Evaluation of Heat Pumps and Electric Vehicles for the Integration of Wind Power in a Future Energy System in Denmark

Master Thesis

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M.Sc. Sustainable Energy Planning and Management
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Front page:

Horns Rev 2 offshore wind farm located in the North Sea, about 30 km off the westernmost point of Denmark

No of wind turbines: 91, Overall installed capacity: 209 MW, Commission date: November 2009

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Abstract

The point of departure of this report is how wind power can be integrated into the heat and transport sector of the future energy system of Denmark. This problem is analysed by the formulation of a research question, which governs the structure of the report.

The scope of this project is to evaluate heat pumps and electric vehicles as technical means for the integration of wind power, in reference to the future energy system of Denmark. Hence, two energy systems, a Business-as-Usual and an Alternative, referring to 2030 are considered. The Alternative energy system differs with the BAU on the wind penetration, which is significantly higher in the former than in the latter. The effects of introducing heat pumps and electric vehicles into these two energy systems are analysed from technical and socio-economic perspective. The options of adding heat storages to individual heat pumps and converting electric vehicles to vehicle-to-grid cars are also investigated.

Based on the knowledge obtained from all the former analyses, conclusions are drawn concerning the ability of heat pumps and electric vehicles to integrate wind power into the future energy system of Denmark. In this way, a thorough answer in the Research Question of the project is given.

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Preface

The present report is written as the Master's Thesis of Nikolaos Alagialoglou at the Master of Science programme in 'Sustainable Energy Planning and Management', at Aalborg University. This Master's Thesis has been conducted during the period from the 1st of February 2011 to the 16th of June 2011, under the supervision of the Associate Professor Poul Alberg Østergaard and the co-supervision of Thomas Engberg Pedersen from COWI A/S, in the framework of an internship at the Energy Department of COWI A/S in Copenhagen, Denmark.

It is worth mentioning that the Chicago style is used for referencing.

Acknowledgements

I would like to express my special thanks to my supervisor Poul Alberg Østergaard who was always available to guide me, although we had a distant cooperation, and helped me to improve the quality of my work with his valuable comments.

I would also like to give special thanks to Thomas Engberg Pedersen, Chief Project and Market Manager at COWI A/S, for the excellent cooperation that we had in the framework of my internship at COWI A/S. I would like to thank him for sharing my concerns over this project and providing me with useful advice based on his wide knowledge within the energy field.

Moreover, I would like to acknowledge Peter Weitzmann, Consulting Engineer at COWI A/S, for our collaboration during my student job at COWI.

I also wish to express my thanks to Else Bernsen, Chief Project Manager at COWI A/S, for giving me the chance to have an internship at the Energy Department of COWI A/S.

Last but not least, I have my family to thank for their support in every single turn of my life.

Nikolaos Alagialoglou
9/6/2011

List of Abbreviations

BAU	Business-as-Usual
CEEP	Critical Excess Electricity Production
CHP	Combined Heat and Power
CO_2	Carbon dioxide
COP	Coefficient of Performance
DE	Dansk Energi (Danish Energy Association)
DEA	Danish Energy Agency
DH	District Heating
DKK	Danish Krone
EEEP	Exportable Excess Electricity Production
EEP	Excess Electricity Production
EV(s)	Electric Vehicle(s)
HP(s)	Heat Pump(s)
IEA	International Energy Agency
Mt	Million tons
NG	Natural Gas
NH_3	Tri-hydrogen nitride (Ammonia)
O&M	Operation and Maintenance
OECD	Organisation for Economic Co-operation and Development
PP	Power Plant
RES	Renewable Energy Sources
V2G	Vehicle-to-Grid

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1 Introduction

1.1 Problem formulation

Today Denmark is among the leading countries in the field of renewable energy and energy savings. Suggestively, the share of renewable energy in gross final energy consumption for Denmark in 2008 was 18.8%, while the average for EU (27 countries) was 10.3% (Eurostat n.d.), the corresponding share for USA was 5% (IEA n.d.), and 3% for Japan (IEA n.d.). This is the result of an active energy policy over the last four decades, aiming at reducing the dependency of Denmark on imported oil and thus ensuring its security of supply. The starting point is placed right after the oil crisis of the 1970s, when oil prices increased significantly (1973) and Denmark was one of the most dependent countries on oil, among the countries of the OECD (Organisation for Economic Co-operation and Development). It is worth mentioning that imported oil was accounting for 90% of the energy supply. However, renewable energy and energy savings were given high priority with impressive results since a stable economic growth has been achieved from 1970 to 2010. More specifically, a number of energy-policy measures were implemented such as the municipal heat planning, the focus on the cogeneration of heat and electricity, the establishment of a wide natural gas grid, the upgrading of buildings' energy efficiency as well as the use of green taxes. These measures along with the oil and gas production from the North Sea contributed to make Denmark to be self-sufficient in energy from 1997. (Danish Energy Agency n.d.) It should be noted that the degree of self-sufficiency for Denmark in 2009 was 119%, while the average for EU (27 countries) is 54% (Eurostat n.d.)[1].

The expansion of the district heating network along with the development of combined heat and power production led to the improvement of the energy efficiency of the system and contributed to the decentralisation of the power and heating supply (see Figure 1.1). In this way a more extended use of biomass was achieved leading to higher shares of renewable energy in the final energy consumption. (Danish Energy Agency n.d.)

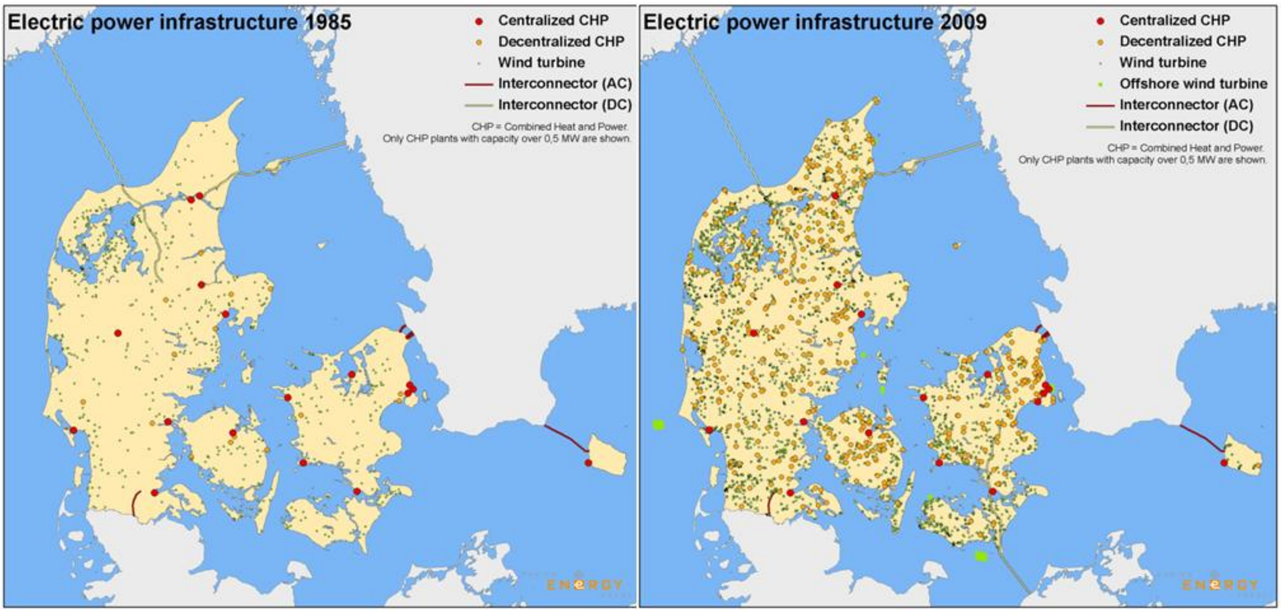

Figure1.1: Overview map of the Danish power infrastructure in 1985 and 2009 (Danish Energy Agency n.d.)

[1] Degree of self-sufficiency is calculated as production of primary energy in relation to observed energy consumption

Furthermore, the expansion of the domestic electricity transmission network and the interconnections with neighbouring countries both facilitated the higher penetration of renewable energy, by enabling the adaptation of high amounts of wind power into the electricity grid. The interconnection of the Nordic electricity grid gave the chance to the interconnected countries to take advantage of different forms of production. (Danish Energy Agency n.d.) As a result, the share of renewable energy amounted to 33%[1] of the Danish electricity supply in 2010, mainly due to the integration of wind-based electricity produced both offshore and onshore and the utilisation of biomass in CHP plants and power plants (Danish Energy Agency 2011).

After all Denmark managed to make a radical change to the energy system towards higher energy efficiency and more renewable energy, by persistently following an active energy policy. This change has satisfied concerns related to the security of supply and also contributed to the growth of exports linked with energy technology and to the job creation.

Although the energy policy of Denmark appears to have been quite effective over the last decades, the path until it becomes entirely independent of fossil fuels is still long. The political willingness to make Denmark 100% independent of fossil fuels by 2050 is clearly expressed by the Government of the country and long-term targets for the energy policy in reference to the future energy system have been set (Klima- og energiministeriet 2011). The vision and the national targets along with the targets that Denmark has adopted in the framework of the EU's Climate and Energy Package (DIRECTIVE 2009/28/EC 2009) are presented in Figure 1.2.

The vision:

- **100% independence of fossil fuels**

Internationally committing targets:

- **30% renewable energy in final energy consumption in 2020**
- **10% renewable energy in transport**
- **20% reduction in 2020 for greenhouse gas emissions not covered by allowances compared with 2005**
- **21% reduction of greenhouse gas emissions on average in the period 2008-2012 compared with 1990 (Kyoto)**

National targets:

- **20% renewable energy in gross energy consumption in 2011**
- **Reduction in gross energy consumption of 4% in 2020 compared with 2006**

Figure 1.2: The government's long-term targets and visions for the energy policy (Danish Energy Agency n.d.)

As stated in (Risø Energy Report 9 2010) a system that will be based on both central and decentralised energy generating units which will be linked with the end-users in an intelligent way is necessary so that ambitious visions such as the one mentioned above can be accomplished. The energy system of the future can not be created by just improving individual components of the existing system. In contrast, it is

[1] According to preliminary energy statistics for 2010, as published in the 'Danish Energy Outlook 2011' by DEA

necessary to perform a holistic optimisation of the entire system in combination with stable energy policies, so that new energy supply technologies can influence the sustainability and the economics of the energy system in a positive way. The optimisation of the system should refer to all the stages from the energy production, the conversion to an energy carrier, the transmission and distribution of the energy to the efficient end-use. Moreover, the future energy system should include a number of supporting technologies in order to deal with the fluctuating nature of renewable energy sources. Only in this way a high share of renewable energy can be integrated and the local resources can be utilised. (Risø Energy Report 9 2010)

At present wind power accounts for 22% of the total electricity supply in Denmark (Danish Energy Agency 2011). A target for 50% wind power penetration is one of the first milestones so that the target of 30% renewable energy in the final energy consumption by 2020, as specified by EU for Denmark, can be achieved (Energinet.dk 2011). According to the Danish Wind Industry Association, the doubling of wind power penetration to the Danish energy system is an ambitious but realistic target that can be reached within the next ten years (Danish Wind Industry Association n.d.). Given the central role of wind power in the future energy system of Denmark, the power system is expected to become the focal point for the change of the energy system (Energinet.dk 2009). The target of 50% wind penetration can not be achieved by simply introducing efficient wind turbines but a number of challenges related to the integration of wind power need to be faced within the next few years (Danish Wind Industry Association n.d.).

In relation to the power grid, the reinforcement and the expansion of it so that power can be transmitted from new wind farms to the points of demand constitutes a challenge. The most important challenge in the integration of wind power refers to the balancing of the power system. A balance between production and consumption needs to be always achieved, given that today the electricity can not be stored efficiently. A 50% of wind penetration will further increase this need. Shortages of electricity production will be much greater than today, in conditions with no wind and the excess of wind-produced electricity will become even greater than today, when the winds are strong (energy 09 2009). Currently, with 22% wind penetration shortage of capacity does not constitute a problem since large power stations have not been displaced by renewable energy yet. Instead excess electricity production is a problem for around 100 hours a year and the problem is expected to be greater by 3-5 times within a few years, unless new means are introduced. (Energinet.dk 2011)

The introduction of new means for the integration of wind power to the power system will make the system more flexible, energy efficient and intelligent so that more renewable energy can be utilised and the challenges are faced. The Danish TSO Energinet.dk is dealing with a number of means for the integration of wind power focusing on the integrated planning of the energy system across the electricity, heat and transport sector. The main intention of Energinet.dk is to ensure both the efficient integration of wind power on market-based principles and high levels of security of supply. Some of the means for dealing with extensive amounts of wind power to the energy system can be seen in Figure 1.3. (Energinet.dk 2009)

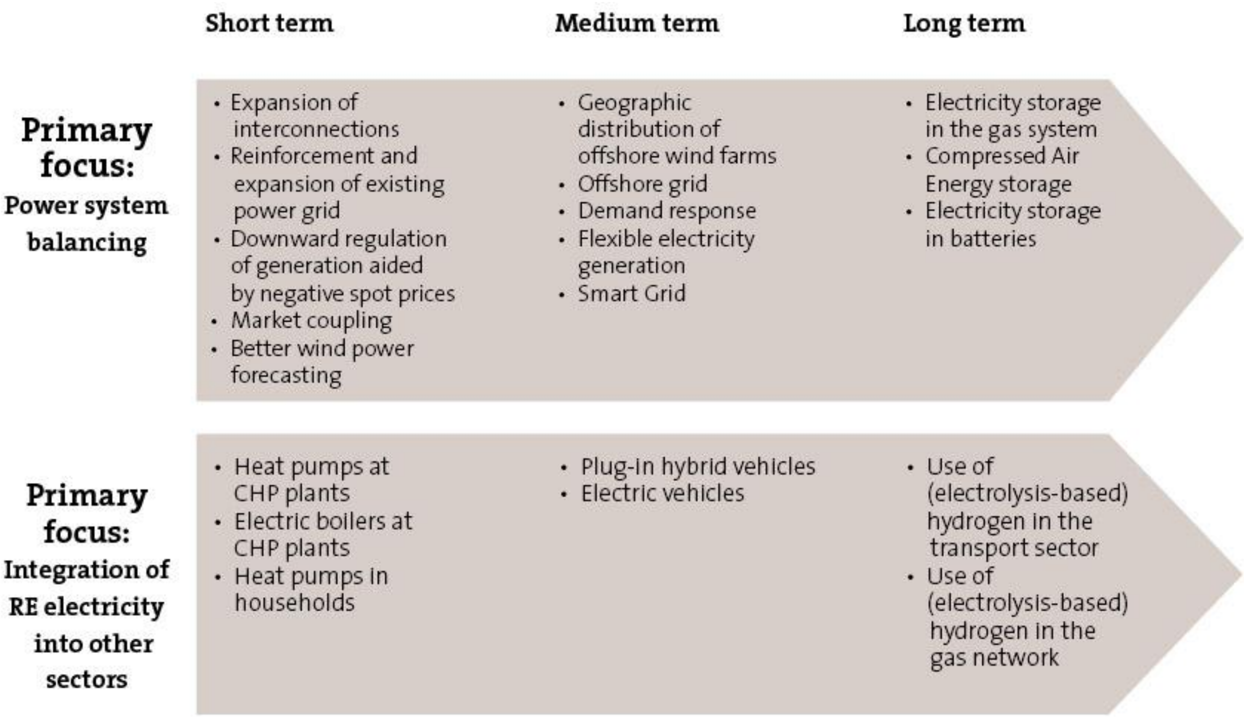

Figure 1.3: Means for balancing the power system and integrating electricity into other sectors (Energinet.dk 2009)

The means related to the integration of renewable energy electricity into other sectors can contribute to the creation of flexible consumption and generation, since new types of electricity consumption can be introduced through e.g. heat pumps and electric vehicles. Furthermore, electricity based-technologies such as heat pumps and electric vehicles are characterised by high efficiency and they are able to expand the use of wind power in sectors other than the electricity. In this way conventional technologies within the heat and transportation sector based on fossil fuels can be displaced and thus the CO_2 emissions of these sectors can decrease. The high efficiency of these technologies can lead to the improvement of the overall efficiency of the energy system. This is really crucial for the accomplishment of targets related to the reduction of greenhouse gas emissions in sectors which are not covered by the emissions' trading system. (Energinet.dk 2009)

Table 1.1: Key figures related to the EU 2020 targets (Energinet.dk 2009)

	RE share of total energy consumption	CO_2 emissions in sectors not subjected to the EU ETS Directive (Million tons/year)	RE share of transport	Improved energy efficiency
Targets for DK according to EU 2020 targets	+13%	-7.5	10%	20%
Heat pumps & electric vehicles 2020	+5%	-3	4%	7%

As it has been concluded in (Energinet.dk 2009), the extended use of heat pumps and electric vehicles can help Denmark to reach the EU committing targets for 2020 at a quite high rate, given that the wind penetration is also increased substantially. Some of the main outputs of the report along with the relevant targets as defined in the EU Climate and Energy Package can be seen in Table 1.1.

All in all, according to the view of Energinet.dk, the integration of wind power into the electricity system and the use of electricity in other sectors will have a central role in the future energy system of Denmark. Optimising the interaction with the heat sector and taking advantage of the chance to build a bridge with the transport sector constitute key solutions for the integration of wind power to the future power system that can be achieved by the implementation of heat pumps and electric vehicles. Heat pumps and electric vehicles can be regulated in a way so that the consumption profile can be adapted to the wind power production. (Energinet.dk 2009)

After referring to a series of radical changes that made Denmark to be self-sufficient in energy, stating the energy vision of the authorities, realising that a new paradigm shift is necessary to happen so that the targets can be reached and mentioning the means for the integration of more wind power to the future energy system with emphasis to the heat and transport sector, the ***Research Question*** of this project naturally arises:

How can wind power be integrated into the heat and transport sector and what are the technical and socio-economic effects of introducing individual heat pumps, large heat pumps as well as electric vehicles, in reference to the future energy system of Denmark?

1.2 Project structure

In this section the structure of the report is presented, as this is composed in order to answer the Research Question of the project. Furthermore, the way that each chapter serves this scope and contributes to the coherence of the report is explained briefly.

The 1st Chapter is the Introduction of the report, where the problem that this project deals with is formulated. This chapter concludes to the Research Question of the project that is governing the structure of the report.

In the 2nd Chapter all the concepts as well as the methods which are put in place, both in the description and the analysis stage of the project, are mentioned. Moreover, the way that all these are used for the scopes of the project is explained.

In the 3rd Chapter the technical means for the integration of wind power that are studied in the framework of this project are presented. The way that heat pumps and electric vehicles can be regulated so that large volumes of wind power can be integrated into the electricity system is described. Furthermore, some of the basic advantages of these technologies compared to similar conventional technologies in the heat and transport sector are mentioned.

The 4th Chapter consists of the description of two energy systems i.e. the Business-As-Usual (BAU) and the Alternative, in reference to 2030, which only differ on the wind penetration. All the technical as well as the economic assumptions that are considered in order to build the BAU energy system along with the differences of the Alternative energy system are mentioned. The chapter closes with a comparative description of the outputs of the two energy systems, after they are optimised. The optimisation of the two energy system is conducted with the EnergyPLAN model. More information relevant to the model and the way it is utilised in this project can be found in Chapter 2 (see Sections 2.2 and 2.3).

In the 5th, 6th and 7th Chapter a techno-economic analysis of individual heat pumps, large heat pumps and electric vehicles is conducted respectively. The technical effects of the introduction of those means of wind integration are analysed in terms of fuel consumption, CO_2 emissions, Critical Excess Electricity Production both in the BAU and the Alternative energy system. Moreover, the socio-economic effects of the above mentioned technologies are identified for both of the two future energy systems. In Chapters 5, 6 and 7 the techno-economic analyses are conducted with the EnergyPLAN model.

The 8th Chapter includes the conclusions of this project which are drawn at two levels. In reference to the first level the focus is on the individual heat sector, the district heating sector and the transport sector separately. The techno-economic effects of the analysed technologies within these three sectors are summarised. Based on that, heat pumps and electric vehicles are evaluated as for their ability to integrate wind power in the future energy system of Denmark. In this way, overall conclusions are drawn in a second level.

