. The same procedure applies for the annual production. The capacities works directly as input to the EnergyPLAN model whereas the production is indirect since the production will be calculated as a result of the capacity, the wind distribution and a correction factor. To correction factor is here adjusted to reach the calculated annual production.

A.1.7 Energy Projection 2012, Danish Energy Agency

The Energy Projection 2012 is a report about the expected development in the energy sector towards 2030. The report covers the development of energy consumption within different sectors of the society, including Individual Heating, Transportation, Industry and Energy Conversion. The data about the development is not given in numbers, but only as figures with excel graphs. This is maybe because of the significant inaccuracy connected to such predictions. This is the best figures found though, so the figures are printed in A4 and the projection from 2011 to 2025 is measured with a ruler. This measured data is used in the setting of the expected development of certain parameters in the model.

A.1.8 Electricity Consumption Projection 2009, Energinet.dk

This source is a report about the development of the electricity consumption in Denmark until 2030. The source is only used for the estimated electricity demand in 2025. The reason that this source is used Instead of the Energy Projection, presented in Section A.1.7, is that here the demand is divided according to the expected development for East Denmark specifically instead the whole country.

A.1.9 Heat Plan of the Capital Region 2, 2012, CTR, HOFOR and VEKS

The HPC2 is used for the data regarding the development of the amounts of waste in the period towards 2025. This document is described in Section 5.4 on page 39. It is also used to set the amount of geothermal DH production in the 2025 Reference. It is here assumed that the development in amounts of produced waste will be the same in the whole East Denmark.

A.1.10 Energy Policy Exposition 2012, The Danish Ministry of Climate and Energy

This document is a political document stating how the government wants to develop the energy sector in Denmark until 2020. The goal here is a share of 50% electricity production from wind turbines. This is followed up by an energy agreement in Danish parliament to implement wind production capacity as presented in the Energy Policy Exposition (The Danish Government et al. 2012). It is here assumed that this target will be met and that the distribution between East and West Denmark will be allocated according to the electricity consumption so that 50% of the electricity consumption in East Denmark will be covered by wind production.

A.2 Data Input - Reference 2011

The tables in this section present the specific values for the EnergyPLAN input of the Reference 2011 setting. Each of the following subsections represents a section under the Input tab in EnergyPLAN. The data presented here are the fields where there is an input. Fields in the model which are not mentioned here are left empty or with a default value.

A.2.1 Electricity Demand

Field	Value	Note / Reference
Distribution		(Energinet.dk 2011a)
Electricity demand	13.51 TWh (Net)	(Energinet.dk 2011a)

Table A.2: EnergyPLAN input data.

A.2.2 District Heating

DH Gr.	Field	Value	Note / Reference
All	Distribution of demand		EnergyPLAN default
1	Demand	2.34 TWh	(DEA 2011b)
1	DHP Efficiency	0.874	(DEA 2011b)
2	Demand	2.45 TWh	(DEA 2011b)
2	CHP capacity	397.6 MWe	(DEA 2011b)
2	CHP efficiency elec.	0.37	(DEA 2011b)
2	CHP efficiency therm.	0.49	(DEA 2011b)
2	TES	8.85 GWh	(DEA 2011b) (Mathiesen 2010)
2	HP capacity	11.06 MWe	(DEA 2011b) (Mathiesen 2010)
2	HP COP	1.95	(Mathiesen 2010)
2	Boiler capacity	961.8 MW	(DEA 2011b)
2	Boiler efficiency	0.958	(DEA 2011b)
2	Boiler fixed share	2.5%	(Mathiesen 2010)
3	Demand	8.86 TWh	(DEA 2011b)
3	CHP capacity	2094.5	Calculated as 14.8% less than "Condensing capacity" (DEA 2011b)
3	CHP efficiency elec.	0.297	(DEA 2011b)
3	CHP efficiency therm.	0.601	(DEA 2011b)
3	Heat Storage	3 GWh	(DEA 2011b) (Mathiesen 2010)
3	Boiler capacity	2011.8 MW	(DEA 2011b)
3	Boiler efficiency	1.185	(DEA 2011b)
3	Boiler fixed share	1%	(Mathiesen 2010)
3	Condensing capacity	2575.7 MW	(DEA 2011b)
3	Condensing efficiency	0.365	(DEA 2011b)
3	PP2 capacity	520.0 MW	(DEA 2011b)
3	PP2 Efficiency	0.263	(DEA 2011b)

Table A.3: EnergyPLAN input data.

Distribution of Fuel	Coal	Oil	Natural Gas	Biomass
DHP	0	0.0629	0.0628	0.7588
CHP Gr. 2	0	0.0043	2.0084	0.5289
CHP Gr. 3	6.4871	0.1349	1.6608	2.9294
Boiler Gr. 2	0	0.0030	0.4486	0.2808
Boiler Gr. 3	0	0.1904	0.3057	0.0121
PP	5.2073	0.1083	1.3331	2.3515
PP2	0	0.2299	0	0

Table A.4: EnergyPLAN input data (DEA 2011b).

A.2.3 Renewable Energy

Field	Value	Note / Reference
Wind distribution		(Energinet.dk 2011a)
Wind capacity	510.57 MW	(DEA 2011d)
Offshore wind capacity	449.35 MW	(DEA 2011d)
Wind capacity correction factor	-0.22	Defined by a total production of 2.605 TWh from on and offshore turbines. (DEA 2011d)

Table A.5: EnergyPLAN input data.

A.2.4 Individual

Field	Values	Note / Reference
Distribution of heat demand		EnergyPLAN default
Coal boiler input	0.0815 TWh	(DEA 2011a)(Statistics Denmark 2011)
Coal boiler thermal efficiency	0.7	EnergyPLAN default
Oil boiler input	1.9810 TWh	(DEA 2011a)(Statistics Denmark 2011)
Oil boiler thermal efficiency	0.85	(IDA 2009)
Natural gas boiler input	3.3571 TWh	(DEA 2011a)(Statistics Denmark 2011)
Natural gas boiler thermal efficiency	0.9	(IDA 2009)
Biomass boiler input	4.4444 TWh	(DEA 2011a)(Statistics Denmark 2011)

Continued on next page

Field	Values	Note / Reference
Biomass boiler thermal efficiency	0.8	(IDA 2009)
HP, demand	1.55 TWh	Defined as an electricity consumption of 0.78 TWh (DEA 2011a)
HP efficiency electric (COP)	3.2	(Mathiesen 2010)
HP capacity limit	0.5	(Mathiesen 2010)

Table A.6: EnergyPLAN input data.

A.2.5 Industry

Field	Values	Note / Reference
Distribution		EnergyPLAN default
Industry, Coal	1.54 TWh	(DEA 2011a)(Statistics Denmark 2011)
Industry, Oil	4.74 TWh	(DEA 2011a)(Statistics Denmark 2011)
Industry, Natural gas	5.19 TWh	(DEA 2011a)(Statistics Denmark 2011)
Industry, Biomass	1.38 TWh	(DEA 2011a)(Statistics Denmark 2011)
Industrial CHP distribution		EnergyPLAN default
DH Gr. 1, DH production	0.0278 TWh	(DEA 2011b)
DH Gr. 1, Electricity production	0.0059 TWh	(DEA 2011b)
DH Gr. 2, DH production	0.0425 TWh	(DEA 2011b)
DH Gr. 2, Electricity production	0	(DEA 2011b)
DH Gr. 3, DH production	0.0146 TWh	(DEA 2011b)
DH Gr. 3, Electricity production	0.0056 TWh	(DEA 2011b)

Table A.7: EnergyPLAN input data.

A.2.6 Transport

Field	Value	Note / Reference
JP (Jet fuel)	4.74 TWh	(DEA 2011a)(Statistics Denmark 2011)
Diesel	13.25 TWh	(DEA 2011a)(Statistics Denmark 2011)
Petrol	7.93 TWh	(DEA 2011a)(Statistics Denmark 2011)
Natural Gas	0	(DEA 2011a)
LPG	0	(DEA 2011a)

Table A.8: EnergyPLAN input data.

A.2.7 Waste

DH Gr.	Field	Values	Note / Reference
All	Distribution of waste		EnergyPLAN default
1	Waste input	2.2612 TWh	(DEA 2011b)
1	DH Production Efficiency	0.679	(DEA 2011b)
1	Elec. Production Efficiency	0.143	(DEA 2011b)
2	Waste input	0.7890 TWh	(DEA 2011b)
2	DH Production Efficiency	0.586	(DEA 2011b)
2	Elec. Production Efficiency	0.128	(DEA 2011b)
3	Waste input	1.8804 TWh	(DEA 2011b)
3	DH Production Efficiency	0.624	(DEA 2011b)
3	Elec. Production Efficiency	0.151	(DEA 2011b)
3	Geothermal, DH Production efficiency	0.020	Defined by a production of 0.04319 TWh. (HGS 2008)
3	Geothermal, Steam for HP efficiency	0.019	Defined by a production of 0.0401 TWh. (HGS 2008)
3	Geothermal, HP COP	2.08	(HGS 2008)

Table A.9: EnergyPLAN input data.

A.3 Data Input - Reference 2025

The tables in this section presents the specific values for the EnergyPLAN input for the reference setting of 2025. The Reference 2025 is based on the Reference 2011 and the data presented here is a complete list of the changes from Reference 2011 to 2025. The values not mentioned here are the same as for Reference 2011. In the Note/Reference column in the tables it is mentioned how the value is expected to change from 2011 to 2025 and from which source this expected development is taken from. The source of the original value is not given again, but can be seen in the tables in Section A.2 on page 109.

A.3.1 Electricity Demand

Field	Value	Note / Reference
Electricity demand	15.514 TWh	(Energinet.dk 2012b)

Table A.10: EnergyPLAN input data.