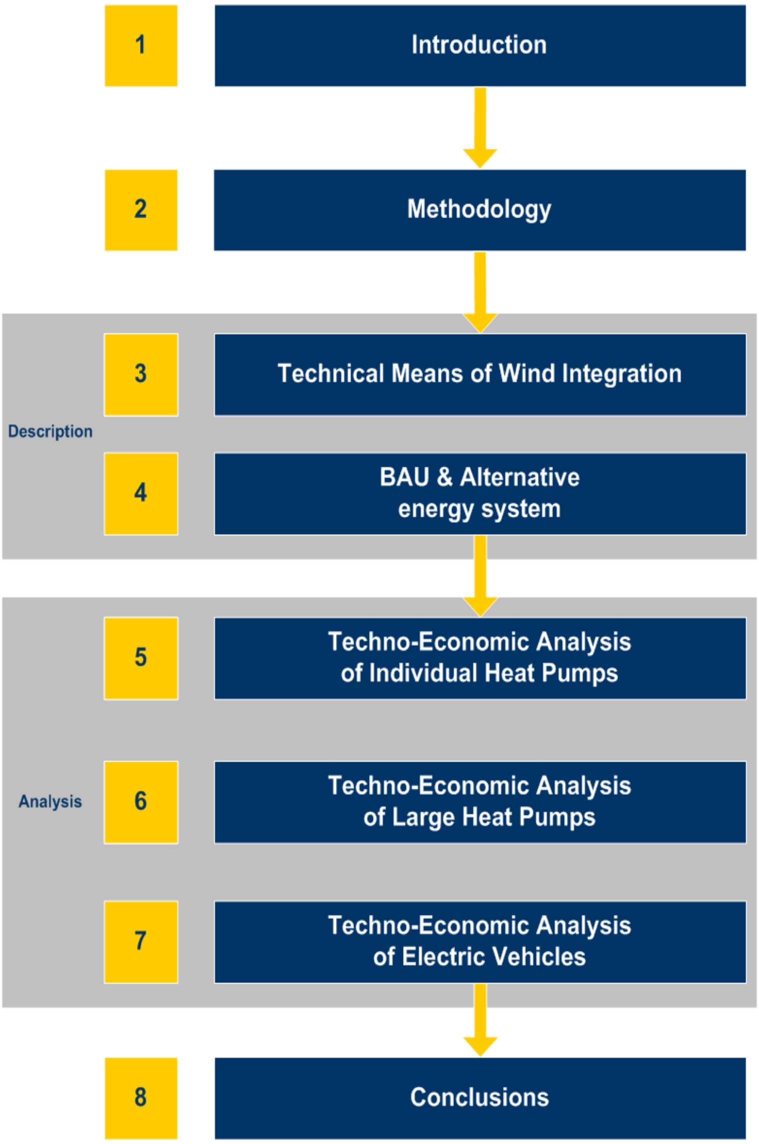

Figure 1.4: Project Structure

1.3 Delimitation

In this section the limitations that apply to this project and guide the analysis that is conducted in the following chapters are set. The reason for setting limitations is to narrow down the scope of the project and make its structure more concrete, given the limited time frame for the completion of this project.

The primary focus of the project is on the integration of wind-produced electricity into the heat and the transport sector. However, there are technical means within these two sectors that are not analysed in the present project such as the use of hydrogen, based on the process of electrolysis, in the transport (fuel cell hydrogen vehicles) and the individual heat sector (hydrogen micro CHP units). A quite profound study in which such technologies are evaluated is the 'Analysis of Power Balancing with Fuel Cells & Hydrogen Production Plants in Denmark' (P. Koustrup 2009). This study has been carried out in the framework of a research project supported by the ForskEL 2007 program from Energinet.dk. Another study in which the utilisation of hydrogen as an energy carrier for wind power in the transportation sector is analysed can be found in (Georges Salgi 2008).

Moreover, the present project analyses the effects of introducing the technical alternatives individually. In this way it is easier to relate the effects on the outputs of the energy system with the actual cause, otherwise it is possible that many synergy effects occur making the analysis of the energy system more complex. However, the way that different technical means of wind integration can be combined is quite important in order to compose a future energy system with an optimal configuration, although this is out of the scope of this project. Such type of analyses have been conducted in other studies, in which complete energy plans for the future energy system of Denmark are provided (IDA 2009, Danish Technological Institute 2007, Danish Energy Association 2009, Danish Ministry of Climate and Energy 2010).

Finally, regarding the geographical delimitation of the project, the future energy system of Denmark is studied and the exchange of electricity with the other Nordic countries in the Nord Pool market is considered as an option. The interconnections with Germany are not taken into account and thus the effect of the electricity trade with Germany is not considered. This is mainly due to the fact that the reference energy system for the needs of this project is based on the baseline projection of Danish Energy Agency (DEA) from April 2009 (Danish Energy Agency 2009) and the interconnection to Germany is not included in the export capacity in the calculations of DEA. Therefore, the same assumptions concerning connections with neighbouring countries are used in the analyses of this project.

2 Methodology

In this Chapter, the overall methodological approach of the problem is explained by differentiating between parts where a qualitative and a quantitative approach is used. Furthermore, some of the basic characteristics of the EnergyPLAN model are presented, since this is the main research tool utilised in the present project. In addition to this, the different research methods used to conduct this study are described.

2.1 Overall methodological approach

In the framework of the present project both a *qualitative* and a *quantitative* approach to the problem, as formulated in the Introduction Chapter, are combined so that a complete answer to the Research Question can be provided. In the following paragraphs it is attempted to spot the points in which the two approaches can be met (see Figure 2.1).

The qualitative approach is mainly expressed in Chapter 3, in which an analysis of the technical means that this project focuses on takes place in a theoretical level. As it has been already defined from the introduction heat pumps and electric vehicles constitute the technical means of wind integration that are going to be analysed at a later stage. Therefore, in the stage of Chapter 3 the intention is to refer to the basic operational principles of those technologies so that it can be ensured that the reader can further follow a qualitative analysis of the way that heat pumps and EVs can contribute to the integration of wind power into a future energy system. This analysis is founded on the concepts described in other projects that have been conducted in reference to the Danish energy system on the long-term. In addition to this, the main advantages of heat pumps and EVs over similar technologies that are operating in the existing energy system within the heat and transport sector are presented. In this way some of the overall effects on the energy system related to the substitution of existing technologies with heat pumps and EVs are identified from a qualitative perspective so that the reader can be prepared to assess the outputs of the quantitative analysis of those technologies that follows.

A mix of qualitative and quantitative approach can be found in Chapter 4. A Business-as-Usual (BAU) energy system is defined which is later utilised to analyse the effects of the selected technical means on a future energy system of Denmark. The BAU energy system reflects the evolution of the future energy system if no new policies are introduced. The BAU energy system of the present project is based on the baseline projection of DEA, who often refers to that as a "frozen policy"-scenario. The technical and economic assumptions that lie behind the BAU energy system are described in the first sections of Chapter 4. After that the Alternative energy system which represents a system with significantly higher wind penetration is defined. The introduction of heat pumps and EVs in a system with such a configuration brings into the foreground possible challenges that the future energy system will have to deal with. Up to this point mainly a qualitative approach is followed. In the last section of Chapter 4 (4.5), mostly a quantitative approach dominates. The outputs of the BAU and the Alternative energy system are presented and compared, after the two systems have been optimised with the EnergyPLAN model (a description of the model follows at Section 2.2). In this way the changes that a significant increase of the wind penetration can cause to the energy system in the long-term are spotted.

The quantitative approach is mainly expressed in Chapters 5, 6 and 7 where techno-economic analyses of individual heat pumps, large heat pumps and EVs are conducted when they are introduced in the BAU and in the Alternative energy system. The technical and economic assumptions related to the implementation of the studied technologies along with the way that are converted to inputs for the EnergyPLAN model are described. Moreover, the effects of heat pumps, EVs and some additional versions of these on the BAU and the Alternative energy system in terms of fuel consumption, CO_2 emissions, Critical Excess Electricity Production (CEEP) and socio-economic costs are analysed and illustrated graphically.

Finally, in Chapter 8, which contains the conclusions of the project, the qualitative and the quantitative approaches are mixed again. The outputs of the analysis part of the project are summarised and illustrated in graphs so that the effects of heat pumps and EVs can be correlated with their ability to integrate large volumes of wind power into the future energy system of Denmark.

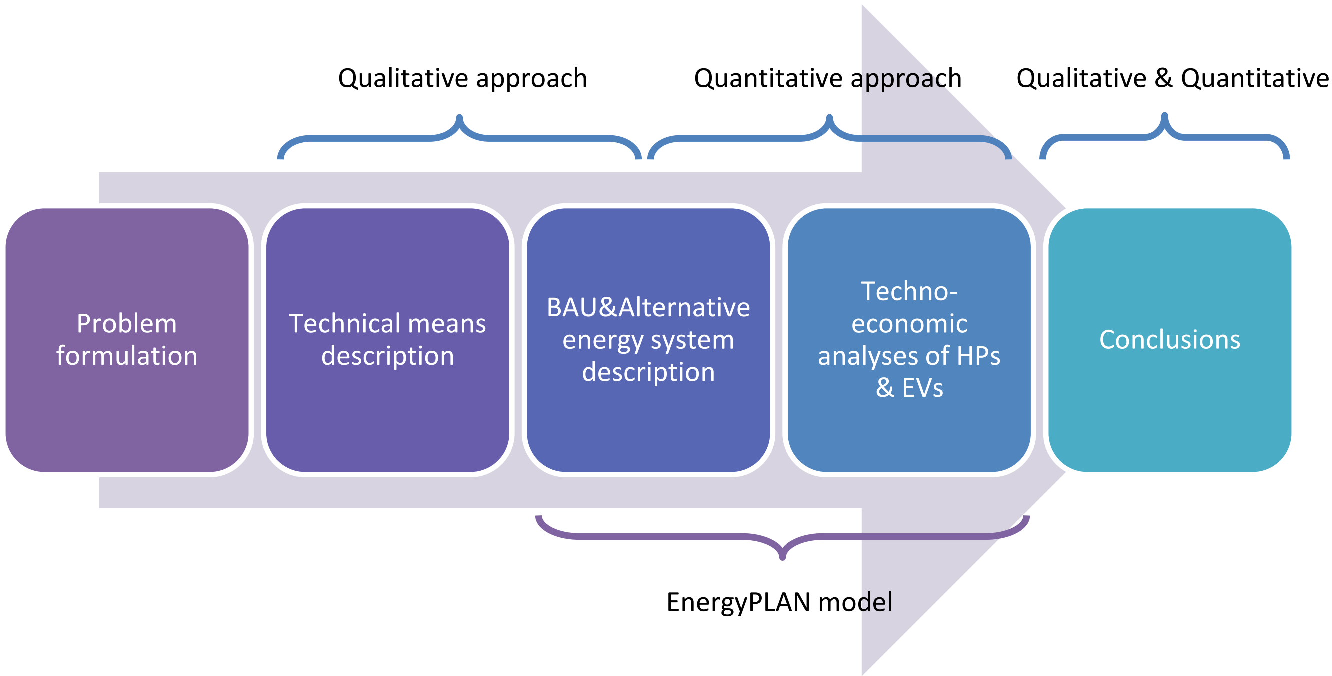

Figure 2.1: Methodology outline

2.2 Research tools: the EnergyPLAN model

The main research tool that is used in the framework of this project is the EnergyPLAN model. It is utilised for the optimisation of the BAU and the Alternative energy system and the techno-economic analyses of the individual heat pumps, the large heat pumps and the electric vehicles (see Figure 2.1).

EnergyPLAN is an Energy Systems Analysis computer model developed by the Sustainable Energy Planning Research Group at Aalborg University. The model was first developed in 1999 and it is expanded continuously. EnergyPLAN is designed in a series of tab sheets and programmed in Delphi Pascal.

A key feature of EnergyPLAN is that analyses are conducted hour by hour for one year period on the basis of either technical optimisation strategies or market-economic strategies. The model mainly aims at assisting the design of national energy planning strategies by analysing the outputs of different national energy systems and investments, either technically or economically. This is done by simulating the entire energy-system including heat, electricity, transport and industrial sectors. Special emphasis is put on the interaction between the production of CHP units and fluctuating renewable energy sources. Finally, it needs to be underlined that EnergyPLAN optimises the operation of a given system instead of optimising investments in the system, as opposed to many other tools. (Lund 2010, Lund 2011, Connolly 2010)

EnergyPLAN is a deterministic input/output model with inputs such as demands, costs, renewable energy sources, units' capacities, different regulation strategies for imports/exports and excess electricity production. Suggestively, the available excess electricity production regulation strategies which can be implemented are the following seven:

1: Reducing RES1 and RES2

2: Reducing CHP production in group 2 (Replacing with boiler)

3: Reducing CHP production in group 3 (Replacing with boiler)

4: Replacing boiler production with electric heating in group 2.

5: Replacing boiler production with electric heating in group 3.

6: Reducing RES3

7: Reducing power plant production in combination with RES1, RES2, RES3 and RES4

It needs to be specified that RES1, RES2, RE3 and RES4 can be one of: wind, offshore wind, photovoltaic, wave power, river hydro, tidal and CSP (Concentrating Solar Power). Moreover, group 2 represents DH systems based on small CHP plants whereas group 3 are DH systems based on large CHP extraction plants. The seven options for regulating excess electricity production are activated in a priority, either individually or in any prioritised sequence.

The outputs of the model can be hourly energy balances, annual productions, fuel balances and total annual costs. The outputs related to the annual socio-economic costs of the system consist of the total variable costs of the studied system, annual investment costs and fixed operation and maintenance costs (O&M). Particularly, the total variable costs include the total annual fuel costs (divided by type of fuel), the variable O&M costs of the units, the total annual electricity exchange costs and the total annual CO_2 emissions costs.

Three different kinds of energy systems analyses can be conducted by EnergyPLAN:

1. A **technical analysis** of national energy system under various technical regulation strategies. The technical analysis requires energy demands, production, efficiencies, capacities, energy sources as well as hourly distribution curves for inputs. The outputs are annual energy balances, fuel consumptions and CO_2 emissions.

2. A **market-economic analysis** of trade and exchanges in international electricity markets. Additional inputs for defining the prices on the market and estimating the response of the prices in import/export changes are required. Economic data for the marginal production cost of the units need also to be inserted in the model.

3. **Feasibility studies** can be conducted with EnergyPLAN by adding data for investment costs, fixed operation and maintenance costs, lifetimes and defining an interest rate. Moreover, the socio-economic impacts of the productions can be defined.

Basically, the model differentiates between the technical regulation and the market-economic regulation, since only one of the two optimisation strategies can be selected. The technical optimisation strategy minimises the import/export of electricity and aims at identifying the least fuel-consuming solution. The market-economic optimisation identifies the lowest-cost solution based on the economic costs of each production unit. (Lund, EnergyPLAN 2010, Lund, EnergyPLAN 2011)

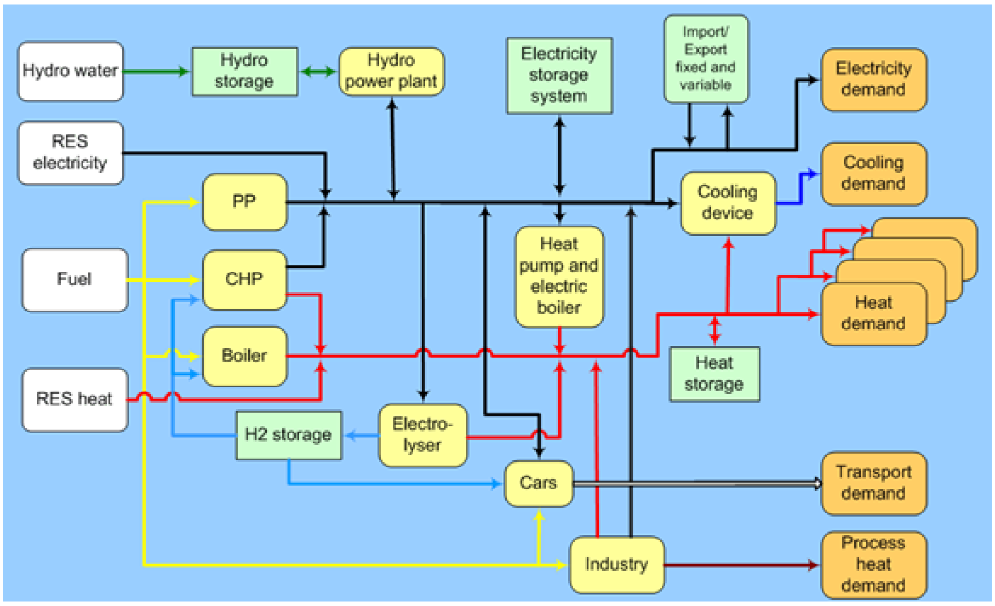

Figure 2.1: Energy system outline in the EnergyPLAN model. Front page view of the model downloadable from: www.energyPLAN.eu

2.3 Research methods

In this section the research methods that are used to serve the scope of this project are presented. A description of the way that document analysis and literature studies, socio-economic analysis and a market-economic optimisation strategy are utilised as research methods is made in the following sub-sections.

2.3.1 Document analysis & Literature studies

Document analysis and literature studies constitute basic tools that are used repeatedly throughout this project in accordance with the needs of each chapter. A wide range of scientific papers and reports as well as data sets were studied and analysed during this project. The sources for this project are mainly official reports coming from Danish authorities within the energy sector such as the Danish Energy Agency and the Ministry of Climate and Energy.

Furthermore, various data sets for the EnergyPLAN model, which have been constructed in the framework of research projects that EnergyPLAN was used for the modelling, are analysed and partly used in this project. The data set ‘Ref2030’, which is the reference scenario in ‘The IDA Climate Plan 2050’ (IDA 2009), formed the basis for the technical inputs of the BAU energy system of this project. This data set along with all the other data sets used in IDA’s Plan are publically available (IDA’s Climate Plan 2050 - Input files to EnergyPLAN n.d.). Other EnergyPLAN data sets that have been used for inspiration can be found in (EnergyPLAN - References n.d.)

2.3.2 Optimisation strategy

As it has been already mentioned in the description of the EnergyPLAN model the user can select between two different optimisation strategies: the Technical and the Market-Economic.

The Technical optimisation strategy is founded on the technical characteristics of the units within the analysed energy system. As long as the energy generating units of the system are able to be regulated so that the difference between the supply and the demand can be covered, the option of importing/exporting electricity is not considered. Electricity is imported from the external market only in case that the electricity production units of the system can not meet the demand. The option of exporting electricity to the external market is used only in situations where excess electricity is produced (e.g. due to high wind speeds). (Connolly 2010)

Therefore, by selecting to apply the technical optimisation strategy the units of the system are regulated so that the modelled energy system can be as less dependent on external electricity systems as possible. This means that electricity is exported only when it is favourable for the operation of the analysed energy system, independently on the price in the external electricity market. According to the view of this project, such an optimisation strategy should be preferred only if EnergyPLAN was used to optimise a system in which the individual technical means of wind integration were combined and introduced altogether into the energy system. In this way all the units of the system would be regulated so that the introduced technologies can be utilised and lead to an optimal system with the lowest possible dependency on other electricity systems.

By selecting to follow the Market-Economic optimisation strategy, the units of the system are regulated in order to match the supply with the demand at the lowest-cost solution. This is done in two steps: initially the marginal production costs of all the energy generating units of the system are calculated and then the lowest-cost combination of the generating units is selected to supply the demand. (Connolly 2010)

When a market-economic optimisation strategy is selected and the analysed energy system is considered to be open for exchanging electricity with an external market, then the system is optimised so that it can take advantage of this market in order to maximise the profit from trading electricity and thus minimise its total annual costs. In this way the regulation of the units is affected by the prices in the external electricity market. This situation also reflects the real situation in the Nordic electricity market where the Nordic countries exchange large amounts of electricity with each others each hour during the year. This interaction between the countries is a big advantage because of the differences in energy structure. For instance, it helps Norway to utilise its hydro power in the most optimal way and it helps Denmark in utilising its wind power in the most optimal way - taking the existing system into consideration.

In the framework of this project, the market-economic optimisation strategy is selected. In this way the techno-economic effects of the technical means of wind integration can be analysed after an optimal introduction of them in terms of costs has taken place. The scope of the project is to evaluate the effects of heat pumps and EVs on the future energy system in terms of fuel consumption, CO_2 emissions, CEEP as well as total annual costs, given that each technology is introduced individually and the units of the system are operating in a basis of minimising their costs. Furthermore, with a market-economic optimisation strategy the value of trading electricity on an external market can be taken into account.