A.3.2 District Heating

DH Gr.	Field	Value	Note / Reference
All	Distribution of demand		EnergyPLAN default
1	Demand	2.46 TWh	Reduction of 5% (DEA 2011c)
2	Demand	2.57 TWh	Reduction of 5% (DEA 2011c)
3	Demand	9.30 TWh	Reduction of 5% (DEA 2011c)

Table A.11: EnergyPLAN input data.

Distribution of Fuel	Coal	Oil	Natural Gas	Biomass
DHP	0	0.0629	0.0628	0.7588
CHP Gr. 2	0	0.0043	2.0084	0.5289
CHP Gr. 3	2.5671	0.0264	0	8.6245
Boiler Gr. 2	0	0.0030	0.4486	0.2808
Boiler Gr. 3	0	0.0992	0.1529	0.2561
PP	2.0582	0.0211	0	6.9151
PP2	0	0.2299	0	0

Table A.12: EnergyPLAN input data (CTR et al. 2011b).

Note for Table A.12: The planned changes of the energy supply in the capital region in (CTR et al. 2011b) are applied to the fuel distribution from 2011. The consumption of coal and natural gas the central CHP plants is moved to the biomass column and 50% of the oil and natural gas consumption for peak load boilers is moved to biomass as well.

A.3.3 Renewable Energy

Field	Value	Note / Reference
Wind capacity	1,521 MW	Defined as a total of 50% wind share (7.76 TWh).
Offshore wind capacity	1,339 MW	(Danish Ministry of Climate and Energy 2012)

Table A.13: EnergyPLAN input data.

A.3.4 Individual

Field	Value	Note / Reference
Oil boiler input	0.9112 TWh	Reduction of 54% (DEA 2011c).
Natural gas boiler input	2.0814 TWh	Reduction of 38% (DEA 2011c).
Biomass boiler input	4.6670 TWh	Increase of 5% (DEA 2011c).
HP, demand	2.945 TWh	Increase of 90% (DEA 2011c).

Table A.14: EnergyPLAN input data.

A.3.5 Industry

Field	Value	Note / Reference
Industry, Coal	0.2163 TWh	Reduction of 86% (DEA 2011c).
Industry, Oil	2.8930 TWh	Reduction of 39% (DEA 2011c).
Industry, Natural gas	2.3376 TWh	Reduction of 55% (DEA 2011c).
Industry, Biomass	3.9471 TWh	Increase of 185% (DEA 2011c).

Table A.15: EnergyPLAN input data.

A.3.6 Transport

Field	Value	Note / Reference
JP (Jet fuel)	5.9197 TWh	Increase of 25% (DEA 2011c).
Diesel	14.5729 TWh	Increase of 10% (DEA 2011c).
Petrol	8.7269 TWh	Increase of 10% (DEA 2011c).

Table A.16: EnergyPLAN input data.

A.3.7 Waste

DH Gr.	Field	Values	Note / Reference
All	Distribution of Waste		EnergyPLAN default
1	Waste input	2.5348 TWh	Increase of 12.1%* (CTR et al. 2011b).
2	Waste input	0.8845 TWh	Increase of 12.1%* (CTR et al. 2011b).
3	Waste input	2.1079 TWh	Increase of 12.1%* (CTR et al. 2011b).
3	Geothermal, DH Production efficiency	0.093	Defined by a production of 0.201 TWh, Values scaled up from 14 to 65 MW (CTR et al. 2011b).
3	Geothermal, Steam for HP efficiency	0.091	Defined by a production of 0.186 TWh, Values scaled up from 14 to 65 MW (CTR et al. 2011b).

Table A.17: EnergyPLAN input data. *From 2011 to 2020 the annual rate of increase of the amounts of waste is 0.5% and from 2021 to 2025 it is 1.4%. This makes a total increase of 12.1% from 2011 to 2025.

A.4 Cost Data

A.4.1 Fuel Prices

Fuel	**Price**		
	Low (Alternative 1)	Medium (Basic)	High (Alternative 2)
Coal	20.1	23.1	25.4
Fuel oil	65.6	88.8	120.1
Diesel / Gasoil	87.3	111.9	146.2
Petrol / JP	94.7	120.1	153.7
Natural Gas	44.0	67.9	91.0
LPG	0	0	0
Waste	0	0	0
Biomass	50.7	54.5	69.4
Dry biomass	35.1	35.1	47.0
Wet biomass	0	0	0

Table A.18: EnergyPLAN input data.

A.4.2 Fuel Handling Costs

	Coal	**Fuel Oil**	**Diesel/Gasoil**	**Petrol/JP**	**Natural Gas**
To central CHP and power stations	0	1.95			3.07
To dec. CHP, DH and industry	0	14.21			15.29
To individual households	0		20.24		23.47
To transportation (road and train)			20.24	15.55	0
To transportation (air)				3.60	

Table A.19: EnergyPLAN input data.

	Biomass	**Dry Biomass**	**Wet Biomass**
To biomass conversion plants	11.79	11.14	40.66
To central CHP and power stations	11.79		
To dec. CHP, DH and industry	8.85		
To individual households	22.27		
To transportation (road and train)	8.85		

Table A.20: EnergyPLAN input data.

A.4.3 CO_2 Content in Fuel and CO_2 Price

CO_2 price
149.2 DKK/t

Table A.21: EnergyPLAN input data.

	Coal	**Oil**	**Natural Gas**	**LPG**	**Waste**
CO_2 content [kg/GJ]	98.5	72.9	56.9	59.64	32.5

Table A.22: EnergyPLAN input data.

A.4.4 Variable Operation and Maintenance Costs

DH and CHP systems		
Boiler	1.12	DKK/MWh-th
CHP	20.14	DKK/MWh-e
HP	2.01	DKK/MWh-e
Electric heating	10.07	DKK/MWh-e
Power Plants		
Hydro power	8.88	DKK/MWh-e
Condensing	19.80	DKK/MWh-e
Geothermal	111.90	DKK/MWh-e
GTL M1	13.43	DKK/MWh-fuel-input
GTL M2	7.52	DKK/MWh-fuel-input
Storage		
Electrolyzer	0	DKK/MWh-e
Pump	8.88	DKK/MWh-e
Turbine	8.88	DKK/MWh-e
V2G Discharge	0	DKK/MWh-e
Hydro power pump	8.88	DKK/MWh-e

Table A.23: EnergyPLAN input data.

A.4.5 Investment, Operation and Maintenance costs

	Investment Costs [M DKK/Unit]	**Period [years]**	**Operation and Maintenance [% of investment]**
Small CHP units	6	25	2.3
HP gr. 2	20	20	0.2
Heat storage CHP	19	20	0.7
Large CHP units	6	25	2.3
HP gr. 3	20	20	0.2
Heat storage solar	19	20	0.7

Continued on next page

	Investment Costs [M DKK/Unit]	Period [years]	Operation and Maintenance [% of investment]
Boilers gr. 2 and 3	1	20	3
Large power plants	7	26	1.822
Wind	9	20	3
Wind offshore	17	20	2.9
Geothermal	20	20	3.42
Electrolyzer	4	20	2.46
Hydrogen storage	75	30	0.5
Pump	4	50	1.5
Turbine	4	506	1.5
Pump storage	56	50	1.5
Indv. Boiler	4	15	2.1
Indv. CHP	6	10	2.8
Indv. HP	9	15	0.6
Indv. Electric heat	2	20	0.9

Table A.24: EnergyPLAN input data.

A.4.6 Specification of Various Additional Investment Costs

	Investment costs [M DKK/Unit]	Period [years]	Operation and maintenance [% of investment]
Waste CHP	1868	20	1.82
Absorp. HP (Waste)	14.2	25	2.42

Table A.25: EnergyPLAN input data.

EnergyPLAN Output B

This appendix gives the main output data from the EnergyPLAN reference models 2011 and 2025. The output of each of the models consist of two data sheets. The first sheet contains a highlight of the most important input values for the systems, monthly values of DH demand and production, monthly values of electricity consumption and production and a fuel balance. The second of the two sheets also contanins monthly values of the DH production, but here divided on the three DH groups. It also contains monthly values of the RE production and a summary of the annual costs in the model.

Input DKeastRef2011.txt

The EnergyPLAN model 10.1

Electricity demand (TWh/year):		Flexible demand	0,00
Fixed demand	13,51	Fixed imp/exp.	0,00
Electric heating	0,00	Transportation	0,00
Electric cooling	0,00	Total	13,51

District heating (TWh/year)	Gr.1	Gr.2	Gr.3	Sum
District heating demand	2,34	2,45	8,86	13,65
Solar Thermal	0,00	0,00	0,00	0,00
Industrial CHP (CSHP)	0,03	0,04	0,01	0,08
Demand after solar and CSHP	2,31	2,41	8,85	13,57

Wind	511 MW	1,39 TWh/year	0,00	Grid
Offshore Wind	449 MW	1,22 TWh/year	0,00	stabili-
Wave Power	0 MW	0 TWh/year	0,00	sation
River Hydro	0 MW	0 TWh/year	0,00	share
Hydro Power	0 MW	0 TWh/year		
Geothermal/Nuclear	0 MW	0 TWh/year		

	Capacities		Efficiencies		
Group 2:	MW-e	MJ/s	elec.	Ther	COP
CHP	398	527	0,37	0,49	
Heat Pump	11	22			1,95
Boiler		962		0,96	
Group 3:					
CHP	2095	4238	0,30	0,60	
Heat Pump	0	0			3,00
Boiler		2102		1,19	
Condensing	2576		0,36		

Heatstorage: gr.2: 9 GWh gr.3: 3 GWh
Fixed Boiler: gr.2: 2,5 Per cent gr.3: 1,0 Per cent

Electricity prod. from	CSHP	Waste (TWh/year)
Gr.1:	0,01	0,32
Gr.2:	0,00	0,10
Gr.3:	0,01	0,28

Regulation Strategy:	Technical regulation no. 2	
KEOL regulation	23450000	
Minimum Stabilisation share	0,30	
Stabilisation share of CHP	1,00	
Minimum CHP gr 3 load	0	MW
Minimum PP	0	MW
Heat Pump maximum share	0,50	
Maximum import/export	0	MW

Distr. Name :	Hour_nordpool.txt	
Addition factor	0,00	DKK/MWh
Multiplication factor	2,00	
Dependency factor	0,00	DKK/MWh pr. MW
Average Market Price	227	DKK/MWh
Gas Storage	0	GWh
Syngas capacity	0	MW
Biogas max to grid	0	MW

Fuel Price level:

	Capacities MW-e	Storage GWh	Efficiencies elec.	Ther.
Hydro Pump:	0	0	0,80	
Hydro Turbine:	0		0,90	
Electrol. Gr.2:	0	0	0,80	0,10
Electrol. Gr.3:	0	0	0,80	0,10
Electrol. trans.:	0	0	0,80	
Ely. MicroCHP:	0	0	0,80	
CAES fuel ratio:		0,000		

(TWh/year)	Coal	Oil	Ngas	Biomass
Transport	0,00	25,92	0,00	0,00
Household	0,08	1,98	3,36	4,44
Industry	1,54	4,74	5,19	1,38
Various	0,00	0,00	0,00	0,00

Output WARNING!!: (1) Critical Excess;

District Heating

	Demand: Distr. heating MW	Production: Solar MW	Waste+ CSHP MW	DHP MW	CHP MW	HP MW	ELT MW	Boiler MW	EH MW	Balance MW
January	2501	0	402	251	1828	8	0	16	0	-4
February	2558	0	402	261	1861	9	0	21	0	4
March	2180	0	402	196	1561	8	0	15	0	-2
April	1747	0	402	121	1203	8	0	13	0	-1
May	1370	0	402	57	894	7	0	10	0	0
June	621	0	402	0	274	7	0	10	0	0
July	621	0	402	0	274	7	0	10	0	0
August	621	0	402	0	274	7	0	10	0	0
September	953	0	402	7	549	7	0	10	0	0
October	1420	0	402	68	934	8	0	10	0	1
November	1863	0	402	141	1301	8	0	10	0	0
December	2224	0	402	203	1537	10	0	73	0	-1
Average	1554	0	402	108	1039	8	0	18	0	0
Maximum	4367	0	402	571	3197	22	0	1288	0	1038
Minimum	544	0	402	0	210	7	0	10	0	-403
TWh/year	13,65	0,00	3,53	0,95	9,12	0,07	0,00	0,15	0,00	0,00

Electricity / Exchange

	Consumption: Elec. demand MW	Flex.& Transp. MW	HP MW	Elec- trolyser MW	EH MW	Hydro Pump MW	Production: Tur- bine MW	RES MW	Hy- dro MW	Geo- thermal MW	Waste+ CSHP MW	CHP MW	PP MW	Stab- Load %	Balance: Imp MW	Exp MW	CEEP MW	EEP MW	Exchange Payment Imp Million DKK	Exp
January	1820	0	195	0	0	0	0	224	0	0	73	1003	715	282	0	0	0	0	0	0
February	1824	0	179	0	0	0	0	456	0	0	73	1021	454	243	0	0	0	0	0	0
March	1671	0	140	0	0	0	0	335	0	0	73	857	546	257	0	0	0	0	0	0
April	1429	0	78	0	0	0	0	273	0	0	73	659	503	257	0	0	0	0	0	0
May	1400	0	44	0	0	0	0	256	0	0	73	489	626	255	0	0	0	0	0	0
June	1353	0	31	0	0	0	0	171	0	0	73	148	993	274	0	0	0	0	0	0
July	1312	0	26	0	0	0	0	217	0	0	73	147	902	259	0	1	1	0	0	0
August	1421	0	26	0	0	0	0	252	0	0	73	147	977	257	0	2	2	0	0	0
September	1443	0	36	0	0	0	0	260	0	0	73	299	849	258	0	1	1	0	0	0
October	1507	0	63	0	0	0	0	345	0	0	73	511	642	242	0	1	1	0	0	0
November	1618	0	123	0	0	0	0	255	0	0	73	713	700	269	0	1	1	0	0	0
December	1667	0	171	0	0	0	0	519	0	0	73	844	402	223	0	1	1	0	0	0
Average	1538	0	92	0	0	0	0	297	0	0	73	569	693	256	0	1	1	0	Average price	
Maximum	2479	0	217	0	0	0	0	960	0	0	73	1717	1731	324	0	184	184	0	(DKK/MWh)	
Minimum	870	0	23	0	0	0	0	0	0	0	73	112	0	100	0	0	0	0	238	177
TWh/year	13,51	0,00	0,81	0,00	0,00	0,00	0,00	2,61	0,00	0,00	0,64	5,00	6,09		0,00	0,00	0,00	0,00	0	1

FUEL BALANCE (TWh/year):

	DHP	CHP2	CHP3	Boiler2	Boiler3	PP	Geo/Nu.	Hydro	Waste	CAES Elc.ly.	BioCon- version	Synthetic Fuel	Wind	Offsh.	Wave	Hydro	Solar.Th.	Transp.	househ.	Industry Various	Total	Imp/Exp Corrected Imp/Exp	Netto	CO2 emission (Mt): Total	Netto
Coal	-	-	6,98	-	-	9,65	-	-	-	-	-	-	-	-	-	-	-	-	0,08	1,54	18,25	-0,01	18,24	6,47	6,47
Oil	0,08	0,01	0,15	0,00	0,05	0,20	-	-	-	-	-	-	-	-	-	-	-	25,92	1,98	4,74	33,12	0,00	33,12	8,69	8,69
N.Gas	0,08	3,01	1,79	0,00	0,07	2,47	-	-	-	-	-	-	-	-	-	-	-	-	3,36	5,19	15,98	0,00	15,98	3,27	3,27
Biomass	0,93	0,79	3,15	0,00	0,00	4,36	-	-	4,93	-	-	-	-	-	-	-	-	-	4,44	1,38	19,99	0,00	19,99	0,58	0,00
Renewable	-	-	-	-	-	-	-	-	0,08	-	-	-	1,39	1,22	-	-	-	-	-	-	2,68	0,00	2,68	0,00	0,00
H2 etc.	-	0,00	0,00	0,00	0,00	0,00	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0,00	0,00	0,00	0,00	0,00
Biofuel	-	-	0,00	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0,00	0,00	0,00	0,00	0,00
Nuclear	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0,00	0,00	0,00	0,00	0,00
Total	1,09	3,81	12,07	0,01	0,12	16,67	-	-	5,01	-	-	-	1,39	1,22	-	-	-	25,92	9,86	12,85	90,02	-0,01	90,01	19,01	18,43

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Output specifications DKeastRef2011.txt The EnergyPLAN model 10.1

District Heating Production

	Gr.1 District heating MW	Gr.1 Solar MW	Gr.1 CSHP MW	Gr.1 DHP MW	Gr.2 District heating MW	Gr.2 Solar MW	Gr.2 CSHP MW	Gr.2 CHP MW	Gr.2 HP MW	Gr.2 ELT MW	Gr.2 Boiler MW	Gr.2 EH MW	Gr.2 Stor-age MW	Gr.2 Ba-lance MW
January	429	0	178	251	449	0	57	383	8	0	1	0	1160	0
February	439	0	178	261	459	0	57	388	9	0	3	0	1032	2
March	374	0	178	196	391	0	57	328	8	0	1	0	1989	-3
April	299	0	178	121	313	0	57	248	8	0	0	0	2297	0
May	235	0	178	57	246	0	57	181	7	0	0	0	2294	0
June	106	0	178	0	111	0	57	47	7	0	0	0	2316	0
July	106	0	178	0	111	0	57	47	7	0	0	0	2318	0
August	106	0	178	0	111	0	57	47	7	0	0	0	2318	0
September	163	0	178	7	171	0	57	106	7	0	0	0	2308	0
October	243	0	178	68	255	0	57	190	8	0	0	0	2415	0
November	319	0	178	141	334	0	57	269	8	0	0	0	2422	0
December	381	0	178	203	399	0	57	324	10	0	6	0	2785	1
Average	266	0	178	108	279	0	57	213	8	0	1	0	2142	0
Maximum	749	0	178	571	784	0	57	527	22	0	313	0	8850	312
Minimum	93	0	178	0	98	0	57	3	7	0	0	0	0	-97
Total for the whole year														
TWh/year	2,34	0,00	1,56	0,95	2,45	0,00	0,50	1,87	0,07	0,00	0,01	0,00		0,00

	Gr.3 District heating MW	Gr.3 Solar MW	Gr.3 CSHP MW	Gr.3 CHP MW	Gr.3 HP MW	Gr.3 ELT MW	Gr.3 Boiler MW	Gr.3 EH MW	Gr.3 Stor-age MW	Gr.3 Ba-lance MW	RES specification RES1 Wind MW	RES2 Offshoı MW	RES3 Wave I MW	RES4 River H MW	Total o MW
January	1623	0	166	1445	0	0	15	0	2305	-4	119	105	0	0	224
February	1661	0	166	1473	0	0	18	0	1085	2	242	213	0	0	456
March	1415	0	166	1233	0	0	15	0	2485	1	178	157	0	0	335
April	1134	0	166	956	0	0	13	0	1025	-1	145	128	0	0	273
May	889	0	166	713	0	0	10	0	1649	0	136	120	0	0	256
June	403	0	166	227	0	0	10	0	1706	0	91	80	0	0	171
July	403	0	166	227	0	0	10	0	1709	0	115	101	0	0	217
August	403	0	166	227	0	0	10	0	1709	0	134	118	0	0	252
September	619	0	166	442	0	0	10	0	1709	0	138	122	0	0	260
October	922	0	166	745	0	0	10	0	1707	1	183	161	0	0	345
November	1209	0	166	1033	0	0	10	0	1588	0	136	119	0	0	255
December	1444	0	166	1213	0	0	67	0	1986	-2	276	243	0	0	519
Average	1009	0	166	826	0	0	17	0	1728	0	158	139	0	0	297
Maximum	2835	0	166	2670	0	0	1068	0	3000	815	511	449	0	0	960
Minimum	353	0	166	177	0	0	10	0	0	-317	0	0	0	0	0
Total for the whole year															
TWh/year	8,86	0,00	1,46	7,25	0,00	0,00	0,15	0,00		0,00	1,39	1,22	0,00	0,00	2,61