A detailed description of all the calculations that lie behind both the technical optimisation strategy and the market-economic can be found in (Lund, EnergyPLAN 2011).

2.3.3 Socio-economic analysis

According to the scopes of this project, the techno-economic effects of heat pumps and EVs are analysed from a socio-economic perspective. This equals to the fact that taxes are not included when the economic consequences related to the introduction of the technical means of wind integration are estimated with the EnergyPLAN model.

A socio-economic study is designed in order to minimise the costs to the society while providing the required energy (Connolly 2010). This is fully in line with the scope of this project, since it aims at identifying the socio-economic consequences related to the introduction of heat pumps and EVs in reference to the future energy system and evaluate their ability to integrate wind power.

Given that in this project the future energy system is considered to be open to an external electricity market and the market-economic optimisation strategy is selected, the future energy system is optimised so that the costs to the society can be minimised while the option of trading electricity is exploited.

The different types of socio-economic costs that are calculated with EnergyPLAN in this project are mentioned in the description of the model (see Section 2.2). These costs include among others fuel costs, investment costs, variable O&M costs and CO_2 costs. However, other aspects of socio-economic costs can be: the job creation, health costs, the balance of payment etc (Connolly 2010). Such types of costs can not be calculated with the EnergyPLAN model but relevant information can be found in (Lund 1998).

2.3.4 Feasibility studies

Feasibility studies constitute another research method that is used in the present project. The investment costs as well as the fixed operation and maintenance costs related to the technologies introduced in the energy system are included when their socio-economic effects are estimated. In this way it can be decided whether the investment for introducing the specific technical means of wind integration is feasible or not. In case that the total annual socio-economic costs of the future energy system become lower after the inclusion of the investment and fixed O&M costs of a mean, then the introduction of the mean should be considered as feasible. Otherwise, the effects of the mean in the total variable costs of the system are not enough to compensate for the investment and the fixed O&M costs of the mean, and thus the implementation of it is not feasible.

3 Technical Means of Wind Integration

In this chapter the technical means that can contribute to the integration of wind-based electricity into the heat and transport sector will be described on a theoretical level. As it has been already mentioned in the Introduction of this report, the focus of the project is on the evaluation of heat pumps and electric vehicles. Hence, the concept under which the operation of these technologies can be optimised in order to better integrate the electricity coming from wind power into the energy system is explained. Moreover, the main advantages of these technologies over similar technologies within the heat and transport sector are presented in the following sections.

3.1 Heat pumps

A heat pump is a device that can extract heat from a heat source (i.e. ambient air, water, ground, or waste-heat from an industrial process) at a low temperature (input heat) and convert it to a higher temperature (output heat) through a closed process. Therefore, heat pumps can be classified to compressor heat pumps (using electricity) and absorption heat pumps (using heat such as steam, hot water or flue gas). The ratio between the heat output and the drive energy defines the coefficient of performance (COP) of the heat pump (Danish Energy Agency 2010).

The utilisation of heat pumps can be favourable for the overall electricity system since they are able to convert electricity to heat with high efficiencies during hours with excess electricity production. At these hours the electricity generation exceeds the demand due to the high wind production. In addition to this, when such a situation happens the price of electricity is typically low. Hence, it can be beneficial to convert electricity into heat both in the case of households and in the case of district heating systems, where heat pumps can be installed. Consequently, it can be stated that heat pumps are good at facilitating the integration of electricity in the heating sector. This applies to a greater extent in reference to energy systems with higher penetration of intermittent wind power. (Danish Energy Agency 2010, Energinet.dk 2007, Energinet.dk 2009)

Heat pumps can be installed either in DH systems along with CHP units (hereinafter referred as large heat pumps) or in households (hereinafter referred as individual heat pumps). In DH systems the operation of heat pumps can be optimised over some days. In applications with individual heat pumps their operation is normally optimised over some hours, maybe one day, for units having hot water as output and combined with thermal storage. This depends on the heat storage capacity; usually it is proportionally smaller for individual heat pumps compared to large heat pumps. In this way heat pumps can act as a buffer for the energy produced by the wind turbines. Therefore, the flexibility of heat pumps accommodates the integration of wind power in the energy system. (Energinet.dk 2009)

3.1.1 Individual heat pumps

Individual heat pumps constitute an efficient and environmentally friendly alternative to oil and NG boilers used to heat Danish households. Heat pumps can contribute significantly to the achievement of Denmark's climate goals and turn Denmark to be carbon neutral. Temporarily, high electricity prices are the most important barrier to the wider expansion of heat pumps. (Danish Energy Association 2009)

The heat production of a heat pump is around 3-4 times more than the electricity that it is consuming. Hence, heat pumps are much more efficient than individual oil and natural gas boilers, which are considered to have efficiency close to 100% (see Figure 3.1). Moreover, the heat that is extracted from the water, the ground or the air and it is utilised by the heat pump, should be perceived as energy coming from renewable energy sources, as it is also suggested in (DIRECTIVE 2009/28/EC 2009). In this way, the use of heat pumps can help Denmark to meet its targets in reference to the share of renewable energy in the primary energy consumption. By substituting the consumption of oil and NG, heat pumps can also make Denmark less dependent on fuels that need to be imported, enhancing in this way its security of supply. (Danish Energy Association 2009)

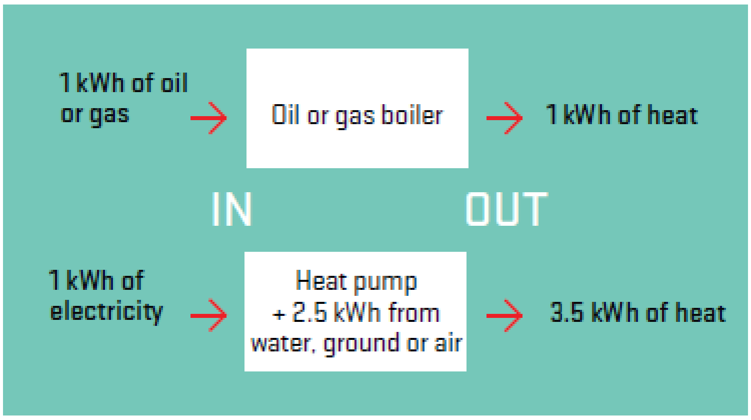

Figure 3.1: Energy balance for heat pumps and oil/gas boilers (Danish Energy Association 2009)

Furthermore, the impact of heat pumps on the environment is quite significant. According to scenarios developed by the Danish Energy Association, currently a heat pump can reduce down to half the CO_2 emissions of a household. In 2025, the CO_2 emissions will be five times less if a heat pump is used instead of a conventional natural gas or oil boiler. As for 2050, the CO_2 emissions related to the heat pump will be zero, since in the scenarios of the Danish Energy Association the electricity production is based to carbon neutral energy sources by 2050. It becomes clear that the higher the penetration of renewable energy in the electricity supply the greater the environmental benefits of shifting to heat pumps.

There are several different types of heat pumps for individual heating. Different heat pumps have different potentials in terms of making the electricity demand more flexible and thus contributing to the better utilisation of the electricity when it is relatively cheap - typically in situations of surplus of wind power.

At present, air-to-air heat pumps, which extract heat from the ambient air and deliver it in the house, are quite widespread on the market. Usually, air-to-air heat pumps are installed in secondary residences or to operate as supplementary to existing heating systems. It is claimed that an air-to-air heat pump typically meets 70% of the heating needs in a dwelling. It should be also noted that air-to-air heat pumps are not able to store energy in the form of hot water. Therefore, a house which is heated by such a heat pump will be relatively quickly cooled if the heat pump is not operating; of course this also depends on the insulation of the house. Moreover, the electricity consumption of an air-to-air heat pump is close related to the air temperature. Finally, as it is stated in (Energinet.dk 2009), there is a limited potential for air-to-air heat pumps to make the electricity consumption more flexible and sensitive to electricity prices, without significant loss of comfort. (Energinet.dk 2009)

Air-to-water heat pumps extract heat from the air and deliver it into a water-circulating system. The same happens with ground-source heat pumps which extract the heat from the ground. In case that these systems are combined with floor heating installations, the hot water is circulating in pipes underneath the concrete floor. In this way the heat is partly stored in the water pipes and in the concrete mass and it is possible to stop the operation of the heat pumps for some time without any compromise to the interior comfort of the residents. Furthermore, the relatively low temperature that is required for the circulating water equals to significantly high COP for the heat pump. An additional advantage of ground-source heat pumps compared to air-to-water is that they are more efficient during the winter since the ground temperature is more constant than the air temperature. Consequently, both of these two types of heat pumps can help to make the electricity consumption more flexible by consuming electricity when the prices are relatively low and interrupting their operation when electricity prices are high. (Energinet.dk 2009)

In the case that water-based heat pumps are combined with additional heat storage units their operation can be optimised typically within a day. In this combination the unit can stop consuming electricity for a few hours when the electricity price is high. Therefore, the heat production can be optimised according to the electricity price over one day. In the winter time that the operation of the heat pump is increased, the ability to be optimised following the price variation within a day is more limited. Particularly, in the cold periods the heat pumps may need to be supplemented with an auxiliary electric heater. (Energinet.dk 2009)

It is also possible to combine the heat pump with a NG, oil or biomass boiler instead of an auxiliary electric heater. This solution is more flexible since there is an option to shift from electricity to an alternative fuel at hours with high electricity prices. In such applications the consumption of electricity can be interrupted for a higher number of hours when the electricity prices are high. This is beneficial for the overall energy system during periods of high electricity demand and low wind generation. However, it constitutes a rather expensive option to have installed two entire systems. (Energinet.dk 2009)

3.1.2 Large heat pumps in DH systems

The dynamic use of heat generating technologies other than CHP units such as large heat pumps, electric heaters and heat boilers in the district heating system constitutes an important measure to increase the flexibility of the energy system. The utilisation of such technologies aims at the efficient use of the produced electricity when the prices are low and/or the electricity production exceeds the demand. Particularly at times with low electricity prices, it is an option to stop the operation of CHP units and produce the required heat on the alternative heating technologies. In this way during periods with high share of electricity coming from wind power, heat pumps can convert the electricity to heat. The produced heat can be either distributed through the existing district heating grid or stored for up to a couple of days in the existing heat storage tanks, in case of a low heat load. In this way, instead of curtailing the electricity production or selling it at low price, electricity can be used to replace natural gas or save the limited biomass resources which are used in CHP plants, for periods with less wind. All in all, it can be stated that large heat pumps installed at both central and local CHP plants can take advantage of the wind power while providing a better flexibility in the power system. (Danish Technological Institute 2007)

3.2 Electric Vehicles

As it is characteristically mentioned in the 'Power to the People' scenario, developed by the Danish Energy Association in reference to 2025 and 2050: 'the cars of the future will run on electricity'. Electric Vehicles (EVs) constitute the most environmentally friendly alternative to conventional petrol and diesel cars. Moreover, it is put forward as the best way to reduce the dependence of Denmark on oil. (Danish Energy Association 2009)

In brief, battery electric vehicles are equipped with batteries where they can store energy electrochemically. As for the basic principle of their operation, EVs need to be plugged in so that they can charge their batteries and they are unplugged to drive. (Willett Kempton 2004)

Electric Vehicles is a technical mean that can contribute significantly to the flexibility of the electricity system. The shift from conventional cars to EVs is going to create a new type of electricity demand since a new type of electricity consuming units is added to the system. The advantage of EVs is that they come with integrated energy storage in their batteries. Therefore, EVs have the ability to consume electricity whenever it is favourable for the operation of the electricity system. This means that EVs can be charged at times when a high share of the electricity production is coming from wind power and when the electricity demand is low, usually at nights. In this way they can charge at times with low electricity prices and contribute to the integration of fluctuating electricity generation based on wind power. Therefore, if the charging of EVs can be controlled so that they respond to price signals, significant socio-economic benefits can be achieved by the optimal operation of the overall energy system. (Energinet.dk 2007, Danish Energy Association 2009, Danish Technological Institute 2007)

In a comparison between electric cars and conventional cars the former appear to be much more energy efficient. It is estimated that electric vehicles can use a given energy input 3-4 times better compared to conventional cars. As it can be seen in Figure 3.2, in the case of an electric vehicle 56% of the energy input is transformed into forward movement while the corresponding percentage for a petrol car is only 16%. (Danish Energy Association 2009)

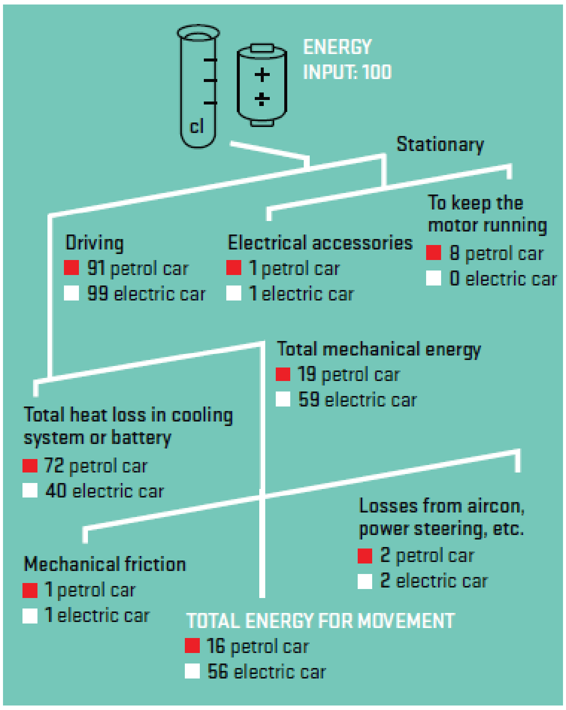

Figure 3.2: Energy balance for EVs and petrol cars (Danish Energy Association 2009)

The higher energy efficiency of EVs comparing to conventional cars leads to lower CO_2 emissions, since EVs use considerably less energy. Of course the emissions of EVs are highly dependent on the way that electricity is produced. For instance, in case that an electric car runs exclusively on electricity produced from wind or other RES then it has no environmental impact at all. According to the calculations of Danish Energy Association (DE), which are valid only for the configuration of the system they have considered in (Danish Energy Association 2009), the CO_2 emissions of an EV are equal to 55 g/km given a share of renewable energy of 30% (see Figure 3.3). The same figure can be reduced down to 25 g/km in reference to the energy system of 2025, in which the RES share is increased. The CO_2 emissions of an EV are supposed to be eliminated, in agreement with the vision of DE for a carbon neutral Danish energy system by 2050. These figures can be put into perspective if it is considered that currently a petrol car emits around 195 g/km CO_2 on average. (Danish Energy Association 2009)

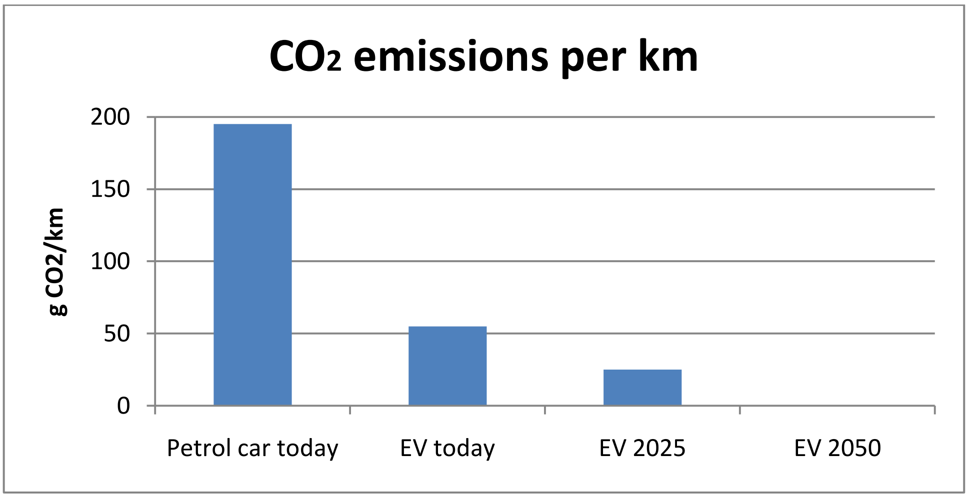

Figure 3.3: CO_2 emissions from EVs and petrol cars as estimated in (Danish Energy Association 2009)

In terms of costs, electric vehicles have lower operation and maintenance costs but higher investment costs compared to conventional diesel and petrol cars. As it is estimated by DE, the daily operational costs of EVs are 50% lower than those of petrol cars. This is mainly due to the fact that the design of EVs is more compact, consisting of fewer mechanical parts. Nevertheless, at present the price of a typical electric car is almost two times higher than the price of a petrol or diesel car. (Danish Energy Association 2009)

To sum up, EVs appear to have several advantages over conventional cars since they are more energy efficient, they have lower CO_2 emissions and lower operation and maintenance costs. On the top of that, electric vehicles have better acceleration and make much less noise than conventional cars, which can be considered as extra assets by private users. What is more important for the common benefit is that the increased use of EVs combined with the high penetration of wind power in the Danish energy system can lead to a synergy effect. This is because a better balancing of the electric system can be achieved along with a reduction of the CO_2 emissions of the transport sector. (Danish Energy Association 2009, Energinet.dk 2007)

Electric Vehicles with Vehicle-to-Grid (V2G) technology

V2G is a technology which is built on the top of electric vehicles and provides the ability to deliver power from the vehicle to the grid, when the vehicles are parked. Moreover, the term V2G is used to describe systems in which the power flow can be partly controlled by real-time signals (see Figure 3.4).

In Figure 3.4 a proposed way of connection between V2G cars and the electric power grid is illustrated. As it can be seen, electricity can flow both ways: from the generating units to the vehicles and from the vehicles back to the grid[1]. The grid operator (here referred as ISO) can send real-time signals either to individual vehicles or to a fleet operator responsible for controlling several vehicles, when they are parked (Willett Kempton 2004).

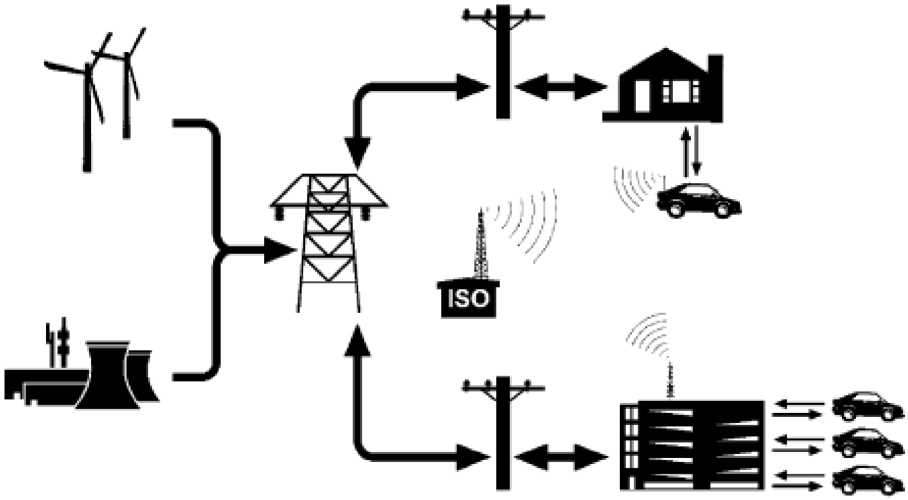

Figure 3.4: Power line and wireless control connections between vehicles and the grid as suggested in (Willett Kempton 2004)

Therefore, the communication of V2G cars with the electric power grid makes V2G cars able to be regulated in various different ways. Similarly with EVs, if V2G cars are regulated according to the needs of the electric system then they can be charged during hours with low electricity demand and high wind-based electricity production, when it is possible to have excess electricity production in the system. In this way the wind power is better utilised and the excess electricity production can be reduced. Moreover, V2G could be discharged when power is needed to the system or when they can replace condensing power in the system, after they have met the transport demand. In this way, converting EVs to V2G systems provides a storage option in an energy system while matching the production with the demand. In case V2G cars are regulated according to the variations of the electricity prices, then they can be charged and store electricity during hours with relatively low electricity price. As for their discharging, they can sell electricity to the grid when prices are high enough in order to make their operation feasible. Consequently, V2G systems constitute an energy storage technology that can increase the flexibility of an energy system and enable it to utilise at maximum intermittent renewable energy sources such as wind power. (W. K. Henrik Lund 2008, Willett Kempton 2004, Lund, EnergyPLAN 2011, P. Koustrup 2009)

As for the advantages of V2G comparing to conventional cars in terms of energy efficiency and CO_2 emissions they are similar with those of EVs. The same applies for the operation and maintenance costs of V2G cars which are lower than petrol and diesel cars. Concerning the investment costs of V2G cars, these are higher compared to EVs. However, minor operational adjustments need in order to add V2G technology in EVs, since they already have grid connections for charging, so the incremental costs are minimal (Willett Kempton 2004).