ANNUAL COSTS (Million DKK)		
Total Fuel =		2839
Uranium =	0	
Coal =	204	
FuelOil =	257	
Gasoil/Diesel=	971	
Petrol/JP =	802	
Ngas =	106	
Biomass =	500	
Food income =	0	
Waste =	0	
Marginal operation costs =		30
Total Electricity exchange =		0
Import =	0	
Export =	-1	
Bottleneck =	1	
Fixed imp/ex=	0	
Total CO2 emission costs =		380
Total Ngas Exchange costs =		523
Total variable costs =		3773
Fixed operation costs =		183
Annual Investment costs =		533
TOTAL ANNUAL COSTS =		4488

	DHP & Boilers MW	CHP2 CHP3 MW	PP CAES MW	Indi-vidual MW	Trans port MW	Indu. Var. MW	Demanc Sum MW	Bio-gas MW	Syn-gas MW	CO2Hy gas MW	SynHy gas MW	SynHy gas MW	Stor-age MW	Sum MW	Im-port MW	Ex-port MW
January	29	974	290	648	0	591	2531	0	0	0	0	0	0	2531	2531	0
February	32	988	184	612	0	591	2408	0	0	0	0	0	0	2408	2408	0
March	24	833	222	527	0	591	2197	0	0	0	0	0	0	2197	2197	0
April	17	635	204	394	0	591	1840	0	0	0	0	0	0	1840	1840	0
May	10	468	254	258	0	591	1581	0	0	0	0	0	0	1581	1581	0
June	5	132	403	189	0	591	1319	0	0	0	0	0	0	1319	1319	0
July	5	132	366	153	0	591	1247	0	0	0	0	0	0	1247	1247	0
August	5	132	396	159	0	591	1283	0	0	0	0	0	0	1283	1283	0
September	6	281	344	224	0	591	1445	0	0	0	0	0	0	1445	1445	0
October	11	489	261	348	0	591	1699	0	0	0	0	0	0	1699	1699	0
November	17	688	284	491	0	591	2071	0	0	0	0	0	0	2071	2071	0
December	54	822	163	594	0	591	2224	0	0	0	0	0	0	2224	2224	0
Average	18	547	281	383	0	591	1819	0	0	0	0	0	0	1819	1819	0
Maximum	717	1507	703	680	0	591	3032	0	0	0	0	0	0	3032	3032	0
Minimum	5	97	0	138	0	591	925	0	0	0	0	0	0	925	925	0
Total for the whole year																
TWh/year	0,16	4,80	2,47	3,36	0,00	5,19	15,98	0,00	0,00	0,00	0,00	0,00	0,00	15,98	15,98	0,00

RES Share: 25,2 Percent of Primary Energy 44,7 Percent of Electricity 6,1 TWh electricity from RES 04-juni-2013 [12:06]

Input DKeastRef2025.txt

The EnergyPLAN model 10.1

Electricity demand (TWh/year):		Flexible demand	0,00
Fixed demand	15,51	Fixed imp/exp.	0,00
Electric heating	0,00	Transportation	0,00
Electric cooling	0,00	Total	15,51

District heating (TWh/year)	Gr.1	Gr.2	Gr.3	Sum
District heating demand	2,46	2,57	9,30	14,33
Solar Thermal	0,00	0,00	0,00	0,00
Industrial CHP (CSHP)	0,03	0,04	0,01	0,08
Demand after solar and CSHP	2,43	2,53	9,29	14,25

Wind	1522 MW	4,13 TWh/year	0,00	Grid
Offshore Wind	1339 MW	3,63 TWh/year	0,00	stabili-
Wave Power	0 MW	0 TWh/year	0,00	sation
River Hydro	0 MW	0 TWh/year	0,00	share
Hydro Power	0 MW	0 TWh/year		
Geothermal/Nuclear	0 MW	0 TWh/year		

	Capacities		Efficiencies		
Group 2:	MW-e	MJ/s	elec.	Ther	COP
CHP	398	527	0,37	0,49	
Heat Pump	11	22			1,95
Boiler		962		0,96	
Group 3:					
CHP	2095	4238	0,30	0,60	
Heat Pump	0	0			3,00
Boiler		2102		1,19	
Condensing	2576		0,36		

Heatstorage: gr.2: 9 GWh gr.3: 3 GWh
Fixed Boiler: gr.2: 2,5 Per cent gr.3: 1,0 Per cent

Electricity prod. from	CSHP	Waste (TWh/year)
Gr.1:	0,01	0,36
Gr.2:	0,00	0,11
Gr.3:	0,01	0,32

Regulation Strategy:	Technical regulation no. 2	
KEOL regulation	23450000	
Minimum Stabilisation share	0,30	
Stabilisation share of CHP	1,00	
Minimum CHP gr 3 load	0	MW
Minimum PP	0	MW
Heat Pump maximum share	0,50	
Maximum import/export	0	MW
Distr. Name :	Hour_nordpool.txt	
Addition factor	0,00	EUR/MWh
Multiplication factor	2,00	
Dependency factor	0,00	EUR/MWh pr. MW
Average Market Price	227	EUR/MWh
Gas Storage	0	GWh
Syngas capacity	0	MW
Biogas max to grid	0	MW

Fuel Price level:

	Capacities	Storage	Efficiencies	
	MW-e	GWh	elec.	Ther.
Hydro Pump:	0	0	0,80	
Hydro Turbine:	0		0,90	
Electrol. Gr.2:	0	0	0,80	0,10
Electrol. Gr.3:	0	0	0,80	0,10
Electrol. trans.:	0	0	0,80	
Ely. MicroCHP:	0	0	0,80	
CAES fuel ratio:		0,000		

(TWh/year)	Coal	Oil	Ngas	Biomass
Transport	0,00	29,22	0,00	0,00
Household	0,08	0,91	2,08	4,67
Industry	0,22	2,89	2,34	3,95
Various	0,00	0,00	0,00	0,00

Output WARNING!!: (1) Critical Excess;

	District Heating										Electricity																			Exchange	
	Demand	Production									Consumption						Production							Balance							
	Distr. heating MW	Solar MW	Waste+ CSHP MW	DHP MW	CHP MW	HP MW	ELT MW	Boiler MW	EH MW	Ba- lance MW	Elec. demand MW	Flex.& Transp. MW	HP MW	Elec- trolyser MW	EH MW	Hydro Pump MW	Tur- bine MW	RES MW	Hy- dro MW	Geo- thermal MW	Waste+ CSHP MW	CHP MW	PP MW	Stab- Load %	Imp MW	Exp MW	CEEP MW	EEP MW	Payment Imp Million EUR	Payment Exp Million EUR
January	2625	0	504	252	1811	11	0	59	0	-12	2090	0	368	0	0	0	0	668	0	0	74	996	807	238	0	86	86	0	0	12
February	2686	0	504	262	1718	15	0	178	0	9	2094	0	339	0	0	0	0	1359	0	0	74	927	373	165	0	298	298	0	0	43
March	2288	0	504	194	1491	13	0	88	0	-1	1919	0	264	0	0	0	0	999	0	0	74	813	557	198	0	259	259	0	0	41
April	1834	0	504	116	1151	12	0	47	0	4	1641	0	147	0	0	0	0	812	0	0	74	625	564	207	0	287	287	0	0	54
May	1439	0	504	49	859	12	0	17	0	-1	1608	0	82	0	0	0	0	762	0	0	74	471	595	195	0	211	211	0	0	39
June	652	0	504	0	222	10	0	11	0	-9	1554	0	57	0	0	0	0	509	0	0	74	123	1001	227	0	95	95	0	0	15
July	652	0	504	0	211	11	0	13	0	0	1507	0	48	0	0	0	0	646	0	0	74	115	965	214	0	244	244	0	0	20
August	652	0	504	0	211	11	0	13	0	0	1632	0	49	0	0	0	0	751	0	0	74	115	986	203	0	244	244	0	0	39
September	1001	0	504	4	500	11	0	14	0	-1	1657	0	67	0	0	0	0	775	0	0	74	274	884	208	0	282	282	0	0	49
October	1491	0	504	60	883	13	0	31	0	2	1730	0	120	0	0	0	0	1028	0	0	74	480	636	180	0	368	368	0	0	66
November	1956	0	504	137	1263	10	0	30	0	12	1858	0	231	0	0	0	0	760	0	0	74	689	749	221	0	183	183	0	0	28
December	2335	0	504	202	1415	16	0	203	0	-5	1914	0	323	0	0	0	0	1548	0	0	74	753	433	151	0	570	570	0	0	93
Average	1631	0	504	106	976	12	0	58	0	0	1766	0	174	0	0	0	0	884	0	0	74	531	713	201	0	261	261	0	Average price	
Maximum	4585	0	504	588	3317	22	0	2159	0	1148	2847	0	402	0	0	0	0	2861	0	0	74	1777	2122	325	0	2493	2493	0	(EUR/MWh)	
Minimum	571	0	504	0	119	7	0	11	0	-830	999	0	41	0	0	0	0	0	0	0	74	59	0	100	0	0	0	0	230	218
TWh/year	14,33	0,00	4,43	0,93	8,57	0,11	0,00	0,51	0,00	0,00	15,51	0,00	1,53	0,00	0,00	0,00	0,00	7,76	0,00	0,00	0,65	4,66	6,27		0,00	2,29	2,29	0,00	0	499