[1] A proposed round-trip electrical efficiency (grid-battery-grid) is equal to 0.9 (Lund, EnergyPLAN 2011)

4 BAU & Alternative Energy System

In this Chapter the main features of the two different energy systems, the Business as Usual (BAU) and the Alternative, that are utilised in order to perform a techno-economic analysis of the technologies listed in Chapter 3 are described. The scopes that the two systems serve in relation to the needs of this project as well as the main technical and economic assumptions that lie behind each of the two systems are presented in this Chapter. Moreover, in this chapter the outputs of the two systems which are the most indicative of their differences are presented, after both the BAU and the Alternative system have been optimised by implementing a Market-Economic optimisation strategy in the EnergyPLAN model.

4.1 Background information for the BAU energy system

The BAU energy system is based on the baseline projection of Danish Energy Authority (DEA) from April 2009 (Danish Energy Agency 2009). Actually, the reconstruction of this projection, as this was made in IDA's Climate Plan 2050 (IDA 2009), is utilised for the needs of this project. In addition to this, the economic assumptions of the BAU system have been updated with the latest version from April 2010 of the assumptions that should be used in socio-economic analyses of energy according to DEA (Forudsætninger for samfundsøkonomiske analyser på energiområdet 2010).

The baseline projection from DEA consists of a projection of the energy consumption and production for Denmark up to 2030, considering the most recent energy policy agreements as these are shaped in the Danish Energy Agreement from February 2008 (Agreements on Danish Energy Policy 2008) and the Danish Energy Conservation Plan, which was approved by the Danish Parliament in June 2005 (Danish Energy Agency 2010).

DEA's baseline projection simply presents the development of Denmark's energy consumption and production under a number of assumptions about technology development, pricing, economic development etc. that may occur between now and 2030, if it is assumed that no new initiatives or measures will be implemented during this period. As DEA states, there are large uncertainties in such long-term projections and this uncertainty will tend to increase over the projection period. Uncertainties derive from growth, price and technology assumptions that may be proved to evolve significantly differently than predicted (Danish Energy Agency 2009).

In the framework of the IDA Climate Plan 2050 the data from DEA's projection have been converted to data ready to be inserted in the 'Reference 2030' EnergyPLAN model (IDA 2009). Therefore, this set of data has been used in this project for the construction of the BAU energy system (see Annex I). Particularly the technical inputs are used without any modifications. On the contrary, the economic inputs are updated so that they take into account the latest expectations of the International Energy Agency (IEA) for the trend in fuel prices which are summarised in the World Energy Outlook (WEO) from November 2009 (International Energy Agency 2009). As a consequence, the fuel prices used in this study are equivalent to an oil price of 116.59 \$/barrel.

4.2 Technical assumptions and inputs of the BAU energy system

In this section technical inputs of the BAU energy system that need to be further commented, along with any assumptions that they have been based on, are summarised. For more analytical data one should look at Appendix I, where data from the reconstruction of DEA's projection in the framework of IDA Plan can be found.

District heating, CHP units and condensing PP

According to DEA's projection, the total district heating demand is equal to 123.59 PJ (or 34.06 TWh) in 2030. This demand is divided between the three different DH Groups of the model. The first group represents DH systems exclusively based on boilers (Group 1), the second based on small-decentralised CHP plants (Group 2) and the third one based on large-central CHP extraction plants (Group 3). It is considered that there are also boilers installed that can provide the required heat when CHP units are not able to do so or when there is no need for electricity produced by CHP plants. The peak of the district heating demand plus 10% is considered to define the boiler capacity. Furthermore, heat storages with a capacity of 40 GWh and 10 GWh are included so that a larger share of CHP can be achieved in the DH production in Groups 2 and 3 respectively.

According to the projections of DEA, the DH demand appears to be stable during the whole period studied up to 2030 despite the fact that heat savings take place. On the one hand, the specific DH consumption per heated area decreases for the period of the projection while the total on the other hand increases due to conversion from individual heating to DH. Therefore, the capacity of the decentralised CHP plants is assumed to be equal to 1,945 MW during the whole period.

As for the capacity of large CHP plants and condensing Power Plants (PP), the installed capacity is defined as 20% more than the peak electricity demand that is observed throughout a year for the BAU energy system, as suggested in (IDA 2009). Consequently, the total capacity of central CHP plants and condensing PP is set up to 8,552 MW.

Renewable Energy for Electricity Production

Wind power, both onshore and offshore, is considered as the only existent RES for electricity production in the BAU energy system. At the end of 2008 a total of 5101 wind turbines were installed in Denmark with a total capacity of 3,163 MW. Out of this total capacity, 423 MW account for wind turbines located offshore. The total annual production from wind turbines is approximately 7 TWh. (Danish Energy Agency n.d.)

As it is stated in DEA's projection, the total electricity production from wind turbines for 2015 is 10.4 TWh and for 2030 is 11.5 TWh. Furthermore, the installed capacity is 3,080 MW for onshore and 1,240 for offshore with 25% and 35% full load hours respectively. However, the installed wind capacity for 2030 is not referred in the forecast of DEA. Therefore, at this point it is assumed that the number of full load hours is going to increase from 2015 to 2030. This assumption is mainly founded on the installation of the right wind turbine in every actual location. Particularly, in (IDA 2009) it is assumed that the number of full load hours is up to 32% for onshore wind turbines and 45% for offshore in 2030. By considering that the production from onshore wind turbines in 2030 remains the same as in 2015, the installed onshore capacity in the BAU energy system is 2,350 MW. As for the installed offshore capacity that is used in the BAU energy system, this is 1,240 MW which is the same as in 2015 but with an increased production due to the assumption for higher number of full load hours.

Individual heat sector

Five different types of heating technologies are utilised in order to cover the individual heat demand. The necessary heat is supplied by oil, natural gas and biomass boilers as well as by heat pumps and solar thermal units. The fuel input for oil, NG and biomass is defined in the projections of DEA for 2030 (see Appendix I). As for the heat pumps, their electricity consumption is projected by DEA so that by considering a COP of 3.2 the heat demand that corresponds to the heat pumps can be found and inserted in the model. The total annual heat demand of individually heated households is 19.53 TWh.

In the case of heat pumps, it is considered that reserve electric boilers should operate to meet peak heat demands. This can be defined in EnergyPLAN by setting a capacity limit for heat pumps as a share of the maximum heat demand. (Lund, EnergyPLAN 2011) Particularly, a capacity limit equal to 0.5 is assumed and this means that whenever (during a year) the hourly heat demand, which corresponds to individual heat pumps, is over the half of the maximum heat demand that occurs at any hour of the year, the operation of the heat pumps is limited and the remaining heat is covered by electric heating. In this way a peak demand is defined and met by electric boilers instead of heat pumps, when it occurs. The selection of the capacity limit reflects the installed capacity of heat pumps in the energy system. By setting a capacity limit of 0.5, it is like assuming that the capacity of heat pumps is 189 MW, as it is proposed in (IDA 2009) with reference to 2030.

It should be also mentioned that solar thermal installations are operating in conjunction with individual biomass boilers, as it is assumed that half of the heat consumers who are using biomass boilers are utilising heat from solar thermal units as well. Moreover, heat storages with capacity equal to 1 day of average heat demand are considered to operate in combination with individual biomass boilers in households.

Industry

The fuel consumption of the Industrial sector including the consumption of Industrial CHP units is taken into account in the BAU energy system. The specific fuel distribution can be found in Appendix I. The annual electricity production of Industrial CHP units is considered equal to 1.93 TWh while the district heating production is 2.65 TWh. Both are assumed to follow a constant distribution. The industrial CHP units are considered supplying heat to District Heating Group 3, which represents DH systems based on large CHP extraction plants.

The oil consumed in the refineries and for non energy uses as well as the NG consumed in the North Sea and in households for uses other than heating are included for the accurate representation of the BAU energy system in relation with the total annual fuel consumption and the total annual CO_2 emissions.

Transport

The distribution of fuel consumption in the Transport sector simply reflects the projections of DEA for 2030 for this specific part of the Danish energy system (see Appendix I).

Waste

The waste resources which are utilised, according to DEA's forecast for 2030, as fuel in district heating plants as well as in both decentralised and centralised CHP units for the production of DH and electricity which is fed to the grid are also listed in Appendix I.

Grid Stabilisation Restrictions

In EnergyPLAN an hourly calculation is conducted when an energy system is optimised and it is assumed that all the production units of the system are able to change their production from one hour to another. Nevertheless, mainly large steam turbines or extraction plants can not produce in a steady state mode of operation below a certain technical minimum, which is typically equal to 20% of the maximum capacity. (Lund, EnergyPLAN 2011) Therefore, a minimum combined production for large steam turbine plants is specified up to 450 MW (3.9 TWh/year) in the definition of the BAU energy system (IDA 2009). By setting such a limitation it is like having a system with steam turbines like the Danish in which 4 to 5 large CHP plants are always operating above the technical minimum production (W. K. Henrik Lund 2008). In this way, the regulation as well as the stability of the electricity network is secured[1].

Critical Excess Electricity Production (CEEP) regulation

Excess Electricity Production (EEP) represents an imbalance between the consumption and the production. In such cases Denmark is forced to export electricity to external electricity markets given that the transmission capacity is sufficient and the neighbouring countries can absorb this electricity. The excess electricity production that can not be exported due to limitations in the transmission capacity is labelled as Critical Excess Electricity Production (CEEP).

One of the main scopes of this project is to investigate how different technologies can contribute to the reduction of the Critical Excess Electricity Production that may occur at specific hours in the future energy system of Denmark. Therefore, there is no need for regulating the CEEP that may arises in the system so that the full extent of CEEP, if such occurs, can be observed. Consequently, none CEEP regulation strategy of those available in EnergyPLAN model (see Section 2.2) is utilised while the BAU energy system is formulated.

Transmission line capacity

As for the transmission capacity, a maximum import/export capacity of 2,500 MW is considered in the BAU energy system. The existing transmission capacity from Jutland to Norway is considered as 1,000 MW and 700 MW from Norway to Jutland. As for the interconnections between Zealand and Sweden, 1,300 MW and 1,700 MW have been taken into account for exports and imports respectively. As it is also stated in IDA's Climate Plan the actual transfer capacity is higher but some limitations exist in the surrounding network. (IDA 2009) It is also assumed that there is a compound electricity transmission grid in Denmark due to the establishment of the Great Belt Power Link, which was commissioned in 2010. This means that there are no local bottlenecks to be considered throughout Denmark. Similarly with the considerations in the baseline

[1]The stabilisation of the grid is ensured by the requirement about the minimum capacity of large CHP units. Even if a minimum grid stabilisation production share is set the outputs of the BAU system do not differ a lot.

projection of DEA, concerning the transmission lines with neighbouring countries, the interconnection with Germany has not been taken into account in the export capacity.

4.3 Economic assumptions and inputs of the BAU energy system

As it has already been mentioned, in this study the economic frame of DEA's baseline projection, which consists of assumptions concerning fuel prices, transport and handling costs of fuels, electricity prices in the external electricity market and CO_2 prices, has been updated with the latest socio-economic assumptions for 2030 as proposed by DEA in (Forudsætninger for samfundsøkonomiske analyser på energiområdet 2010) from April 2010. It should also be noted that all the economic inputs have been converted to 2011 price levels according to the price index in (Forudsætninger for samfundsøkonomiske analyser på energiområdet 2010). In this way, the economic inputs are comparable between them and all the economic quantities are expressed in today prices something which is more coherent for the reader.

Moreover, investment costs, lifetimes as well as variable and fixed costs for various technologies involved in the analyses of this project are based on the (Technology Data for Electricity and Heat Generating Plants 2005) and the updated version of this catalogue as issued by DEA in June 2010 (Technology Data for Energy Plants 2010)**.**

Fuel prices

The assumptions for fuel prices in 2030 are in line with the fuel price trends recommended by the International Energy Agency (IEA), which expects an oil price equal to 116.59 $/barrel for 2030 (see Table 4.1).

Table 4.1: Fuel prices assumptions for 2030 in DKK/GJ (Danish Energy Agency 2010)

Crude oil	Coal	Natural gas	Fuel oil	Diesel fuel Diesel	Petrol JP	Straw	Wood pellets
113.8	25.14	76.71	79.66	142.25	151.35	37.56	81.52

The transmission, distribution, handling and transport costs of fuels based on the most updated fuel price assumptions from the Danish Energy Authority are found in Table 4.2.

Table 4.2: Fuel handling costs in DKK/GJ (Danish Energy Agency 2010)

	Coal	Natural Gas	Fuel oil	Diesel fuel Diesel	Petrol JP	Biomass[1]
For Power Plants	0.53	3.38	1.8			12.92
For decentralised CHP, DH & Industry	-	8.86	14.85			8.65
For Individual households	-	22.29		22.59		47.6
For road transport	-			24.5	33.09	
For aviation	-				5.41	

All prices listed in Tables 4.1 and 4.2 are in 2008 prices. However, the prices have been converted to 2011 prices before they are inserted in EnergyPLAN.

[1] Biomass is considered to be straw for plants and wood pellets for individual households

Variable O&M Costs

The variable O&M costs used in this project are retrieved from (IDA 2009, Technology Data for Electricity and Heat Generating Plants 2005, Technology Data for Energy Plants 2010). The costs have been converted to 2011 prices by using the factor that is recommended in (Forudsætninger for samfundsøkonomiske analyser på energiområdet 2010).

Table 4.3: Variable operation and maintenance costs in 2011 prices (DKK/MWh)

Variable O&M costs	DKK/MWh
Boilers in DH systems	1
CHP	23
Condensing Power Plants	17
Individual Boilers	11

Electricity and CO_2 price

The most updated assumptions from DEA concerning the electricity price level on the Nord Pool market as well as the CO_2 quota price have been used in the electricity market exchange analyses that take place in this project. The electricity price level of the Nord Pool market for 2030 is expected to be 454 DKK/MWh in 2008 prices (or 473 DKK/MWh in 2011 prices) along with a CO_2 price for 2030 equal to 290 DKK/ton in 2008 prices (or 302 DKK/MWh in 2011 prices). (Danish Energy Agency 2010)

It should be stated that a CO_2 quota price is used in this project so that the estimated CO_2 costs coming from the total CO_2 emissions of the studied energy system can be calculated. In this way whenever a reduction in the total CO_2 emissions of the energy system is achieved it is translated as a reduction in the total CO_2 costs of the system.

External Electricity Market Definition

An external electricity market should be defined so that economic calculations based on the exchange of electricity on the Nord Pool market can be conducted. A price variation is inserted in the model and it is used as a starting point for the calculation of the hourly electricity prices. Particularly, the profile of electricity prices in the Nord Pool market from 2008 with an average electricity price of 420.73 DKK/MWh is used in this project. This standard profile can be adjusted by a series of inputs such as an addition factor and a multiplication factor so that the resulting average price of the external electricity market is in compliance with the assumptions of DEA for an electricity price of 454 DKK/MWh (2008 price levels) in the Nord Pool market in 2030. Imports and exports of electricity can also modify the standard price variation; the way that this is modelled is presented later.

In other studies conducted with the EnergyPLAN model an addition factor is used to express the effect of the CO_2 price in the electricity prices (IDA 2009). Furthermore, a multiplication factor is normally used to represent an increase in fuel prices, which usually increases the electricity prices proportionally every hour as it is claimed in (Connolly, A User's Guide to EnergyPLAN 2010).

In the framework of this project only a multiplication factor is used to modify the initial price distribution in order to go from the average price of 2008 to the projected average price of 2030. By using an addition factor it is like assuming that there is always a constant part in the electricity price due to the CO_2 price. This constant part is based on a certain emission factor for all the hours of the year so this presupposes that the same marginal production unit determines the electricity price at all hours of the year, which is not the case.

Moreover, as it can be observed there are some hours in which the starting electricity price is equal to zero, probably because at these hours the price in the market is determined by the wind power units. The use of an addition factor is problematic during these hours because it will lead to non-zero prices during all the hours of the year, which is something that cannot be predicted with certainty.

In contrary, by using just a multiplication factor it is assumed that the price variation in 2030 is the same as this of the starting price distribution from 2008 and as a consequence the number of hours in which the electricity price is zero will be the same between 2008 and 2030. One should be aware that it is possible that the number of hours when the electricity price is zero will increase in 2030 comparing to 2008, due to higher wind penetration, as it is also possible that the number will decrease, due to the contribution of other means such as heat pumps, EVs etc. As it has already been mentioned this is hard to predict without knowing the exact configuration of the system.

It should be made clear that a number of uncertainties can affect the distribution of the electricity price in the external market and the actual profile cannot be predicted accurately. Nevertheless, it is attempted to create a profile which is as representative of the external electricity market as it is possible. The electricity price curve either the initial one or the added or the multiplied should not be perceived as anything but a statistical variation which is further impacted by import/export. In other words, it is a statistical cloud of prices that is used to estimate the economic performance of a system in the time horizon of a year. It should not be considered as a list of electricity prices through which the electricity price on a given hour can be identified and provide a certain figure for the economy at that hour.

Price elasticity

As it was mentioned before, the standard price variation of the electricity price is further modified by a factor that represents the reaction of market to imports/exports of electricity called price elasticity DKK/MWh/MW along with an adjustment price of non-predictable export/import (DKK/MWh) (E. M. Henrik Lund 2004). The price elasticity represents the way that the market price can change due to increase in the production or the consumption (Brian Vad Mathiesen 2009). In this project it is assumed a price elasticity of 0.02 DKK/MWh/MW and a basic price level for price elasticity of 150 DKK/MWh. These specific assumptions are founded on a series of considerations which are analytically described in (E. M. Henrik Lund 2004).

Based on the abovementioned inputs, EnergyPLAN is able to estimate the market price (p_x) at any given hour based on the standard price variation and the actual amount of imports/exports of Denmark via the following formula:

$$p_X = p_i + (p_i / p_o)* Fac_{depend} * d_{Net-Import}$$

where p_i is the system market price in DKK/MWh, Fac_{depend} is the price elasticity in DKK/MWh/MW, p_o is the basic price level for price elasticity in DKK/MWh and $d_{Net\text{-}Import}$ is the imports/exports from/to the Nord Pool market in MW (Lund, EnergyPLAN 2011).

When electricity is imported from the Nord Pool market it leads to an increase in the market electricity price while a decrease in the market price is stimulated by the export of electricity. Therefore, export is considered as negative and import as positive in the above formula. (EnergyPLAN 2011)

Interest rate

A real interest rate (interest rate minus inflation) of 6% is used in this project whenever an investment is introduced both in the BAU and the Alternative energy system. Such an interest rate is in agreement with the proposal of the Danish Energy Agency when conducting socio-economic calculations within the energy field. According to DEA such a recommendation for a real interest rate is reasonable since it reflects the loss of alternative returns that the invested resources could have brought if invested in other projects. (Danish Energy Agency 2007)

Although 6% is the official rate that should be used, there are considerations about using a lower interest rate. A reduction of the interest rate that is used in socio-economic impact assessments of energy projects has been proposed in the Danish Parliament. According to this proposal an interest rate around 3-3.5% should be used, since this corresponds to the suggestions of the European Commission and it is also in agreement with the level of the interest rate in neighbouring countries of Denmark. (Folketinget 2011)

As it is discussed in IDA's Climate Plan 2050, an interest rate up to 6% would lead to wide range socio-economic losses given that the real interest rate in the market is about 2% per anno. Therefore, by setting a rate of 6% it is possible that socio-economic investments with a rate of return between 2% and 6% per anno will be considered as non-feasible. Moreover, the argumentation of DEA for using such a high interest rate is opposed by stating that there is no documentation for alternative projects that can have a real interest return of 6% per anno. (IDA 2009)

However, in the analyses conducted in this project the interest rate is considered to be equal to 6% since this is still the official level that is recommended for Denmark by the authorities.

4.4 Description of the Alternative energy system

The scope of the Alternative energy system is to represent a system with a different configuration compared to the BAU energy system. A system with higher share of renewable energy so that any possible challenges that could occur from that in a future energy system in Denmark can be identified. Such an Alterative energy system would help to analyse the effects of the different technical means of wind integration, which have been presented in Chapter 3, on the outputs of a system and the way they can contribute to the regulation of the problems that may otherwise arise from the high penetration of fluctuating renewable energy sources.

In the Alternative energy system all the inputs -technical and economic- remain the same as these have been described in the previous sections of this Chapter for the BAU energy system, apart from the wind capacity. This has been highly increased so that an Alternative energy system that serves the scopes of this project is created. The objective is to have an energy system with 70% - 80% wind penetration. This is partly achieved by increasing the current onshore wind capacity by 50% in the Alternative system, in reference to 2030. Such an increase has been also proposed before by the Danish Society of Engineers in (IDA 2009). Therefore, the onshore wind capacity will be set up to 4,500 MW corresponding to annual electricity production of 12.6 TWh, considering the same full load hours as in BAU energy system (32%).

The assumption concerning the offshore wind capacity for the Alternative energy system for 2030 has been based on the Offshore Wind Turbine Action Plan which was first published by Danish Energy Agency in 1997 and was updated in 2008 (Danish Energy Agency 2008). In the framework of this action plan potential sites for the installation of offshore wind turbines have been spotted with an overall capacity of 4,600 MW. This is the offshore wind capacity that has been considered for the Alternative energy system which leads to a total annual electricity production of approximately 18.4 TWh based on full load hours of 45%, as it was used in the BAU energy system.

All in all, the **wind penetration** in the **Alternative** energy system is up to **74.3%**, given that the total electricity produced by wind turbines (onshore and offshore) is 31.02 TWh/year and the total electricity demand is 41.73 TWh/year. It should be stated that the **wind penetration** in the **BAU** energy system is **27.6%** (11.51 TWh out of 41.73 TWh).

4.5 Outputs of BAU and Alternative energy system

In this section some of the most indicative technical and economic outputs of both the BAU and the Alternative energy system are presented in parallel. In this way the differences of the two systems in terms of fuel consumption, CO_2 emissions, critical excess electricity production, and total annual costs can come into the foreground.

Generally speaking, when a Market-Economic optimisation strategy is followed, the model identifies the least cost solution of the system considering an electricity market in which all the plants are regulated in order to optimise their economic profit. Hence, the resulting market price that is dependent on the demand and supply of electricity is identified at each hour. Furthermore, an exact balance production of all the various units of the system is identified. The balance production from a certain unit is the production in which the resulting market price becomes equal to the marginal production cost of the unit. In this way the electricity production units can be sorted out starting from the option with the lowest marginal costs and taking into account that each change supply affects the market price. (Lund, EnergyPLAN 2011)

Having in mind the basic principles of the Market-Economic optimisation strategy in EnergyPLAN, an attempt to analyse the different regulation of the units in the BAU and the Alternative energy system is made. The one and only difference in the inputs of the two energy systems is the wind capacity, which is approximately 2.5 times greater in the Alternative energy system comparing to the BAU. This major difference is reflected in the electricity production coming from wind, which is significantly higher in the Alternative energy system, while the electricity demand is exactly the same for the two energy systems. As a result the operation of all the other energy generating units of the Alternative system is regulated so that the increased wind power can be integrated. This means that the model attempts to take advantage of the relatively high wind production and minimise the costs of the system.

In both the BAU and the Alternative energy system, wind power (onshore and offshore) is utilised at maximum and the electricity production of wind turbines is given priority, since it is considered to have zero marginal production costs. The same applies for Waste and Industrial CHP units which are not subjected to any regulation, so their electricity production remains the same in the BAU and the Alternative system (see Figure 4.1). In general the electricity that is produced from renewable energy sources is equal to 26.1 TWh/year for the BAU energy system and 42.8 TWh/year for the Alternative energy system. The share of CHP and power plants is determined by the share of biomass compared to the total fuel consumption of these units (Lund, EnergyPLAN 2011).

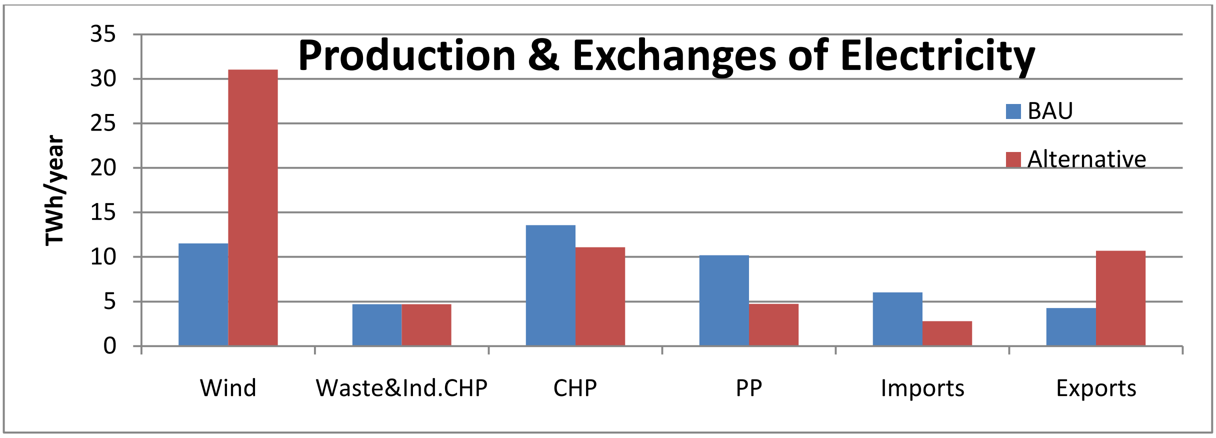

Figure 4.1: Production and exchanges of electricity in the BAU and the Alternative energy system[1]

As for the regulation of the CHP units, it should be taken into account that a high share of the electricity demand that was covered by these units in the BAU system, it is covered by the wind production in the Alternative. Hence, in the Alternative system a share of the heat production can be moved from CHP units to boilers which constitute a lower cost solution (see Figure 4.2). This is due to the higher thermal efficiency of boilers comparing to CHP units. In other words, the same amount of heat can be produced by consuming less natural gas. As a result the electricity production of CHP units appears to be lower in the Alternative system (see Figure 4.1). All these changes have an effect on the fuel consumption, the CO_2 emissions and the costs of the Alternative system.

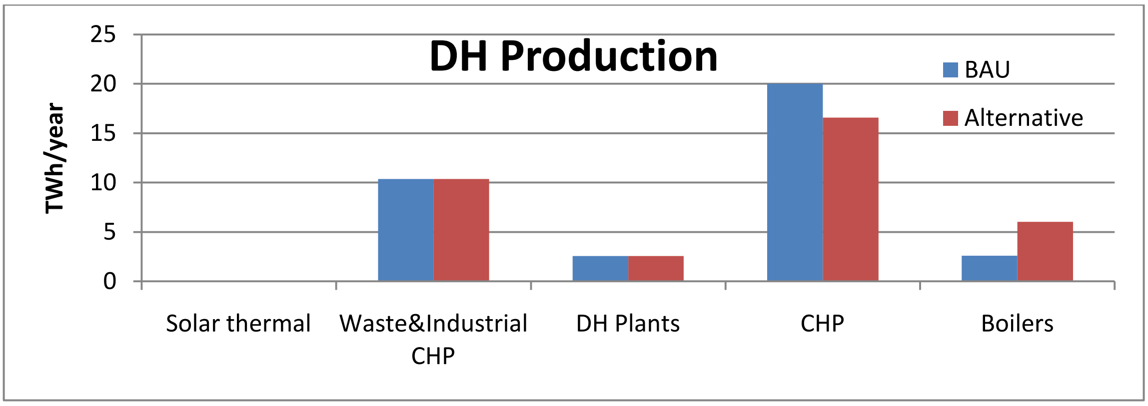

Figure 4.2: District heating production in the BAU and the Alternative energy system

[1] In the case of the Alternative energy system only the exportable electricity production is illustrated and not the critical excess electricity production.

A reduction in the electricity production of Power Plants is also stimulated by the high wind production in the Alternative system. The Power Plants produce only when the electricity price is higher than their marginal production costs and this does not happen so often in the Alternative system as it happens in the BAU, due to the increased wind production. In addition to this, the imports of electricity are reduced while the exports are significantly increased in the Alternative system. The potential for exports is quite high in the Alternative energy system since a share of the electricity that is co-produced in CHP plants can be exported.

The high potential for exporting electricity stimulated by the high wind production leads to the production of critical excess electricity of 1.88 TWh per year in the Alternative energy system. Particularly, it can be observed that critical excess electricity is produced during 1,459 hours annually. In the case of the BAU energy system there is no CEEP at any hour of the year.

It is also interesting to have a look at the graphs of Figure 4.3 in which the existence of CEEP in the Alternative energy system can be also depicted graphically. The graphs in Figure 4.3 should not be used to extract any accurate data about specific electricity demands and productions within the two systems. Nevertheless, they can be used in order to evaluate the difference of the two energy systems in terms of CEEP qualitatively.

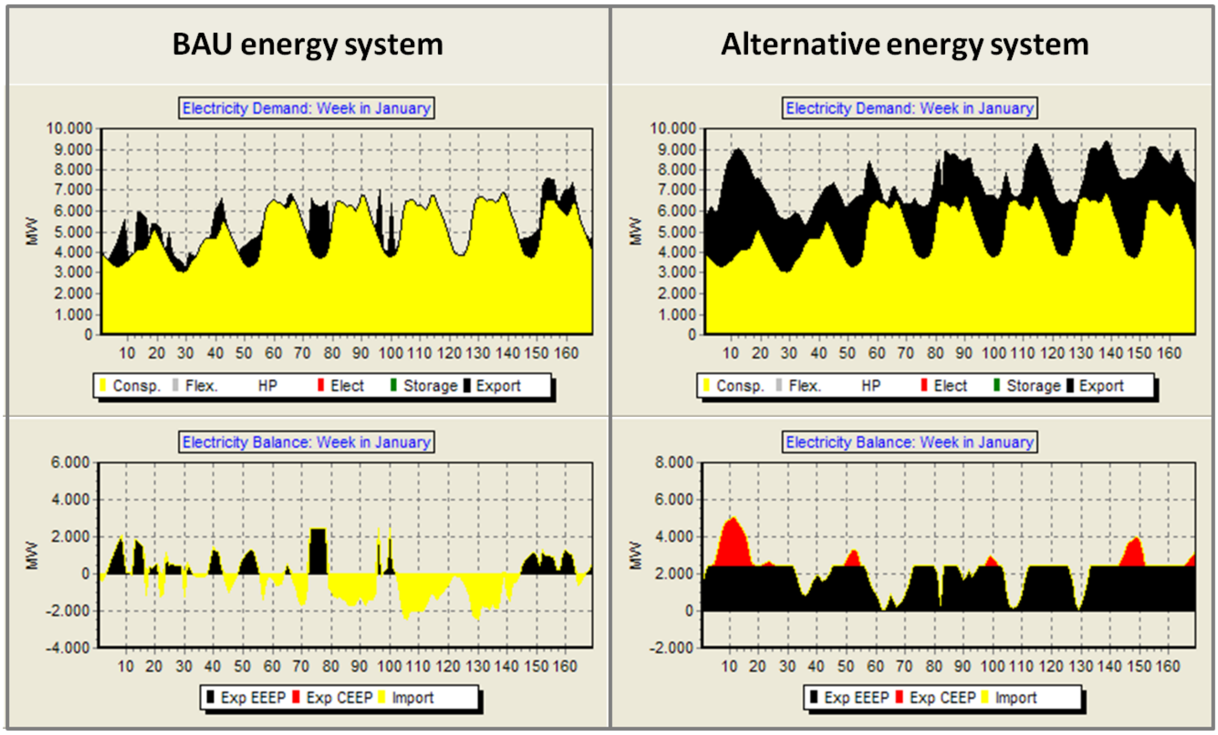

Figure 4.3: Electricity demand and balance during a week in January for both the BAU and the Alternative energy system

In the top left graph of Figure 4.3, the electricity demand of the BAU energy system during the first week of January is illustrated with the yellow colour while the electricity that is produced from the units of the system and it could be potentially exported is presented with black colour. In the bottom left graph the electricity balance during the same week for the BAU system is presented. In this graph the exportable excess electricity production appears in black. Therefore, it can be concluded that in the case of the BAU energy system, during this specific week, all the potential export can be actually exported since the available transmission line capacity is enough. By looking at the graphs to the right, the situation seems to be quite different for the Alternative energy system. The electricity that could be potentially exported is much higher due to the fluctuating electricity production coming from wind power. In the bottom right graph, it can be seen that there is critical excess electricity production (CEEP in red colour) in the system during a significant number of hours, for the same week of January, even though all the available transmission line capacity (2500 MW) is exploited. The same situation is repeated during many other weeks of the year.

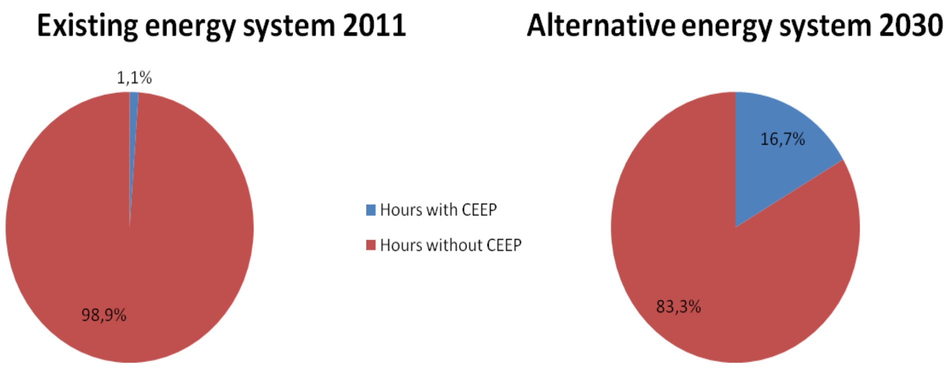

Figure 4.4: Hours with CEEP in the existing energy system of 2011 (Energinet.dk 2011) and in the Alternative system of 2030

The intensity of the problem of CEEP in reference to the future energy system can be realised by considering that today (2011) excess production constitutes a problem for almost 100 hours annually, given that the wind penetration is up to 22% (Energinet.dk 2011). Therefore, if the wind capacity is multiplied during the next years without implementing any technical means to integrate it to the system (as it happens in the case of the Alternative energy system), it seems that the problem will become 14-15 times greater by 2030 (see Figure 4.4).

All the differences in the operation of the units between the two systems, as described above, are reflected in their total annual fuel consumption. As it can be seen in Figure 4.5, this is up to 233.96 TWh for the BAU energy system while for the Alternative is 237.42 TWh, including wind as a resource[1]. In case that wind is excluded, the fuel consumption of the Alternative energy system appears to be significantly lower than this of the BAU system.

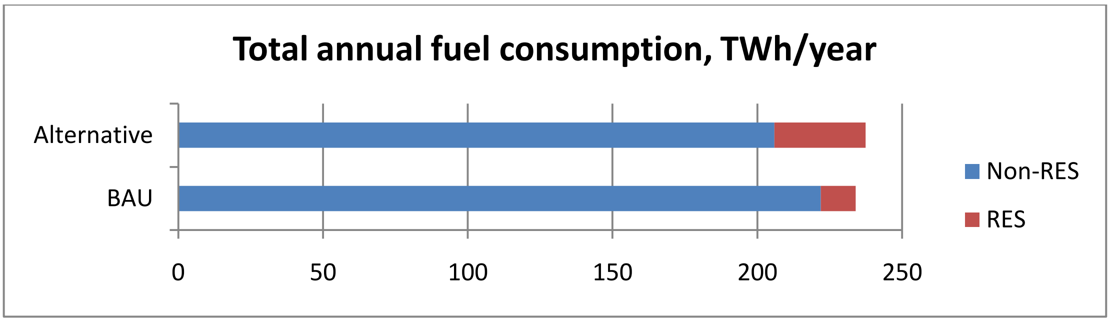

Figure 4.5: Fuel consumption divided into RES and non-RES fuels in the BAU and the Alternative energy system in 2030

[1] Wind is calculated as equal to the electricity production coming from wind power when finding the fuel equivalent

The reduction in the consumption of non-RES[1] fuels in the Alternative system is mainly related to the reduction of coal that is consumed in CHP plants and Power Plants. There is also a considerable reduction in the biomass consumed in PP and a smaller reduction in the NG consumption related to the more efficient use of it in boilers instead of CHP plants for the production of heat. In Figure 4.6, the distribution of the fuel consumption per type of fuel for both the BAU and the Alternative energy system are illustrated for comparison.

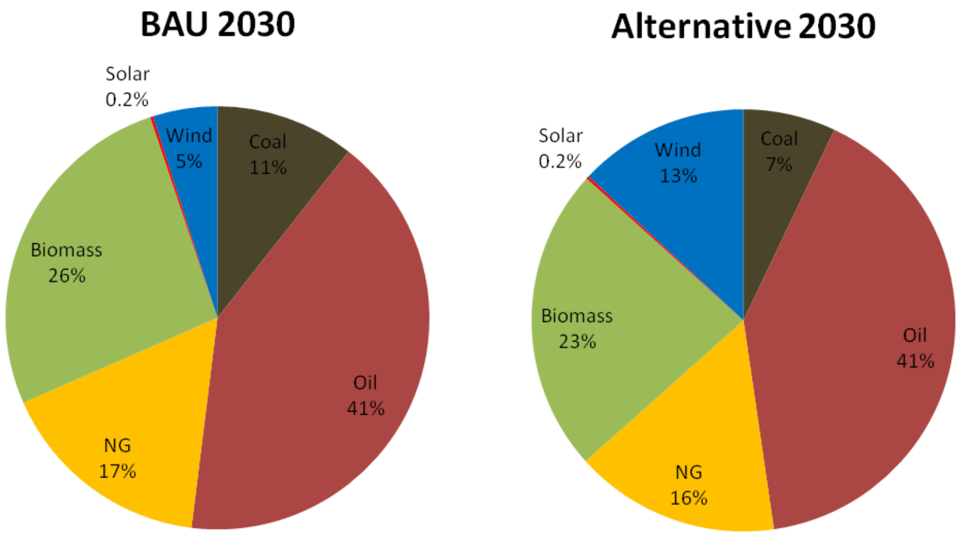

Figure 4.6: Fuel distribution in BAU and Alternative energy system

According to Figure 4.6, the share of renewable energy sources (incl. biomass) in the primary energy consumption is up to 31.6% for the BAU energy system and up to 36.6% for the Alternative.

In reference to the total annual CO_2 emissions of the two systems, these are lower for the Alternative compared to the BAU energy system (see Figure 4.7). This is mainly due to the reduction in coal consumption. Particularly, the CO_2 emissions are equal to 43.61 Mt for the BAU energy system and 40.53 Mt for the Alternative system. Therefore, it can be stated that there is a reduction of 7% between the total annual CO_2 emissions of the two systems. However if the CO_2 emissions coming from sectors such as transport, households (individual heating), industry and various (i.e. refineries, non-energy uses etc.) are cut off, the figure changes significantly (look only at the light blue part of the bars in Figure 4.7). This is because the CO_2 emissions of the above mentioned sectors are not affected by the increase in the wind penetration. The CO_2 emissions related to the production of DH and electricity are equal to 12.12 Mt for the BAU energy system and 9.04 Mt for the Alternative energy system, corresponding to a reduction of 25%. This figure is more representative of the effect that the wind penetration has on the CO_2 emissions of each system.