FUEL BALANCE (TWh/year):

	DHP	CHP2	CHP3	Boiler2	Boiler3	PP	Geo/Nu.	Hydro	Waste	CAES Elc.ly.	BioCon- version	Synthetic Fuel	Wind	Offsh.	Wave	Hydro	Solar.Th.	Transp.	househ.	Industry Various	Total	Imp/Exp Corrected Imp/Exp	Imp/Exp Corrected Netto	CO2 emission (Mt): Total	CO2 emission (Mt): Netto
Coal	-	-	2,65	-	-	3,93	-	-	-	-	-	-	-	-	-	-	-	-	0,08	0,22	6,87	-1,44	5,43	2,44	1,93
Oil	0,08	0,01	0,03	0,00	0,04	0,04	-	-	-	-	-	-	-	-	-	-	-	29,22	0,91	2,89	33,21	-0,01	33,20	8,72	8,71
N.Gas	0,08	2,62	-	0,18	0,06	-	-	-	-	-	-	-	-	-	-	-	-	-	2,08	2,34	7,35	0,00	7,35	1,51	1,51
Biomass	0,91	0,69	8,89	0,11	0,10	13,20	-	-	5,53	-	-	-	-	-	-	-	-	-	4,67	3,95	38,04	-4,83	33,21	0,65	0,00
Renewable	-	-	-	-	-	-	-	-	0,39	-	-	-	4,13	3,63	-	-	-	-	-	-	8,16	0,00	8,16	0,00	0,00
H2 etc.	-	0,00	0,00	0,00	0,00	0,00	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0,00	0,00	0,00	0,00	0,00
Biofuel	-	-	0,00	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0,00	0,00	0,00	0,00	0,00
Nuclear	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0,00	0,00	0,00	0,00	0,00
Total	1,06	3,32	11,56	0,29	0,20	17,17	-	-	5,92	-	-	-	4,13	3,63	-	-	-	29,22	7,74	9,39	93,63	-6,28	87,35	13,31	12,15

04-juni-2013 [12:06]

Output specifications DKeastRef2025.txt The EnergyPLAN model 10.1

District Heating Production

	Gr.1 District heating MW	Gr.1 Solar MW	Gr.1 CSHP MW	Gr.1 DHP MW	Gr.2 District heating MW	Gr.2 Solar MW	Gr.2 CSHP MW	Gr.2 CHP MW	Gr.2 HP MW	Gr.2 ELT MW	Gr.2 Boiler MW	Gr.2 EH MW	Gr.2 Stor-age MW	Gr.2 Ba-lance MW
January	451	0	199	252	471	0	64	386	11	0	18	0	5138	-8
February	461	0	199	262	482	0	64	299	15	0	95	0	3684	9
March	393	0	199	194	410	0	64	291	13	0	46	0	5594	-3
April	315	0	199	116	329	0	64	216	12	0	33	0	3451	4
May	247	0	199	49	258	0	64	177	12	0	5	0	4756	0
June	112	0	199	0	117	0	64	50	10	0	1	0	7716	-8
July	112	0	199	0	117	0	64	40	11	0	2	0	8087	0
August	112	0	199	0	117	0	64	40	11	0	2	0	7888	0
September	172	0	199	4	179	0	64	103	11	0	3	0	6516	-1
October	256	0	199	60	267	0	64	168	13	0	20	0	3963	2
November	336	0	199	137	351	0	64	248	10	0	20	0	6606	9
December	401	0	199	202	419	0	64	207	16	0	134	0	2804	-2
Average	280	0	199	106	293	0	64	185	12	0	31	0	5521	0
Maximum	787	0	199	588	822	0	64	527	22	0	608	0	8850	435
Minimum	98	0	199	0	102	0	64	0	7	0	0	0	0	-282
Total for the whole year														
TWh/year	2,46	0,00	1,75	0,93	2,57	0,00	0,56	1,62	0,11	0,00	0,28	0,00		0,00

	Gr.3 District heating MW	Gr.3 Solar MW	Gr.3 CSHP MW	Gr.3 CHP MW	Gr.3 HP MW	Gr.3 ELT MW	Gr.3 Boiler MW	Gr.3 EH MW	Gr.3 Stor-age MW	Gr.3 Ba-lance MW	RES specification RES1 Wind MW	RES2 Offshoı MW	RES3 Wave I MW	RES4 River H MW	Total o MW
January	1704	0	241	1425	0	0	41	0	1869	-4	355	313	0	0	668
February	1743	0	241	1419	0	0	83	0	1148	0	723	636	0	0	1359
March	1485	0	241	1200	0	0	42	0	1795	2	531	468	0	0	999
April	1190	0	241	936	0	0	14	0	1490	0	432	380	0	0	812
May	934	0	241	682	0	0	11	0	2410	-1	405	357	0	0	762
June	423	0	241	172	0	0	11	0	2682	0	271	238	0	0	509
July	423	0	241	171	0	0	11	0	2692	0	344	303	0	0	646
August	423	0	241	171	0	0	11	0	2692	0	399	352	0	0	751
September	650	0	241	398	0	0	11	0	2692	0	412	363	0	0	775
October	967	0	241	715	0	0	11	0	2662	0	547	481	0	0	1028
November	1269	0	241	1015	0	0	11	0	2421	2	404	356	0	0	760
December	1516	0	241	1208	0	0	69	0	1351	-3	823	724	0	0	1548
Average	1059	0	241	791	0	0	27	0	2162	0	470	414	0	0	884
Maximum	2975	0	241	2791	0	0	1554	0	3000	837	1522	1339	0	0	2861
Minimum	371	0	241	119	0	0	11	0	0	-595	0	0	0	0	0
Total for the whole year															
TWh/year	9,30	0,00	2,12	6,95	0,00	0,00	0,24	0,00		0,00	4,13	3,63	0,00	0,00	7,76

ANNUAL COSTS (Million EUR)

Total Fuel =		3258
Uranium =	0	
Coal =	77	
FuelOil =	153	
Gasoil/Diesel=	987	
Petrol/JP =	925	
Ngas =	62	
Biomass =	1055	
Food income =	0	
Waste =	0	
Marginal operation costs =		29
Total Electricity exchange =		0
Import =	0	
Export =	-499	
Bottleneck =	499	
Fixed imp/ex=	0	
Total CO2 emission costs =		266
Total Ngas Exchange costs =		241
Total variable costs =		3795
Fixed operation costs =		279
Annual Investment costs =		748
TOTAL ANNUAL COSTS =		4822

	DHP & Boilers MW	CHP2 CHP3 MW	PP CAES MW	Indi-vidual MW	Trans port MW	Indu. Var. MW	Demanı Sum MW	Bio-gas MW	Syn-gas MW	CO2Hy gas MW	SynHy gas MW	SynHy gas MW	Stor-age MW	Sum MW	Im-port MW	Ex-port MW
January	42	623	0	401	0	266	1332	0	0	0	0	0	0	1332	1332	0
February	103	482	0	379	0	266	1230	0	0	0	0	0	0	1230	1230	0
March	56	469	0	327	0	266	1117	0	0	0	0	0	0	1117	1117	0
April	34	348	0	244	0	266	892	0	0	0	0	0	0	892	892	0
May	10	285	0	160	0	266	722	0	0	0	0	0	0	722	722	0
June	3	81	0	117	0	266	468	0	0	0	0	0	0	468	468	0
July	4	64	0	95	0	266	429	0	0	0	0	0	0	429	429	0
August	4	64	0	98	0	266	432	0	0	0	0	0	0	432	432	0
September	5	166	0	139	0	266	575	0	0	0	0	0	0	575	575	0
October	20	270	0	216	0	266	773	0	0	0	0	0	0	773	773	0
November	26	400	0	304	0	266	996	0	0	0	0	0	0	996	996	0
December	120	333	0	368	0	266	1087	0	0	0	0	0	0	1087	1087	0
Average	36	298	0	237	0	266	837	0	0	0	0	0	0	837	837	0
Maximum	822	849	0	421	0	266	1722	0	0	0	0	0	0	1722	1722	0
Minimum	3	0	0	85	0	266	359	0	0	0	0	0	0	359	359	0
Total for the whole year																
TWh/year	0,31	2,62	0,00	2,08	0,00	2,34	7,35	0,00	0,00	0,00	0,00	0,00	0,00	7,35	7,35	0,00

RES Share: 49,3 Percent of Primary Energy 103,5 Percent of Electricity 16,1 TWh electricity from RES 04-juni-2013 [12:06]

EnergyPRO Data Input C

This appendix describes the data sources on which the reference scenario is based and how the data have been treated to fit as input for the EnergyPRO model. Hereafter the specific input values are presented in tables with references to the described sources. The data is described in chronological order by when it is put into the model. The reference models for 2011 and 2025 used in EnergyPRO are found on the CD attached to this report.

The economic values used in 2025 has not been extrapolated by any discount rate. The reason for this is, that the values in this year is thought to be in 2011 values, since the same values of the Annual Investments and O&M has been used in 2011 as well as in the 2025 calculations. The values of the investments the additional technologies have been found in Appendix A.4 on page 116 in order to use the same values in the two models.

C.1 External Conditions

The weather data is from 2011 and are loaded from the EnergyPRO data files for external conditions. The data gives the hourly average temperature, which is used to determine when there is a heat demand, set in the Demand input, described later. The electricity spot prices in East Denmark in 2011 are found in the EnergyPRO data as well and is given on hourly basis. The other external conditions are set according to C.1.