[1] non-RES: coal, oil, NG and biomass; RES: wind and solar

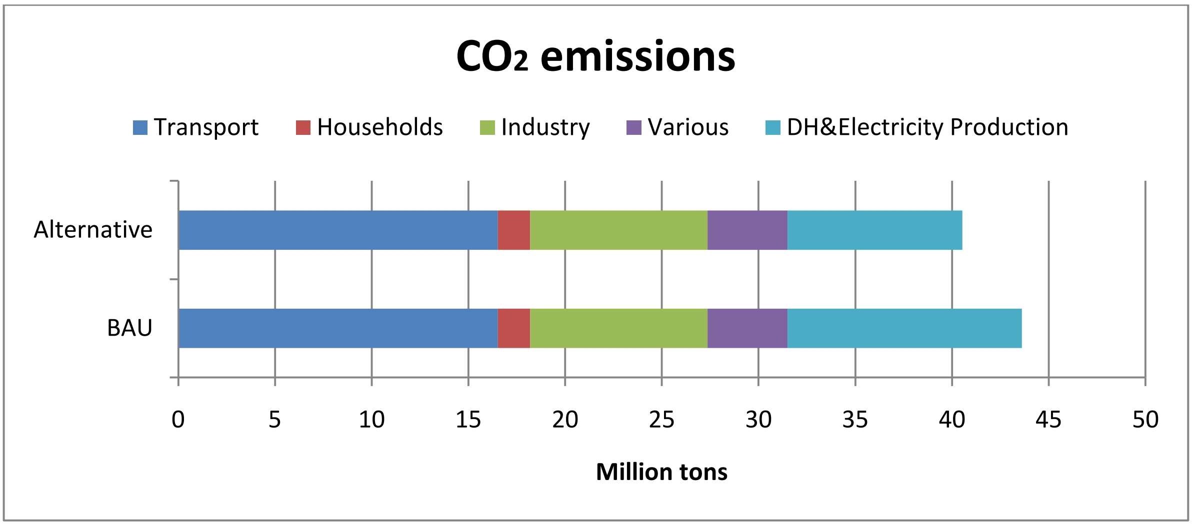

Figure 4.7: Total annual CO_2 emissions per sector of the BAU and the Alternative energy system

The reduction in both the consumption of non-RES fuels and the CO_2 emissions in the case of the Alternative energy system when compared to the BAU energy system, result in lower total fuel and CO_2 emissions costs (see Figure 4.8). Moreover, the marginal operation costs of the Alternative system are lower that those of the BAU, due to the reduced operation of CHP plants and condensing Power Plants.

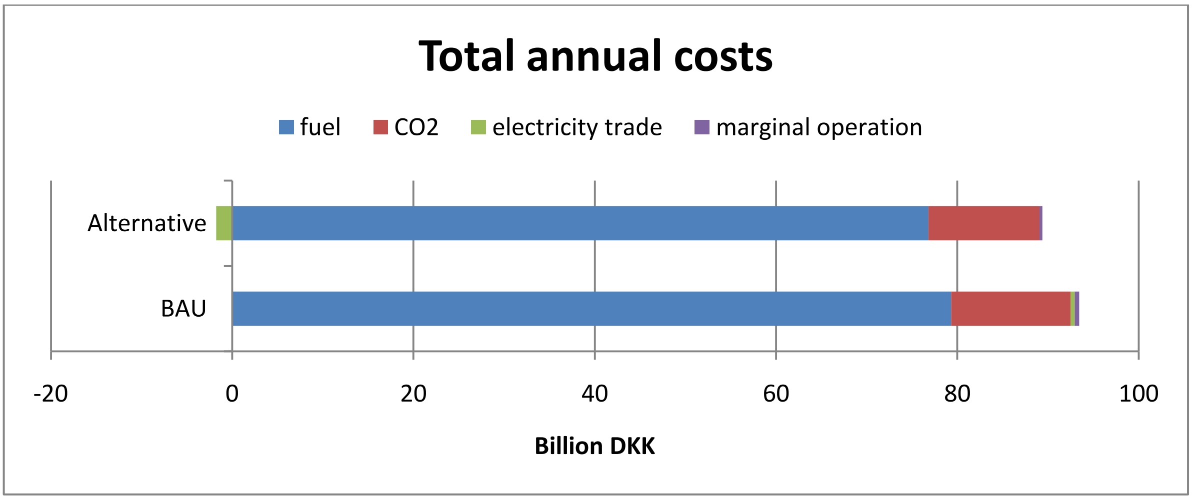

Figure 4.8: Distribution of total annual costs for the BAU and the Alternative energy system

As for the costs related to the electricity trade, in the case of the BAU energy system the imported electricity is higher than the exported electricity and this leads to annual costs of 457 million DKK. In contrary, in the case of the Alternative energy system, the exports are higher than the imports and so an annual profit of 1781 million DKK is achieved, although the resulting price of the exported electricity is much lower in the Alternative comparing to the BAU system. Consequently, the total annual costs are equal to 93,431 million DKK for the BAU energy system and 87,614 million DKK for the Alternative energy system.[1]

[1] The total annual costs are identical to the total variable costs for both the BAU and the Alternative energy system, since there are not any investment and fixed O&M costs to include at this stage.

5 Techno-Economic Analysis of Individual Heat Pumps

In this Chapter the techno-economic consequences of the expansion of individual heat pumps both in the Business-as-Usual and in the Alternative energy system in reference to 2030 are investigated. The option of adding heat storages operating in combination with individual heat pumps will be also examined in both energy systems.

5.1 Inputs and assumptions

The scope of this section is to describe all the assumptions and inputs that are used in the analysis of the individual heat pumps with the EnergyPLAN model. The sub-section 5.1.1 includes technical and economic data referring to the expansion of the existing individual heat pumps while the sub-section 5.1.2 referring to the addition of heat storages.

5.1.1 Expansion of individual heat pumps

Based on estimations of Energinet.dk the potential for individual electric heat pumps - outside the district heating areas - in the long term is approximately equal to 50% of the total annual heat demand. This corresponds to 500,000 units installed in households located out of district heating areas, while currently (2010) there are 80,000 heat pumps in Denmark. (Energinet.dk 2010)

As it has been already stated in the description of the BAU system, the total annual heat demand of individually heated buildings is estimated in EnergyPLAN, according to the inputs from the baseline projection of DEA for 2030, at 19.53 TWh. In DEA's projection individual heat pumps which are going to be existent in 2030 will cover 3.26 TWh (including the contribution of reserve electric boilers) i.e. 16.7% of the total heat demand.

In the following sub-sections a further expansion of individual heat pumps is considered so that they can meet 50% of the total heat demand both in the BAU and the Alternative energy system. This means that heat pumps are replacing all the individual oil and natural gas boilers. The heat demand in individually heated households is supplied 50% by biomass boilers and 50% by electric heat pumps, after their expansion (see Table 5.1).

Table 5.1: Distribution of annual heat demand before and after the expansion of individual heat pumps

Heating technology	Before	After
Oil boiler	2.23	0
NG boiler	4.31	0.03
Biomass boiler	9.74	9.74
Heat Pump	3.26	9.77
Total	19.53	19.53

The expansion of the heat pumps is based on a combination of ground-source and air-to-water heat pumps. An average cost for the ground-source heat pumps is 100,000 DKK/system whereas for the air-to-water systems the cost is 50,000 DKK/system. Furthermore, average annual fixed O&M costs of 0.9% and 0.6% of the total investment costs are considered respectively for the two types of heat pumps. Based on the fact that the lifetime of the piping system of the ground source heat pumps is about 40 years, it needs to be assumed that half of the investment in this type of heat pumps has a lifetime of 40 years. Consequently, an investment up to 55 million DKK/MW_e is introduced in the model for individual heat pumps, with 15 years lifetime and fixed O&M costs equal to 0.7% of the investment. (IDA 2009)

5.1.2 Heat storages in individual heat pumps

Assuming that the number of buildings that are individually heated is approximately 1 million and then based on the total annual individual heat demand estimated in EnergyPLAN, the average annual heat demand of such a building is around 19,500 kWh (Energinet.dk 2010). This figure is also confirmed in (Danish Energy Authority 2005) where it is stated that the average annual consumption of heat and hot water in a typical household is around 18,100 kWh.

By introducing heat storage of 1 day of average heat demand in the buildings heated by individual heat pumps, a 500 litres tank would be sufficient to heat water from 20 °C to 50 °C.

The cost for such a heat storage unit (including heat exchanger and connections) is approximately 15,000 DKK (IDA 2009). Therefore, an investment up to 7,500 million DKK is considered for introducing 500,000 heat storage units operating in combination with individual heat pumps, which are responsible for covering 50% of the total individual heat demand.

The fixed operation and maintenance costs are considered to be equal to 1% of the investment and the lifetime for the heat storage units up to 20 years (IDA 2009).

5.2 Individual heat pumps in the BAU energy system

The individual oil and NG consumption is replaced by the electricity demand of the extra individual heat pumps that are introduced in the system. Therefore, the electricity production of both the CHP units and the condensing Power Plants (PP) of the system are increased so that the increased electricity demand can be met, something which leads to the reduction of boilers' heat production, given that anyway more heat is co-generated in CHP units. The expansion of individual heat pumps is also affecting the electricity exchange in the external electricity market. Particularly, the imported electricity is larger while the exported is smaller after the introduction of the extra heat pumps. This means that the system is optimised in a way that a share of the increased electricity demand (due to the demand of heat pumps) is preferred to be met by importing electricity from the external market than by producing it locally.

A series of changes can be observed in the fuel balance: the fuel consumption in small CHP plants (CHP2) and in condensing PP is increased as it is expected, whereas fuel is saved both in boilers operating in combination with small CHP units in DH systems and in individual boilers. As a consequence the **total fuel consumption** of the system is **decreased by 4.7 TWh**, since the required heat is produced in a more efficient way. This reduction corresponds to **fuel savings of 2%**, given that the total annual fuel consumption of the **BAU** energy system from 233.96 TWh goes down to 229.26 TWh after the expansion of the **individual heat pumps** (see Figure 5.1).

The reduction in the fuel consumption is also reflected to the **CO_2 emissions** of the system. Therefore, the decrease in the oil and NG consumption in the **BAU** system leads to a decrease in the total annual CO_2 emissions of **0.83 million tons or 1.9%**, despite the increase of the coal consumed in condensing PP.

There is no Critical Excess Electricity Production (CEEP) in the BAU energy system after the expansion of individual heat pumps something which is expected since not even in the BAU system before the expansion of heat pumps there was any CEEP.

In terms of total annual costs savings are observed after the expansion of individual heat pumps. The savings are mainly savings in fuel costs, which are connected to the overall fuel savings in the system, and savings in CO_2 emission costs connected with the CO_2 emissions reduction. The electricity exchange costs are increased since more electricity is imported and less is exported. Therefore, the electricity price on the market is increased something that leads to higher total electricity exchange costs. In the calculation of the total annual costs, the annual investment costs as well as the fixed operation costs of the extra heat pumps that are introduced in the system are also considered. These costs were not existent in the BAU system before the expansion of the individual heat pumps. All in all, the cost savings overpass the extra costs that occur and a **socio-economic profit of 500 million DKK or 0.5%** per year is achieved with the expansion of **heat pumps** in individually heated buildings in the **BAU** energy system (see Figure 5.3).

Adding heat storage

In general when an analysis of the effects of individual heat pumps is conducted it should be considered that the marginal production cost of heat on heat pumps is compared to electric heating and the least-cost solution is selected, given that a market-economic optimisation strategy is followed. The role of heat storage is to be utilised so that lowest market prices of the electricity consumed by heat pumps can be achieved. (EnergyPLAN 2011)

The addition of heat storage facilities in conjunction with an expansion of individual heat pumps results in an even higher utilisation of heat pumps. When there was no option of storing the heat produced from heat pumps, 95% of the heat demand that corresponds to individual heat pumps was covered by the heat pumps themselves and 5% by electric boilers (operating to cover the peak demands). After adding the option of heat storage the contribution of heat pumps goes up to 97% of the heat demand. As a result the electricity demand increases due to the expansion of heat pumps but less than it had increased when there was not an option of heat storage. This happens because heat storage as it is mentioned above raises the utilisation of heat pumps against electric boilers which can produce the required heat more efficiently.

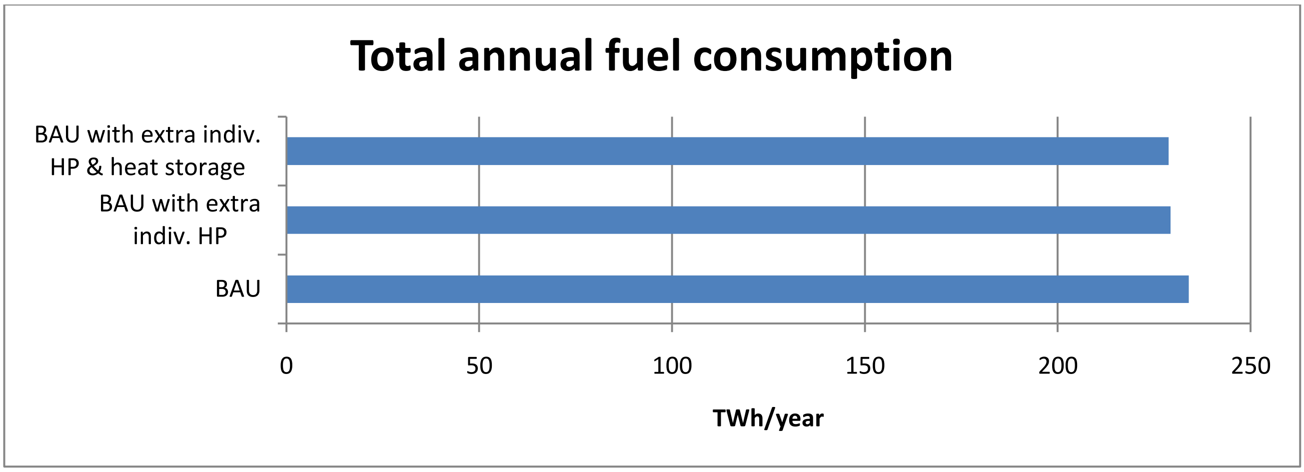

Figure 5.1: Total annual fuel consumption of the BAU energy system before and after the expansion of individual heat pumps and the addition of heat storage

In the case that heat storage is added on the top of the expansion of individual heat pumps, the electricity production of condensing PP is slightly decreased, compared to the BAU energy system with the extra heat pumps. This is due to the higher utilisation of heat pumps over electric heating which leads to a slightly reduced electricity demand (compared to BAU with extra HPs). Therefore, the coal consumed in PP decreases and so does the total fuel consumption. In absolute values, **5.2 TWh or 2.2% of fuel is saved** comparing to the **BAU** energy system which means that the system becomes even more efficient (see Figure 5.1). The extra fuel savings that can be achieved by the addition of **heat storage** are also reflected in the total annual **CO_2 emissions** of the system which are further reduced, with a **reduction** going up to **1 million tons or 2.3%** (see Figure 5.2).

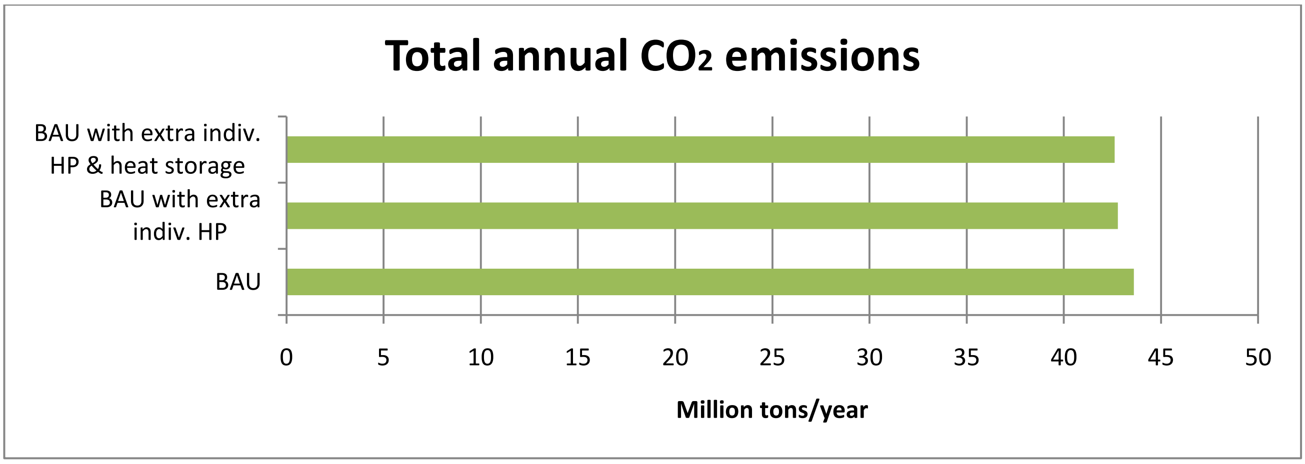

Figure 5.2: CO_2 emissions of the BAU energy system before and after expanding individual HPs and adding heat storage

The reduction in fuel consumption leads to lower fuel costs comparing to the BAU system both before and after the expansion of the individual heat pumps. A further reduction is observed also in the total CO_2 emissions costs. Therefore, by adding the option of heat storage a reduction of 85 million DKK in the total variable costs of the system is reached despite the slight increase in the electricity exchange costs. However, by considering the investment and the fixed operation costs of the heat storages the total annual costs of the system become higher comparing to the BAU energy system both with and without the extra individual heat pumps. Therefore, the addition of heat storages along with the extra individual heat pumps results in a **socio-economic loss** of **140 million DKK** comparing to the BAU system.

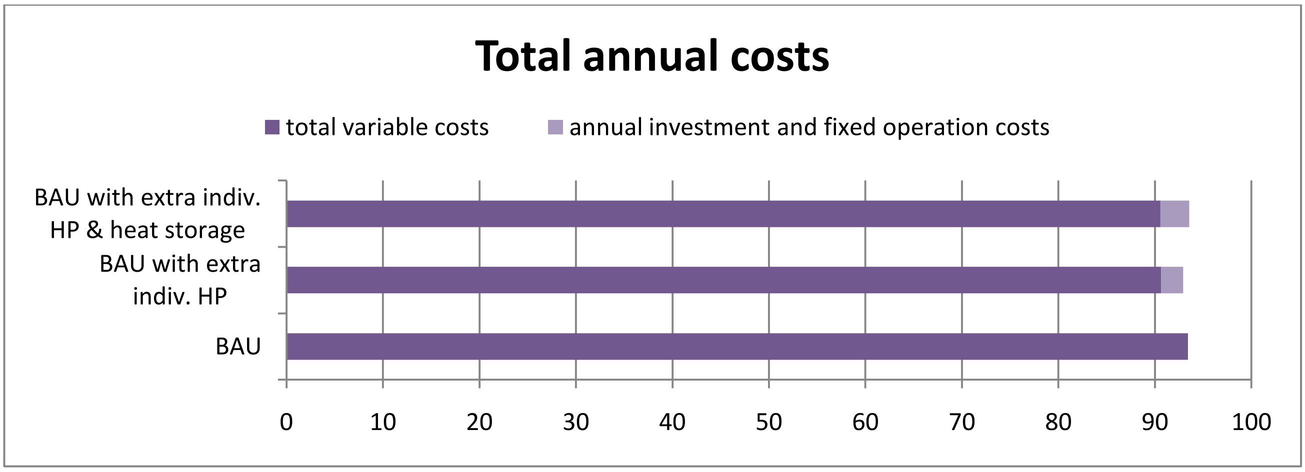

Figure 5.3: Total annual costs of the BAU energy system before and after expanding individual HPs and adding heat storages

5.3 Individual heat pumps in the Alternative energy system

Similar changes are observed in the energy performance of the Alternative energy system by the expansion of the individual heat pumps with those occur in the BAU energy system. The electricity demand is higher since electricity is consumed both in the extra heat pumps that have been introduced in the system and in the electric boilers that operate along with the heat pumps in order to cover peak heat demands. The additional electricity demand is met by condensing Power Plants, small CHP plants and large CHP plants. The augmented operation of CHP plants leads to higher district heating production from those units so that the district heating production of large scale boilers, which are operating in conjunction with CHP units, decreases. Furthermore, a share of the additional electricity demand is covered by increasing the imports of electricity from the external electricity market.

All the above mentioned changes in the operation of the energy generating units of the Alternative energy system are reflected in the fuel balance of the system. On the one hand, the consumption of coal, natural gas and oil is higher in the condensing Power Plants, the small and the large CHP plants after the expansion of the individual heat pumps in the Alternative energy system. On the other hand, less natural gas is consumed now in the large scale boilers operating in DH systems and of course the consumption of natural gas and oil is almost eliminated in the individual buildings since the required heat demand is covered by the extra heat pumps that have been introduced in the system. All in all, a **reduction** in the **total fuel consumption** of **5.8 TWh or 2.5%** is observed by the expansion of the **individual heat pumps** in the **Alternative** energy system (see Figure 5.4).

The CO_2 emissions related to the consumption of coal are higher after the expansion of the **individual heat pumps** since the total annual coal consumption is higher. However, the reduction in the natural gas and oil consumption leads to lower CO_2 emissions related to these fuels. Finally, the total **CO_2 emissions** become approximately **1.5 million tons or 3.7%** less than it was before the introduction of the extra individual heat pumps in the **Alternative** energy system (see Figure 5.5).

In the case of the Alternative energy system, as it has been already mentioned in Section 4.5, there is Critical Excess Electricity Production (CEEP) and the total value for the whole year is equal to 1.88 TWh. A reduction of **0.32 TWh** in the CEEP can be achieved by the expansion of **heat pumps** in individually heated buildings. In other words the benefit from the extra individual heat pumps in the regulation of CEEP is a **17% reduction of the CEEP**, which was observed in the **Alternative** energy system initially.

As for the economic consequences of the additional individual heat pumps in the system it should be stated that an overall socio-economic benefit is achieved. Particularly, cost savings consist of savings in fuel costs and CO_2 emissions costs which are connected with the lower consumption of fossil fuels in the system. Nevertheless, the expansion of individual heat pumps is responsible for higher operation costs, due to the increased operation of condensing Power Plants and CHP plants. Moreover, the benefits from the electricity exchange in the external electricity market are lower comparing to those of the Alternative system before the expansion of heat pumps. This is mainly because the costs of importing electricity, to cover a share of the increased electricity requirements due to the operation of more heat pumps, are increased although the benefits from exporting electricity are slightly increased (lower exports but with a higher average price). Consequently, the additional individual heat pumps create a socio-economic benefit of **3.3 billion DKK** in terms of total annual variable costs. If the fixed operation costs and the investment costs that correspond to the extra **individual heat pumps** that are introduced in the **Alternative** energy system are also taken into account then the **socio-economic benefits** are equal to **1 billion DKK or 1.1%** in terms of total annual costs (see Figure 5.6).

Adding heat storage

In the Alternative energy system, similarly with the case of the BAU system, the introduction of heat storage after the expansion of the individual heat pumps leads to higher utilisation of heat pumps and a more efficient production of the required heat in the individually heated buildings. Therefore, the electricity production of condensing Power Plants and CHP plants is increased comparing to the initial Alternative energy system but not that increased as in the case of the Alternative system after the expansion of heat pumps. By adding the option of heat storages, the electricity that is required by the heat pumps can be also partly provided by electricity production that appears as critical excess (CEEP) in the Alternative energy system, since heat storage can operate as a buffer for heat pumps so that they can consume electricity to produce heat at hours with low electricity price, when it is possible to have CEEP in the system due to high wind production. This means that the addition of heat storages enables the system to integrate wind power in a better way. As a consequence, the electricity production of both condensing PP and CHP plants is lower than it was without the option of heat storage. In this way a series of synergy effects happens; the fuel savings, the reduction of CEEP and the CO_2 emissions savings that were achieved by the expansion of individual heat pump in the Alternative energy system are further improved after the addition of heat storage facilities.

A reduction of CEEP of **0.37 TWh/year** is achieved by **adding heat storage** on the top of the expansion of individual heat pumps in the **Alternative** energy system. This is translated to **19.7% less CEEP** due to heat storage (the reduction is 17% by just expanding individual heat pumps).

As it can be seen in Figure 5.4, **fuel savings** up to **6.16 TWh or 2.6%** can be achieved by the introduction of **heat storages** in conjunction with the expansion of individual heat pumps in the **Alternative** system (0.34 TWh more fuel saved after the addition of heat storage on the top of the expansion of individual heat pumps).

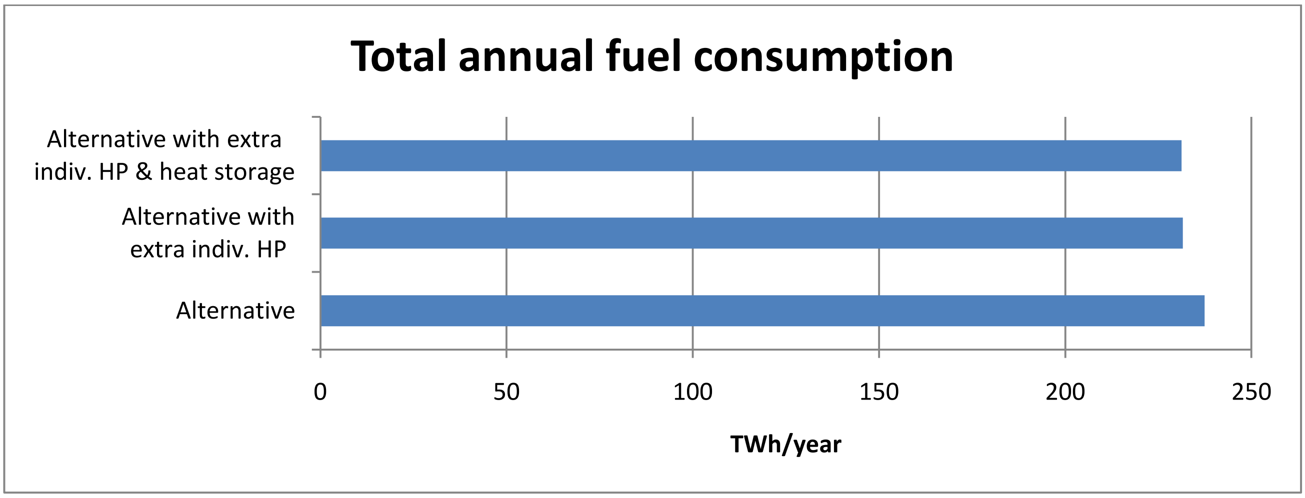

Figure 5.4: Total annual fuel consumption of the Alternative energy system before and after the expansion of individual heat pumps and the addition of heat storage

The **reduction** in the total **CO_2 emissions** of the **Alternative** system after the addition of heat storages goes up to **1.52 million tons or 3.8%**, which means that 0.04 more million tons of CO_2 can be avoided by combining the expansion of individual heat pumps with heat storage in the Alternative energy system (see Figure 5.5).

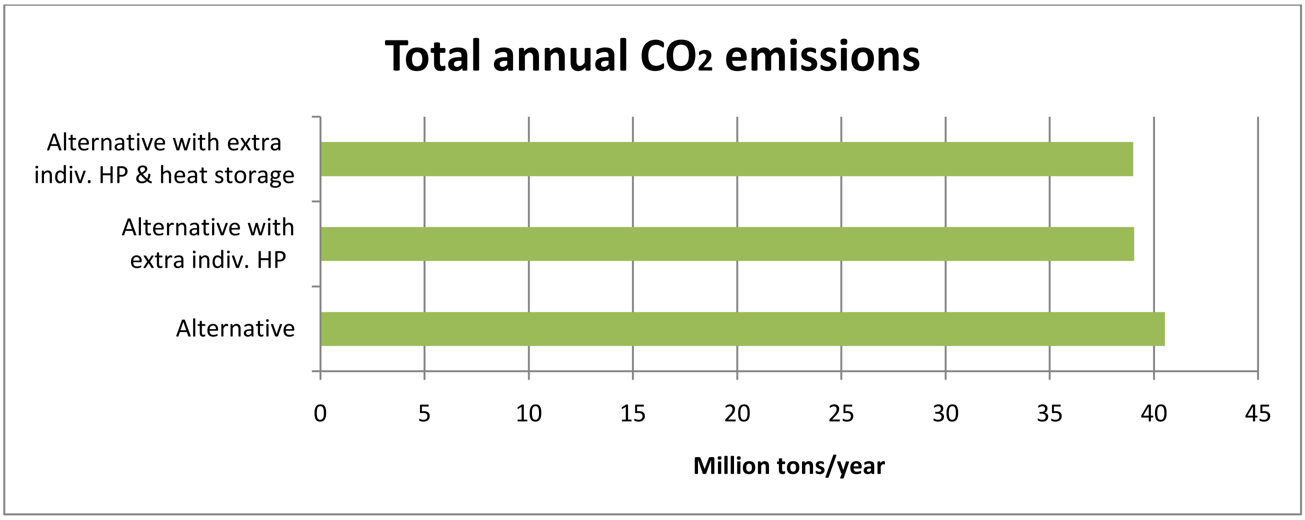

Figure 5.5: Total annual CO_2 emissions of the Alternative energy system before and after the expansion of individual heat pumps and the addition of heat storage

As for costs, the total variable costs of the Alternative energy system are further improved after the introduction of heat storages combined with individual heat pumps. This mainly applies because the fuel costs, the operation costs as well as the CO_2 emission costs are further decreased. Even when considering the annual investment costs and the fixed operation costs of the heat storages a **socio-economic profit** up to **393 million DKK or 0.45%** is made by introducing an expansion of the individual heat pumps with the option of **heat storage** in the **Alternative** energy system (see Figure 5.6).

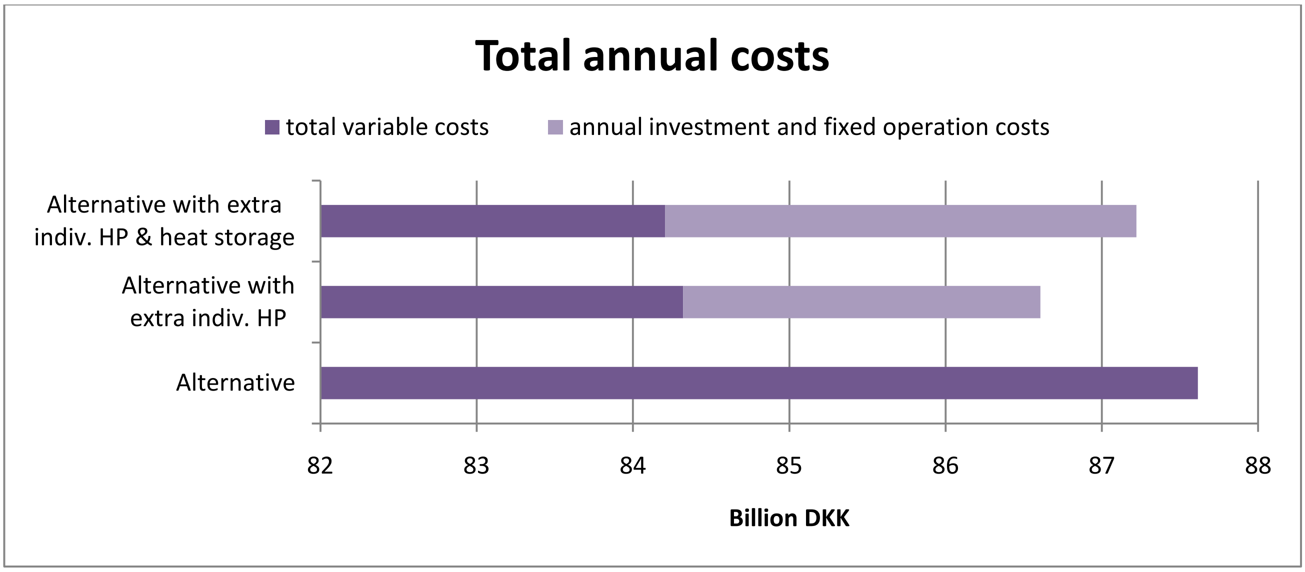

Figure 5.6: The effect of individual heat pumps and heat storage to the total annual costs in the Alternative energy system

6 Techno-Economic Analysis of Large Heat Pumps

In this Chapter the techno-economic effects of introducing large heat pumps in DH systems both in the BAU and in the Alternative energy system, in reference to 2030, are analysed. The Chapter starts with a description of the technical and economic assumptions that are used for modelling the introduction of large heat pumps with the EnergyPLAN model.

6.1 Inputs and assumptions

According to estimations of the Danish Energy Association, the potential for installing heat pumps in district heating system is equal to an overall capacity of 2,000 MW_{th}, in reference to the year 2025 (Danish Energy Association 2009). In addition, it is also considered that this overall heat capacity is distributed to 378 MW_{th} in decentralised areas and 1,560 MW_{th} in central areas (equal to 1,938 MW_{th} in total), as it is proposed in (Energinet.dk 2009). Such a distribution is adopted in this study since it takes into account the distribution of the available heat sources required by heat pumps to operate.

In the (Technology Data for Energy Plants 2010) the specifications of two different types of large electric heat pumps for district heating systems are provided. The one type refers to heat pumps based on a heat source of 35 °C and the other type refers to heat pumps in which the average outdoor temperature is used as heat source. The COP of the first ones is equal to 3.8 in reference to the year 2030 while the second ones have a COP of 3. In the framework of this study, an average COP of 3.4 is used in the analyses.

As for the investment cost of large heat pumps, it is considered to be up to 14.54 million DKK/MW_e (in 2011 prices), based on an average specific investment cost of the two different types of heat pumps that were mentioned above. In addition to this, annual fixed O&M costs equal to 0.23% of the investment are taken into account. Moreover, the variable O&M costs for large heat pumps are set to 3.96 DKK/MWh_e in 2011 prices, based on the fact that an overall check is needed for every 10,000 hours of operation costing approximately 1500 €/MW_{th}. All the costs mentioned here are based on figures obtained from (Technology Data for Energy Plants 2010). The way that the data are handled in order to be inserted in the EnergyPLAN model is described in Appendix III.

It should be stated that the above mentioned specifications are based on the fact that CO_2 is used as refrigerant in heat pumps. Concerning large compression heat pumps, CO_2 along with NH_3 are the refrigerants that will be probably used in the future. On the one hand, heat pumps using NH_3 constitute a well tested technology, commercially available. Moreover, they are cheaper than CO_2 heat pumps but they are not able to deliver a supply temperature much above 55 °C, since the condensation temperature of NH_3 is about 60 °C. On the other hand, CO_2 heat pumps may be still a new technology which is more expensive but they can be used for applications with temperatures up to 90 °C. Given that the Danish district heating system operates with a supply temperature of 75 °C or higher, CO_2 is selected as the appropriate refrigerant for large heat pumps in this study.

6.2 Large heat pumps in the BAU energy system

The operation of heat pumps in EnergyPLAN is determined by comparing their marginal operational costs, including fuel costs, with the corresponding costs of other relevant options such as boilers, CHP and heat storage. The least-cost solution is selected at an hourly basis by the model.

After the introduction of large heat pumps in the BAU energy system, a share of the district heating demand is produced by heat pumps instead of CHP plants and boilers. Therefore the heat production of CHP plants is reduced and this means also a reduction in the electricity production of CHP. In addition to this, the electricity demand increases due to the electricity required by heat pumps in order to operate. As a result the implementation of large heat pumps creates a gap between the electricity demand and production, which is filled by condensing power plants and imports of electricity along with a small reduction in exports of electricity.

The utilisation of heat pumps is different between decentralised areas with small CHP plants and central areas with large CHP plants. Actually, it is observed that heat pumps operate for 6,845 hours per year in the decentralised areas while the hours of operation are much less in central areas, equal to 1,989. As it has been referred in the beginning of this sub-section, the operation of the heat pumps is inextricably linked with their feasibility. It seems that heat pumps constitute the least-cost solution during higher number of hours in the decentralised areas compared to central areas. This is because in the decentralised areas the CHP plants and the boilers are mainly fuelled with natural gas which is more expensive comparing to coal which is mainly the fuel in CHP plants of central areas. Therefore, the heat production of heat pumps in the decentralised areas is higher comparing to central areas (2.36 TWh/24% over 2.16/10%), irrespectively with the installed capacity in these areas (see Figure 6.1).

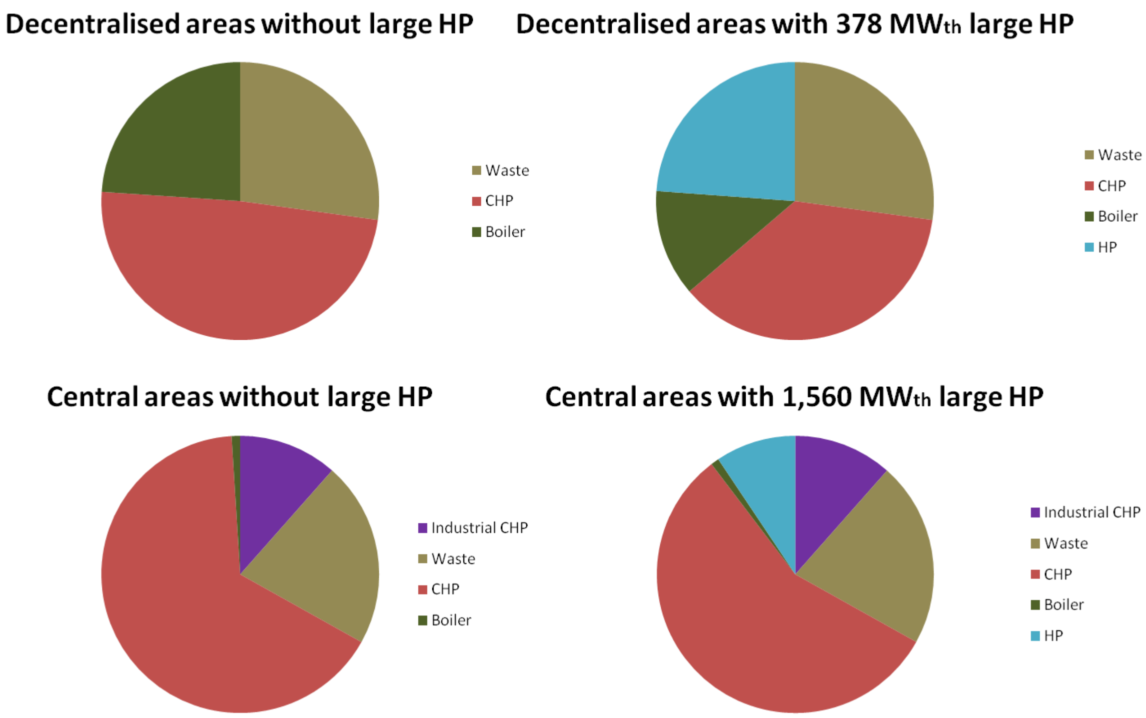

Figure 6.1: Heat production in decentralised and central areas before and after the introduction of large heat pumps in the BAU energy system

The fuel consumption in CHP plants and boilers in both the central and decentralised areas is affected in correspondence with the changes in the operation of those units after the introduction of large heat pumps, as presented in Figure 6.2. Particularly, there is a significant reduction in the NG consumed in CHP and boilers in the decentralised areas and in the coal consumed in CHP plants in the central areas as well as a minor reduction in NG consumed in boilers in central areas. However, as it was already mentioned the electricity production of PP increased and so does the coal consumption in these units. All in all, the coal consumption remains almost the same after the introduction of large heat pumps in the BAU energy system while there is a reduction in the NG consumption (see Figure 6.2). Therefore, the **total annual fuel consumption is reduced** by **3.72 TWh or 1.6%** due to the operation of **large heat pumps** in the **BAU** energy system.

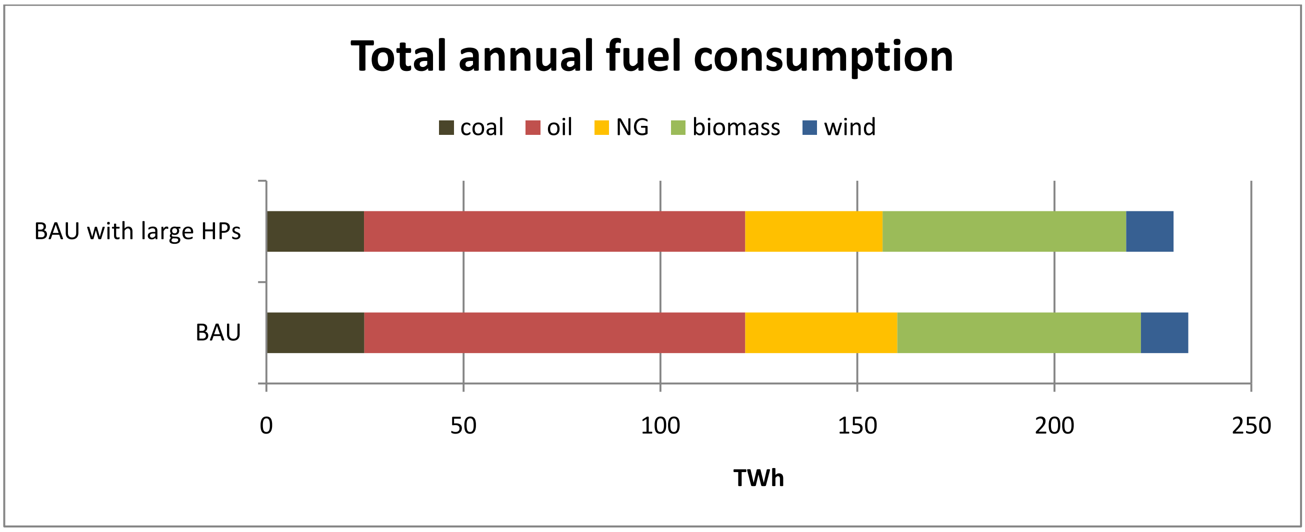

Figure 6.2: Total annual fuel consumption per type of fuel before and after the introduction of large HPs in the BAU energy system

The reduction in the consumption of natural gas stimulates also a **reduction** of **0.77 Mt or 1.8%** in the **total annual CO_2 emissions** of the **BAU** energy system after the introduction of **large heat pumps** (see Figure 6.3).