Planning Period	01.01.2011 - 31.12.2011
Time Series	Weather data
	Electricity Spot prices for East DK 2011
Indexes	None
	Describes the development of e.g. heat demand
Holidays	Danish
Currency	DKK

Table C.1: External conditions for Reference Scenario EnergyPRO 2011.

2025 Scenario: Changes in the scenario for 2025 has been moving the period to be 01.01.2025 to 31.12.2025 and extrapolate the electricity spot market prices to 2025. To find the electricity spot market prices on hourly basis in 2025 an annual average estimate from 2025 of 616 DKK/MWh has been used (DEA 2011e). A correlation between the average price from 2011 and the average price in 2025 has been multiplied to the hourly price in 2011 to give the price on hourly basis in 2025. This means that the prices are high at the same hours in 2025 as in 2011 and low at the same hour, see Section 8.3.1 on page 75.

C.2 Demand

The demand is divided into three different consumer parts; Heat losses in the grid, heat sale to the consumers in CTR and heat sale to VEKS, see Table C.2. The annual capacities of the demands are taking from the annual accounts in CTR from 2011. (CTR 2011)

	Heat Loss	**Heat Sale CTR**	**Heat Sale VEKS**
Capacity 2011	180 TJ	18,411 TJ	308 TJ
External Conditions	No - Divided into monthly amounts	Demand depending/variates on ambient temperature	No – Divided into monthly amounts
Dependent Fraction	-	60,0% - how much of the heat demand that depend on ambient temperature	-
Reference Temperature	-	17°C – when ambient temperature is below this, there is a heat demand	-
Profile	None fixed profile – assuming constant heat loss	Fixed profile of demand	None fixed profile
Costs	-	101 DKK/GJ (Magnusson 2013)	101 DKK/GJ

Table C.2: Input for demand profiles (DEA 2011e).

2025 Scenario: In 2025, the demand is expected to increase due to new construction in the transmission grid. The demand has therefore been increased by 5% corresponding to a demand in 2025 of 19,331.55 TJ. The heat sale price of 101 DKK/GJ has been used in 2025 as it is difficualt to predict the development of the prices. Heat loss and heat sale to VEKS is assumed to be the same. These assumptions are based on the interview with (Magnusson 2013).

C.3 Energy Units

Due to confidential agreements are the plants not used specifically in the model plant by plant. Instead have each plant been divided according to use of fuel. The values found for these calculations are found from the confidential spreadsheet, the data source Count of Energy producers 2011, described in Appendix A. At first are the plants with postal code in the area of CTR sorted to a new sheet, that is for all plants with postal codes in Frederiksberg, Gentofte, Gladsaxe, Tårnby, and Copenhagen Municipalities. Next, each plant is divided into type of fuels. Under this step, the percentage of each fuel type used at each plant is calculated according to the annual fuel use (Primary Energy Supply, PES), given in TJ.

These percentage of each fuel used at the plants is then used to calculate the capacity of each fuel type, which is shown in Table C.3. The different fuels are then added up for all the plants, giving the electricity and heat capacity in MW. The division according to fuel type is both done to consider the confidential agreements and to ease the modeling for the end year of 2025. Using this method, the use of each fuel type in 2025 is easy to adjust according to the Climate Plan, e.g. with higher share of VE and lower use of fossil fuel types. This is thought to be a valued method, since the capacities for heat and electricity of each fuel are calculated according to the given capacities of each plant. Though, it is thought that it might decrease the flexibility of the system, since smaller plants are no longer in operation as single units, but considered according to fuel.

Fuel	**Fuel Use [TJ]**	**El Capacity [MW]**	**Heat Capacity [MW]**	**El Produced [TJ]**	**Heat Produced [TJ]**	**El Delivered [TJ]**	**Heat Delivered [TJ]**
Coal	12,880	246	327	4862	3,532	4,529	3,532
Fuel oil	370	9	16.3	100.0	195.0	90.0	195.0
Gas oil	559	0.0	775	0.0	544	0.0	544
LPG	25	0.2	0.6	4.5	14.6	4.0	14.6
Natural gas	6,401	222	1,005	1,272	4,926	1,237	4,926
Waste	4,317	28.2	108	763	2,541	676	2,541
Bio gas	145	0.6	9.5	12	82	12	82
Straw	1,575	35	48	282	1,120	224	1,120
Wood chips	22	0.1	0.5	3.9	13	3.4	13
Wood pellets	4,465	98	137	800	3,175	635	3,175
Geothermal	95	0.0	14	0.0	95	0.0	95

Table C.3: Capacities.

C.4 Fuels

The annual use of fuel is found from the confidential spreadsheet, the data source Count of Energy producers 2011, described in Appendix A. The other input of values for heat value and production price is taken from a spreadsheet published by The Danish Energy Agency containing socioeconomic recommendations of which values to use in such calculations. All values are based on numbers from 2009 which has been extrapolated to 2011 and further. (DEA 2011e)

In the model is used the production price an værk (an v), if this is given, otherwise is used the given value an kraftværk (kv). Production prices for Waste, biogas and geothermal are estimated to be very small, according to (Magnusson 2013).

2025 Scenario: The fuel prices in 2025 has been calculated by use of the calculated average inflation rate. Some of the fuels will no longer be used in 2025, due to the outphasing of fossil fuels to reach the CO_2 neutral goals in the climate plan, i.e. fuel oil, fuel gas and LPG are no

Fuel	Annual Consumption [TJ]	Calorific Value [GJ/t]	Production Price [DKK/GJ]	Input Price [DKK/t]
Coal	12,880.5	24.60	20.09	494
Fuel oil	369.6	40.65	67.4	2,740
Gas oil	559.1	42.70	101.40	4,330
LPG	24.8	46.1 MJ/kg	75.00	3,458
Natural gas	6,401.2	39.46 [GJ/1000Nm^3]	67.0	2,643 [DKK/1000Nm^3]
Waste	4,317	10.50	1.00	1.00
Bio gas	145.3	55.5	5.00	0.005
Straw	1,575.4	14.50 (15% moisture)	35.30	512
Wood chips	21.5	10.05 (42.3% moisture)	44.50	447
Wood pellets	4,464.7	17.50 (7% moisture)	70.50	1,224
Geothermal	95.0	Input as boiler	2.00	-

Table C.4: Overview of fuels in Reference Scenario 2011 (DEA 2011e).

longer used. The fuels based on biomass increases, while the use of fossil fuel decreases. In Table C.5 is given the used fuels as well as the calculated prices for 2025.

Fuel	Annual Consumption [TJ]	Production Price [DKK/GJ]
Coal	107	24
Natural gas	214	87
Waste	7,162	1.51
Bio gas	128	7.6
Straw	214	43
Wood chips	5,238	52
Wood pellets	14,004	78
Geothermal	2,031	3.0
Bio oil	214	80

Table C.5: Overview of fuels in Reference Scenario 2025.

The value of bio oil has not been found from a specific source, since it is difficult to predict the price of fuel in 2025. Instead has the price been set so that it is bit more expensive than wood pellets, due to the priority setting in the model. In this way, the boiler is used for peak load operation as intended and not as base or medium load heat coverage, which would be the case if the price on bio oil were lower than wood pellets.

The annual use of fuel in 2025 has been calculated based on the CO_2 neutral scenario presented in (CTR et al. 2011b). The used values for the calculations are taken from the graph shown in Figure C.1.

The values read from the graph is for the Copenhagen area in total. Therefore the percentage of each fuel has been calculated according to total fuel use, and the percentage of each fuel is then used to calculate the use of each fuel in the CTR area. This is the value presented under "Annual Use" in Table C.5

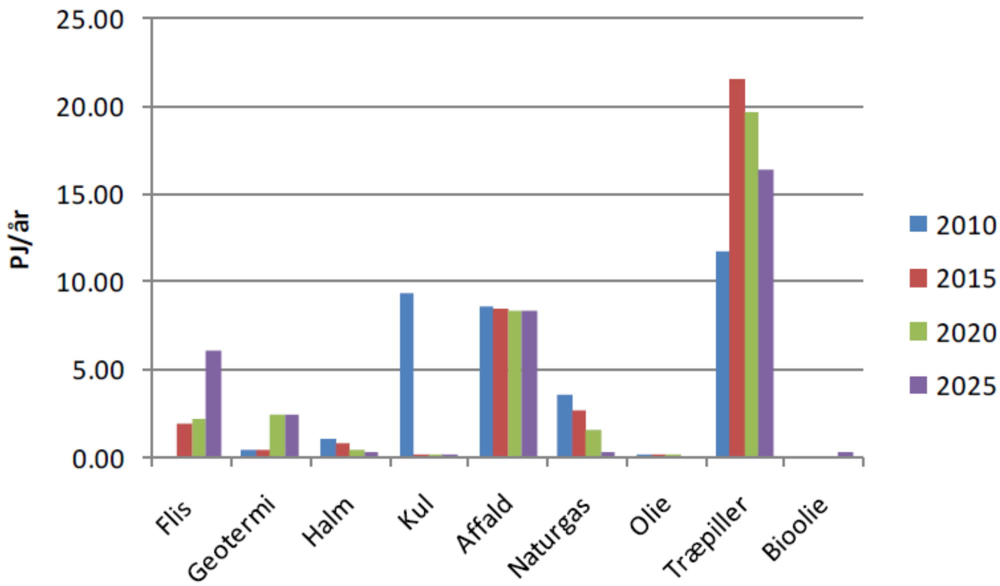

Figure C.1: Use of fuel to the heat production in the Copenhagen area based on the CO_2 neutral scenario presented in (CTR et al. 2011b).

C.4.1 Fuel Capacity

The fuel capacity used as input for each fuel serving as plants is then calculated using the electricity capacity and the electricity efficiency according to the following formula, i.e. the total capacity;

$$\text{Fuel capacity} = \frac{\text{Electricity capacity}}{\eta_{\text{el}}} \tag{C.1}$$

The electricity efficiency of each plant is found from (DEA 2012d). The specific electricity and heat capacity for each plant according to fuel is then calculated based on the deliverance percentage of the annual fuel use. The calculated capacities are used as input for each energy unit based on fuel type, see values in Table C.6.

2025 Scenario: The same calculation have been made for the fuels in the 2025 Scenario. The efficiencies have been updated to the values expected in 2025 from (DEA 2012d).

Fuel	Fuel Capacity [MW]	El deliverance %	El Capacity [MW]	Heat deliverance %	Heat Capacity [MW]
Coal	537	0.4	189	0.3	147
Fuel oil	15.5	0.2	3.8	0.5	8.2
Gas oil	774	0.0	0.0	1.0	752
LPG	0.3	0,2	0,05	0,6	0,2
Natural gas	483	0.2	93	0.8	365
Waste	118	0.2	18.4	0.6	68.8
Bio gas	3.0	0.1	0.24	0.4	1.3
Straw	120	0.1	17	0.7	85
Wood chips	0.5	0.2	0.08	0.6	0.3
Wood pellets	214	0.1	30	0.7	152
Geothermal	14	0.0	0.0	1.0	14

Table C.6: Calculated fuel capacity.

C.5 Thermal Store

In 2011 there is only implemented one TES, which is placed in connection to Amagerværket. TES has a capacity of 24,000 m^3 corresponding to 1 GWh in the EnergyPRO model. (Vattenfall 2013) Inputs about the TES given in the model are shown in Table C.7. In the Reference scenario 2011 are only CHP Wood chips, CHP Wood pellets and CHP straw connected to the store, as this is the case for the existing system.

Volume m^3	Temp. in top ^{o}C	Temp. in bottom ^{o}C	Utilization
24,000	90	50	90% - the net volume effectively used

Table C.7: Input for existing thermal store in reference scenario 2011.

2025 Scenario: For the Reference Scenario in 2025, the capacity of the TES is set to the same value. For the other scenarios, this value will be gradually increased in order to investigate if there are any benefits by having a larger TES capacity in DH grid in CTR area. A capacity of 300,000 m^3 is expected to be available at the dry dock in Nordhavn.

C.6 Economy – Revenues

The revenues from the system have been divided into three groups; Sale of heat to CTR, sale of heat to VEKS and revenues from the electricity market.

Sale of heat to CTR: From the interview with (Magnusson 2013) is the sale price of heat from the transmission in CTR known to be 73.00 DKK/GJ without fixet costs and 101.00 DKK/GJ including fixet costs. The price including fixed costs has been used in the analysis. This value is not taking into consideration in the socio-economic calculations (Annual SEC), see Section 8 on page 71.

Sale of heat to VEKS: See information above. This revenue is taking into account in the Annual SEC.

Electricity Market: To set up the electricity market a new time series has been loaded under external conditions from the EnergyPRO data files. This time series is the spot market prices on electricity for East Denmark hour by hour throughout 2011, see more under Section C.1. The prices are given in DKK/MWh.

2025 Scenario: The heat sale prices in CTR and to VEKS have been extrapolated to 2025, using the calculated inflation rate. For the hourly prices in the spot market in 2025, these values have been calculated based on the expected average price in 2025 given in (DEA 2011e). From the average price in 2011 of 368,13 DKK/MWh an correlation has been found to match the expected average price of 616.00 DKK/MWh, which is used to calculate the price hour by hour in 2025.

C.7 Economy – Operation Expenditures

The operations costs have been divided into three main categories; Fuel costs, Annual operation and maintenance (O&M) and Annual investments.

Fuel Costs: Each type of fuel is typed as received fuel and has a cost according to unit. The production prices is what the plant pays and these are given in Table C.4 under input price. Special cases have been assumed for waste, biogas and geothermal, since these do not have a specific price. To prioritize these fuels, the price have been set very low, which is in concordance with what CTR use in their models (Magnusson 2013).

Annual O&M: The Annual O&M includes the fixed assett investments of CTR. This number is given in the Annual Report from 2011 and is 71.8 M DKK per year. (CTR 2011)

Annual Investments: The Annual Investments are for the reference scenario in 2011 divided into three subcategories; annual investments, heat purchase and electricity purchase. The annual investments are known to be 62.3 M DKK per year, while the heat purchase is a far higher cost of 1,760.5 M DKK per year. This is the heat that CTR buys from the energy producing plants in the area. This values is not considered in the Annual SEC as this is thought to be included in the fuel costs. The electricity purchase has an annual cost of 63.2 MDKK. The electricity is for instance used to drive the pumps in the transmission system. (CTR 2011)

2025 Scenario: The values for fuel costs, Annual O&M, and Annual Investments have been used for 2025. Additional to these costs will be calculated investments in larger TES capacity as well as HPs and EBs. These values are found in (DEA 2012d) and given in the description of technologies in Chapter 3. Further additional electricity purchase to drive the HPs and EBs have been included in the model, by connecting the HP and EB to the electricity market and using the command "Payment included in operation strategy".

C.8 Operation Strategy

In EnergyPRO it is possible to set up, how the different units are operating. Two main parts need to be considered under this: the net heat production cost and the setup for the energy units.

Net Heat Production cost: The operation strategy for the energy units has been set to minimizing the net production costs. This means that the model priorities the cheapest available fuel (or electricity) at all times.

Energy Unit Setup: The only three CHP units in this scenario connected to TES are the units, that in 2011 were driven on these fuels and connected to an actual TES. Only the boiler is allowed on partial load. And all CHP plants are connected to the spot market.

At last most of the units is set to be calculated according to the operation strategy – also high or low priorities are given by the program. High priority are chosen for the CHP waste and geothermal, since these are known to be prioritized as baseload at all times.

2025 Scenario: Here are most CHP plants (except coal, NG and biogas) allowed partial load and have direct access to TES. Also the installed HP and EB have access to TES as well as the electricity market.

C.9 Environment and Emissions

The emissions used is from the socio economic recommendations from the Danish Energy Agency (DEA 2011e).

C.10 Wind Production

The wind production and its impact on the electricity price is assumed to be included by the fluctuation factor, see Section 8.3.1 on page 75.

C.11 Heat Pumps and Electric Boilers

The HPs implemented in the model have all been modelled with a COP of 3. In all scenarios including HP, the same settings have been used by allowing production to TES, demand and connected to the electriciy market in order to include the used electricity in the HP in the economic calculations. In the TES + EB scenario, the installed EB have been modelled as a HP with COP 1.

EnergyPRO Output D

This appendix shows prints from the EnergyPRO reports, that are available to the user. Two different prints on annual basis are here provided for both the 2011 and 2025 Reference.

Annual Income: this print shows the values of the revenues and costs to the modeled system of CTR and states the annual income of this system. If the value is negative, this means that there is no income, but a cost from the system. If the annual income is positive, this means that the system is profitable with the given inputs to the model.

It is important to notice, that in these calculations for the alternative scenarios, additional investment in larger TES, HP and EB capacities as well as O&M costs are not included in the model, but added to the calculation in a spreadsheet afterwards. The annual income found in the model is therefore the parameter in the report named "Annual SEC" and the economic parameter named "Annual SEC inclusive investment" takes the additional investments from the added capacities into account and subtract these values from the Annual SEC.

Energy Conversion: the annual fuel and energy conversions in the model are presented in this print. From this it is possible to see how the distribution of fuel have been in the model andtherefore indicates how the heat and electricity have been produced in the system.

Reference Scenario - 2011 Uden vind

Scenario 1 - CTR - 2011

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Course Registration
Time-limited until June 30. 2013

5001

Operation Income from 01-01-2011 00:00 to 01-01-2012 00:00

(All amounts in DKK)

Revenues								
Sale of Heat								
Heat Sale VEKS	:	308,2 TJ	at	101.000,0	=	31.128.200		
Sale of Heat Total							**31.128.200**	
Spot Market								
Eastern Denmark Spot	:				=	906.412.243		
Spot Market Total							**906.412.243**	
Total Revenues								**937.540.443**
Operating Expenditures								
Fuel Costs								
Waste	:	352.540,3 ton	at	1,0	=	352.540		
Natural Gas	:	160.307,3 1000Nm3	at	2.643,82	=	423.823.778		
Fuel Oil	:	5.935,0 ton	at	2.739,81	=	16.260.711		
Gas Oil	:	42.411,5 ton	at	4.329,78	=	183.632.558		
LPG	:	0,0 ton	at	0,0	=	0		
Straw	:	217.836,4 ton	at	511,85	=	111.499.559		
Coal	:	682.495,3 ton	at	494,214	=	337.298.747		
Wood Chips	:	1.563,6 ton	at	447,225	=	699.273		
Wood Pellets	:	246.022,5 ton	at	1.223,75	=	301.070.079		
Bio Gas	:	1.703.286,5 kg	at	0,005	=	8.516		
Fuel Costs Total							**1.374.645.761**	
Annual O&M								
Fixed O&M	:				=	71.800.000		
Annual O&M Total							**71.800.000**	
Annual investment								
Annual Investments/Fixed Asset	:				=	62.300.000		
Electricity Purchase	:				=	63.224.000		
Annual investment Total							**125.524.000**	
Total Operating Expenditures								**1.571.969.761**
Operation Income								**-634.429.318**

Reference Scenario - 2011 Uden vind
Scenario 1 - CTR - 2011

Energy conversion, annual

Calculated period: from 01-01-2011 00:00 to 01-01-2012 00:00

Heat demands:

Heat Loss	180,1 TJ
Heat Sale CTR	18.411,0 TJ
Heat Sale VEKS	308,2 TJ
Total	18.899,3 TJ
Max heat demand	1.453,8 MW

Heat productions:

CHP Waste	602.068,8 MWh/year	11,5 %
Geothermal	30.240,0 MWh/year	0,6 %
Boiler Gas Oil	487.956,4 MWh/year	9,3 %
CHP Coal	1.278.873,6 MWh/year	24,4 %
CHP Fuel Oil	35.453,5 MWh/year	0,7 %
CHP LPG	0,0 MWh/year	0,0 %
CHP Natural Gas	1.327.508,6 MWh/year	25,3 %
CHP Biogas	11.378,9 MWh/year	0,2 %
CHP Straw	623.616,1 MWh/year	11,9 %
CHP Wood Chips	2.619,0 MWh/year	0,0 %
CHP Wood Pellets	850.090,6 MWh/year	16,2 %
Total	5.249.805,6 MWh/year	100,0 %

Electricity produced by energy units:
Nord Pool Spot:

	All periods [MWh]	Of annual production
CHP Waste	161.018,4	6,6%
CHP Coal	1.639.425,6	66,8%
CHP Fuel Oil	16.429,7	0,7%
CHP Natural Gas	339.341,2	13,8%
CHP Biogas	1.750,6	0,1%
CHP Straw	124.723,2	5,1%
CHP Wood Chips	1.746,0	0,1%
CHP Wood Pellets	170.128,0	6,9%
Total	2.454.562,6	100,0%
Of annual production	100,0%	

Peak electric production:

CHP Waste	18.400,0 kW-elec.
CHP Coal	188.700,0 kW-elec.
CHP Fuel Oil	3.800,0 kW-elec.
CHP Natural Gas	93.200,0 kW-elec.
CHP Biogas	200,0 kW-elec.
CHP Straw	17.000,0 kW-elec.
CHP Wood Chips	200,0 kW-elec.
CHP Wood Pellets	30.400,0 kW-elec.

Hours of operation:
Nord Pool Spot:

	Total [h/Year]	Of annual hours
CHP Waste	8.751,0	99,9%
CHP Coal	8.688,0	99,2%
CHP Fuel Oil	4.350,0	49,7%
CHP Natural Gas	3.641,0	41,6%
CHP Biogas	8.753,0	99,9%

Reference Scenario - 2011 Uden vind

Scenario 1 - CTR - 2011

Energy conversion, annual

CHP Straw	7.365,0	84,1%
CHP Wood Chips	8.730,0	99,7%
CHP Wood Pellets	5.700,0	65,1%
Out of total in period	8.760,0	

Production unit(s) Not connected to electricity market:

	Total [h/Year]	Of annual hours
Geothermal	2.160,0	24,7%
Boiler Gas Oil	3.190,0	36,4%
CHP LPG	0,0	0,0%
Out of total in period	8.760,0	

Turn ons:

CHP Waste	7
Geothermal	0
Boiler Gas Oil	168
CHP Coal	9
CHP Fuel Oil	314
CHP LPG	0
CHP Natural Gas	60
CHP Biogas	6
CHP Straw	86
CHP Wood Chips	10
CHP Wood Pellets	76

Fuels:

By fuel

	Fuel consumption
Waste	352.540,3 ton
Natural Gas	160.307,3 1000Nm3
Fuel Oil	5.935,0 ton
Gas Oil	42.411,5 ton
LPG	0,0 ton
Straw	217.836,4 ton
Coal	682.495,3 ton
Wood Chips	1.563,6 ton
Wood Pellets	246.022,5 ton
Biogas	1.703.286,5 kg

By energy unit

CHP Waste	1.028.242,5 MWh	=352.540,3	ton
Geothermal	0,0 MWh	=0,0	----
Boiler Gas Oil	503.047,8 MWh	=42.411,5	ton
CHP Coal	4.663.718,3 MWh	=682.495,3	ton
CHP Fuel Oil	67.015,8 MWh	=5.935,0	ton
CHP LPG	0,0 MWh	=0,0	ton
CHP Natural Gas	1.757.146,6 MWh	=160.307,3	1000Nm3
CHP Biogas	26.259,0 MWh	=1.703.286,5	kg
CHP Straw	877.396,6 MWh	=217.836,4	ton
CHP Wood Chips	4.365,0 MWh	=1.563,6	ton
CHP Wood Pellets	1.195.942,9 MWh	=246.022,5	ton
Total	10.123.134,5 MWh		

Reference Scenario - 2025 - NEP Uden vind

Scenario 1 - CTR - 2011

Operation Income from 01-01-2025 00:00 to 30-12-2025 00:00

(All amounts in DKK)

Revenues								
Sale of Heat								
Heat Sale VEKS	:	306,5 TJ	at	101.000,0	=	30.957.478		
Sale of Heat Total							**30.957.478**	
Spot Market								
Eastern Denmark Spot	:				=	1.183.162.484		
Spot Market Total							**1.183.162.484**	
Total Revenues								**1.214.119.962**
Operating Expenditures								
Fuel Costs								
Waste	:	537.356,1 ton	at	1,0	=	537.356		
Natural Gas	:	198,9 1000Nm3	at	3.448,8	=	686.040		
Straw	:	25.491,2 ton	at	627,85	=	16.004.669		
Coal	:	4.917,1 ton	at	578,1	=	2.842.560		
Wood Chips	:	804.676,0 ton	at	526,62	=	423.758.479		
Wood Pellets	:	421.459,6 ton	at	1.358,0	=	572.342.173		
Bio Gas	:	118.278,6 m3	at	0,1	=	11.828		
Bio oil	:	118.278,6 m3	at	1.558,0	=	184.278.121		
Fuel Costs Total							**1.200.461.227**	
Annual O&M								
Fixed O&M	:				=	71.800.000		
Annual O&M Total							**71.800.000**	
Annual investment								
Annual Investments/Fixed Asset	:				=	62.300.000		
Electricity Purchase	:				=	63.224.000		
Annual investment Total							**125.524.000**	
Total Operating Expenditures								**1.397.785.227**
Operation Income								**-183.665.265**

Reference Scenario - 2025 - NEP Uden vind

Scenario 1 - CTR - 2011

Energy conversion, annual

Calculated period: from 01-01-2025 00:00 to 30-12-2025 00:00

Heat demands:

Heat Loss	179,1 TJ
Heat Sale CTR	19.156,1 TJ
Heat Sale VEKS	306,5 TJ
Total	19.641,7 TJ
Max heat demand	1.525,7 MW

Heat productions:

CHP Waste	918.244,8 MWh/year	16,8 %
Geothermal	583.704,0 MWh/year	10,7 %
CHP Coal	9.240,0 MWh/year	0,2 %
CHP Natural Gas	1.545,6 MWh/year	0,0 %
CHP Biogas	8.703,0 MWh/year	0,2 %
CHP Straw	72.885,2 MWh/year	1,3 %
CHP Wood Chips	1.311.819,0 MWh/year	24,0 %
CHP Wood Pellets	1.456.767,1 MWh/year	26,7 %
Boiler Bio oil	1.093.124,6 MWh/year	20,0 %
Total	5.456.033,2 MWh/year	100,0 %

Electricity produced by energy units:

Nord Pool Spot:

	All periods [MWh]	Of annual production
CHP Waste	245.678,4	14,7%
CHP Coal	11.760,0	0,7%
CHP Natural Gas	414,0	0,0%
CHP Biogas	1.740,6	0,1%
CHP Straw	14.577,0	0,9%
CHP Wood Chips	747.916,4	44,8%
CHP Wood Pellets	647.343,4	38,8%
Total	1.669.429,8	100,0%
Of annual production	100,0%	

Peak electric production:

CHP Waste	28.200,0 kW-elec.
CHP Coal	1.400,0 kW-elec.
CHP Natural Gas	3.000,0 kW-elec.
CHP Biogas	200,0 kW-elec.
CHP Straw	2.300,0 kW-elec.
CHP Wood Chips	113.400,0 kW-elec.
CHP Wood Pellets	297.100,0 kW-elec.

Hours of operation:

Nord Pool Spot:

	Total [h/Year]	Of annual hours
CHP Waste	8.712,0	100,0%
CHP Coal	8.400,0	96,4%
CHP Natural Gas	138,0	1,6%
CHP Biogas	8.703,0	99,9%
CHP Straw	6.350,0	72,9%
CHP Wood Chips	6.621,0	76,0%
CHP Wood Pellets	2.764,0	31,7%
Out of total in period	8.712,0	

Production unit(s) Not connected to electricity market:

	Total [h/Year]	Of annual hours

Reference Scenario - 2025 - NEP Uden vind
Scenario 1 - CTR - 2011

Energy conversion, annual

Geothermal	8.712,0	100,0%
Boiler Bio oil	2.264,0	26,0%
Out of total in period	8.712,0	

Turn ons:

CHP Waste	0
Geothermal	0
CHP Coal	66
CHP Natural Gas	54
CHP Biogas	2
CHP Straw	323
CHP Wood Chips	160
CHP Wood Pellets	155
Boiler Bio oil	260

Fuels:

By fuel

	Fuel consumption
Waste	537.356,1 ton
Natural Gas	198,9 1000Nm3
Straw	25.491,2 ton
Coal	4.917,1 ton
Wood Chips	804.676,0 ton
Wood Pellets	421.459,6 ton
Biogas	1.354.845,4 kg
Bio Oil	118.278,6 m3

By energy unit

CHP Waste	1.567.288,7 MWh	=537.356,1	ton
Geothermal	0,0 MWh	=0,0	----
CHP Coal	33.600,0 MWh	=4.917,1	ton
CHP Natural Gas	2.180,4 MWh	=198,9	1000Nm3
CHP Biogas	20.887,2 MWh	=1.354.845,4	kg
CHP Straw	102.673,0 MWh	=25.491,2	ton
CHP Wood Chips	2.246.387,3 MWh	=804.676,0	ton
CHP Wood Pellets	2.048.762,1 MWh	=421.459,6	ton
Boiler Bio oil	1.126.932,6 MWh	=118.278,6	m3
Total	7.148.711,3 MWh		