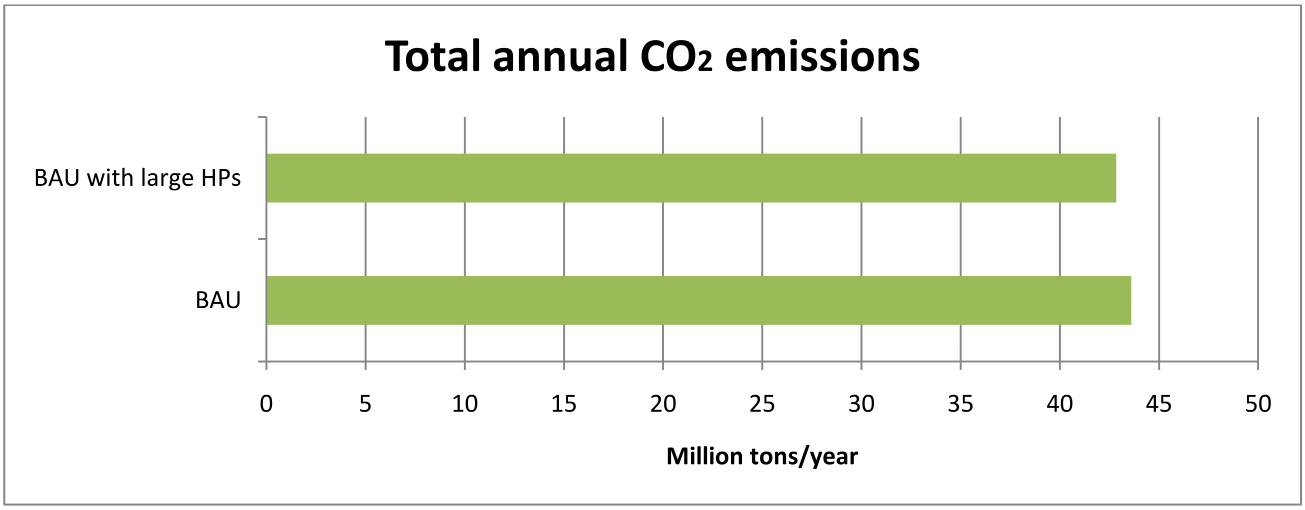

Figure 6.3: Total annual CO_2 emissions before and after the introduction of large HPs in the BAU energy system

The reduced fuel consumption and CO_2 emissions that can be achieved after the introduction of large heat pumps in the BAU energy system lead to lower annual fuel and CO_2 emissions costs. The annual marginal operation costs become also a bit lower due to the limited operation of CHP and boilers. However, the annual costs related to the trade of electricity become higher when large heat pumps are installed in the system. This is because imports of electricity increase (and so does the average price of imported electricity) while exports decrease in order to meet the electricity required by heat pumps. Finally, the **total annual variable costs** of the **BAU** energy system become **lower by 571 million DKK or 0.6%** when **large heat pumps** are introduced (see Figure 6.4).

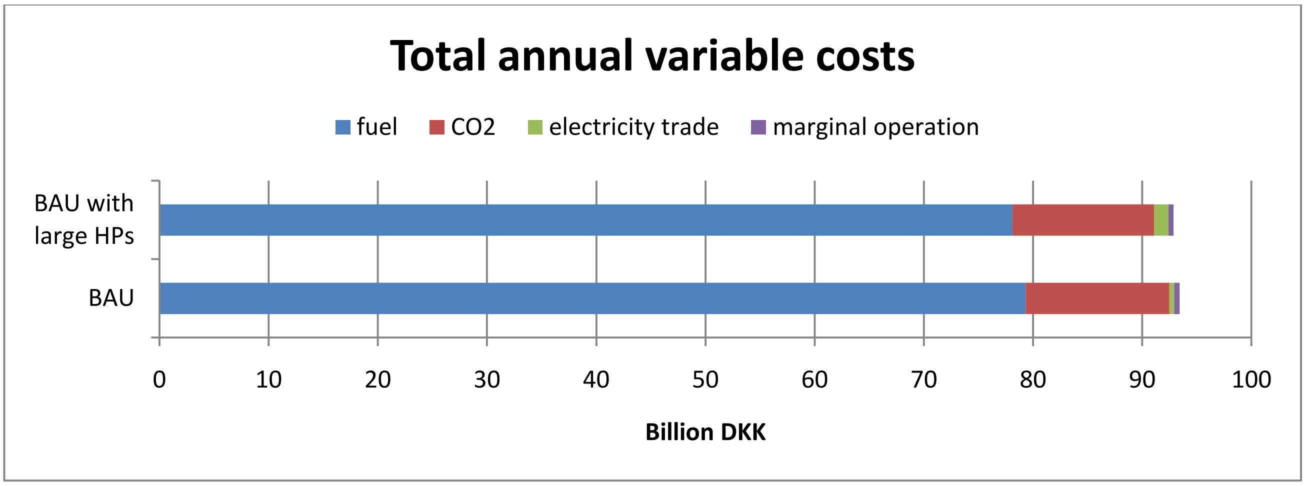

Figure 6.4: Total annual variable costs before and after the introduction of large HPs in the BAU energy system

When the investment costs as well as the fixed O&M costs that correspond to the installation of 2,000 MW_{th} of heat pumps are taken into account the situation presented in Figure 6.4 is reversed. Hence, an **annual socio-economic loss of 170 million DKK or 0.18%** is created by the introduction of **large heat pumps** in the **BAU** energy system (see Figure 6.5).

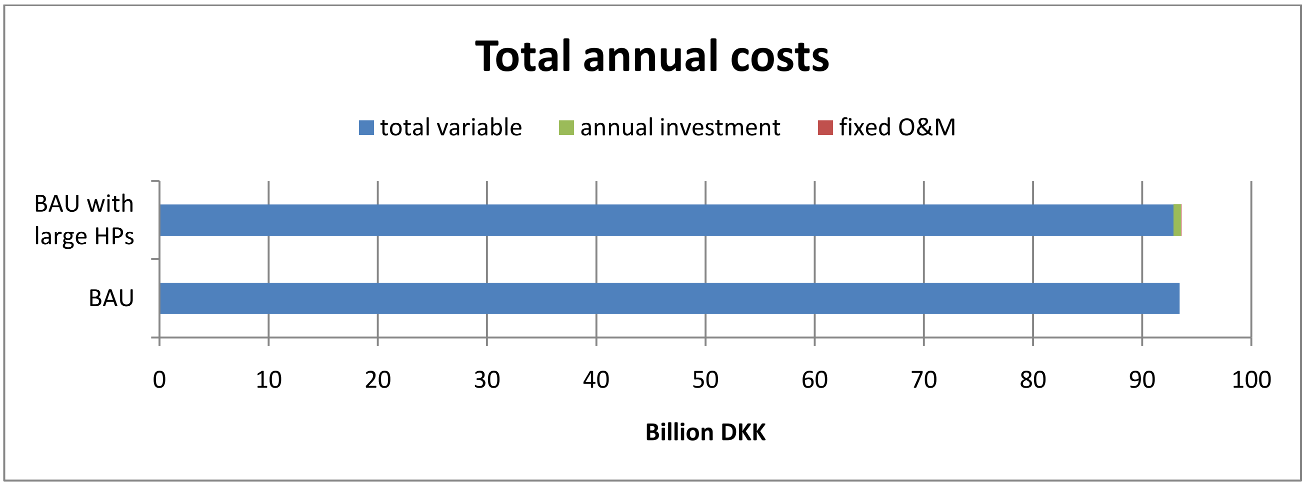

Figure 6.5: Total annual costs before and after the introduction of large HPs in the BAU energy system

Something more that is worth to be noted is that the total annual CEEP remains to be zero, as it would be expected, in the BAU energy system after introducing the large heat pumps.

6.3 Large heat pumps in the Alternative energy system

The utilisation of heat pumps in the Alternative energy system is higher comparing to the BAU energy system. This happens because the production of heat in heat pumps comparing to boilers and CHP plants becomes the low-cost solution for more hours during the year in the Alternative energy system. This is mainly because both a share of the electricity required by heat pumps and the electricity needed to cover the reduced electricity production of CHP plants can be produced in biomass-fired power plants. While in the BAU energy system this electricity is produced in coal-fired power plants which is more costly. Of course this is related to the high electricity production of wind turbines that give the chance to produce electricity in PP by consuming biomass without exceeding the limited biomass resources. Apart from that, a share of the electricity demand of heat pumps is covered by reducing the exports and increasing the imports of electricity.

By looking at the hourly outputs of the EnergyPLAN model, it is observed that large heat pumps are operating for 6,746 hours in the decentralised areas and for 3,708 hours in the central areas in the Alternative energy system (both at full and partial load). Similarly to the BAU energy system, the utilisation of heat pumps is higher in the decentralised areas comparing to the central areas. However, in the Alternative energy system the hours of operation in the central areas have almost doubled comparing to the BAU energy system (see Figure 6.6). This happens because in central areas heat pumps are replacing NG-fired boilers, which were operating more in the Alternative system than in the BAU before the introduction of heat pumps. Boilers are operating more in the Alternative than in the BAU and CHP units are operating less in the Alternative than in the BAU. This is because in the Alternative a higher share of electricity demand can be covered by wind power so that it does not worth to produce electricity in CHP plants while also the heat can be produced in boilers at a higher efficiency.

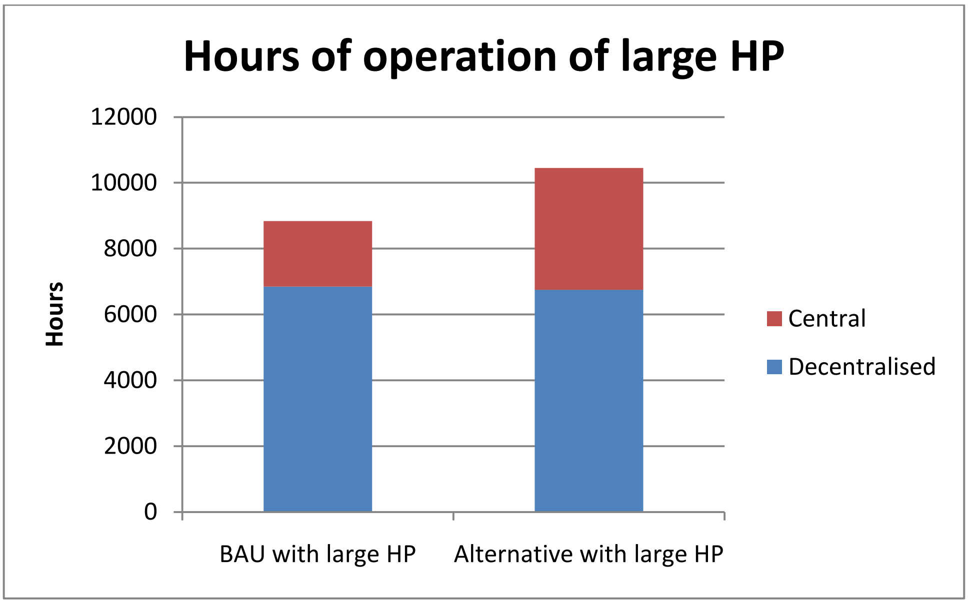

Figure 6.6: Hours of operation for large HP in central and decentralised areas in the BAU and Alternative energy system

The changes described above affect the total fuel consumption of the system correspondingly. On the one hand, there is a reduction in coal consumption of central CHP plants and a reduction in the NG consumed in boilers and CHP plants both in the central and decentralised areas. On the other hand, the biomass consumption of condensing PP increases. As a result there is a **reduction** of **7.65 TWh or 3.2%** in the **total annual fuel consumption** of the **Alternative** energy system after the introduction of **large heat pumps** (see Figure 6.7).

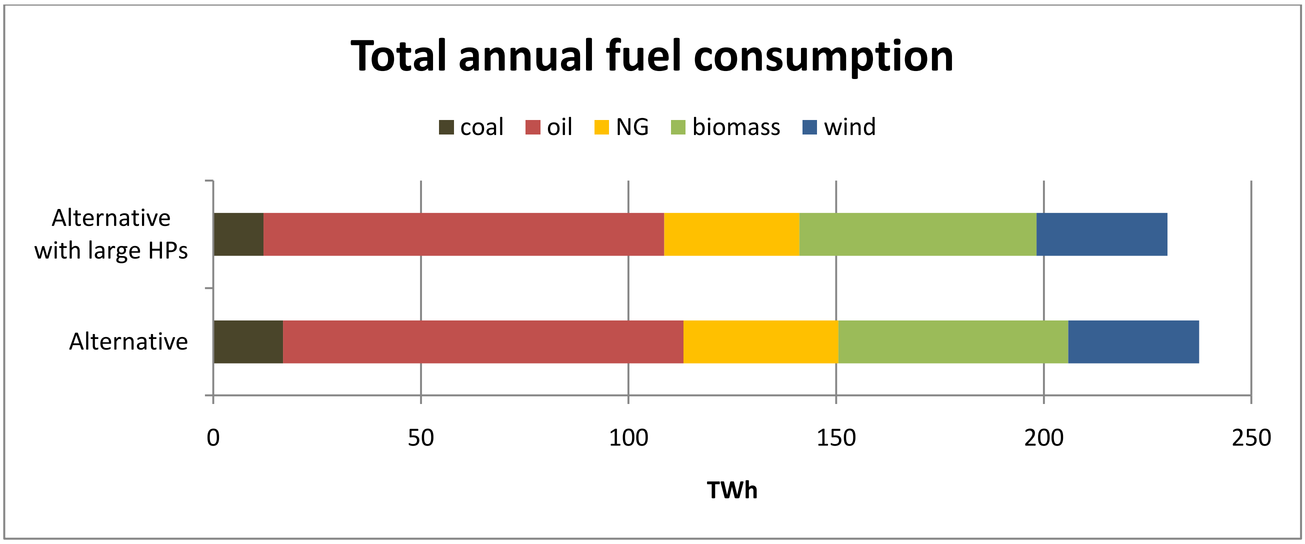

Figure 6.7: Total annual fuel consumption before and after the introduction of large HP in the Alternative energy system

The reduction in the total consumption of coal and natural gas leads the **total annual CO_2** emissions of the **Alternative** energy system to a **reduction** of **2.57 Mt/year or 6.3%** (see Figure 6.8).

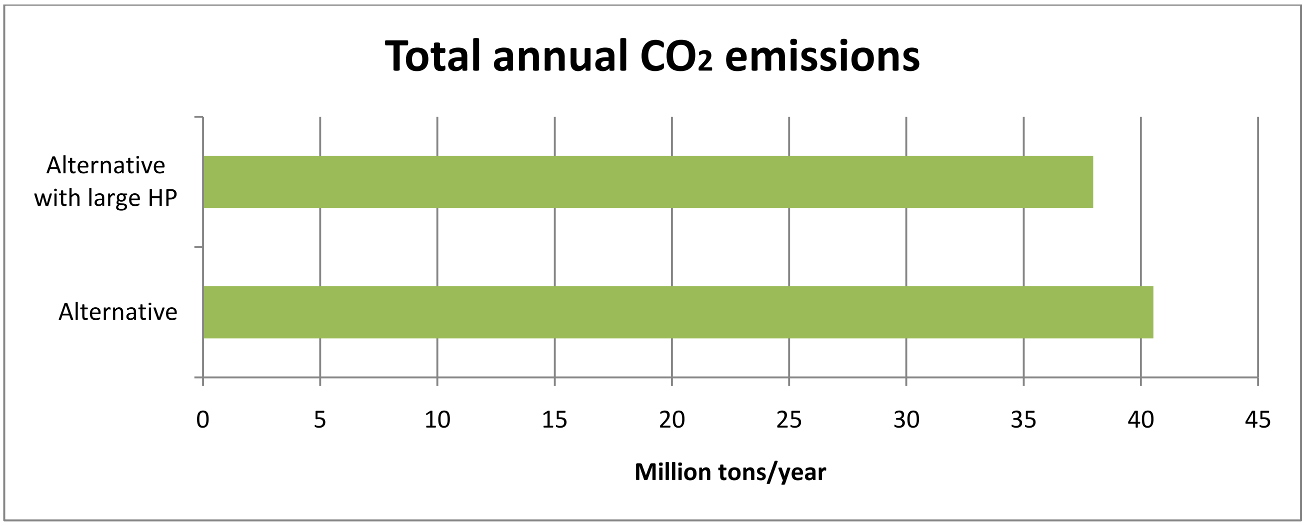

Figure 6.8: Total annual CO_2 emissions before and after the introduction of large HP in the Alternative energy system

The implementation of **large heat pumps** to the **Alternative** energy system has also a significant effect to the critical excess electricity production (**CEEP**) which reduces by **0.42 TWh/year** (see Figure 6.9). This reduction is equal to **22%** and the total number of hours with CEEP from 1,459 goes down to 1,249 per year.

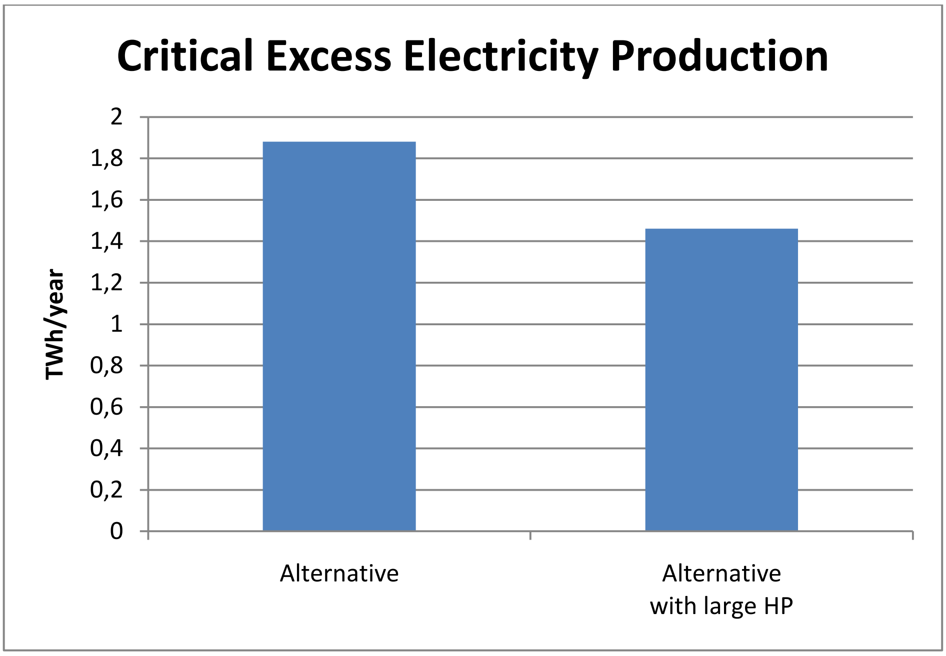

Figure 6.9: CEEP in the Alternative energy system before and after the introduction of large heat pumps

Another benefit from the operation of **large heat pumps** in the **Alternative** energy system is that the **total variable costs** of the system **decrease** by approximately **1.8 billion DKK per year or 2.1%** (see Figure 6.10). This is mainly related to lower fuel costs and CO_2 emissions costs. A reduction in the variable costs is achieved even though the profit from the electricity trade becomes lower after the implementation of large heat pumps, since the cost of imports increases more than what the income from export increases.

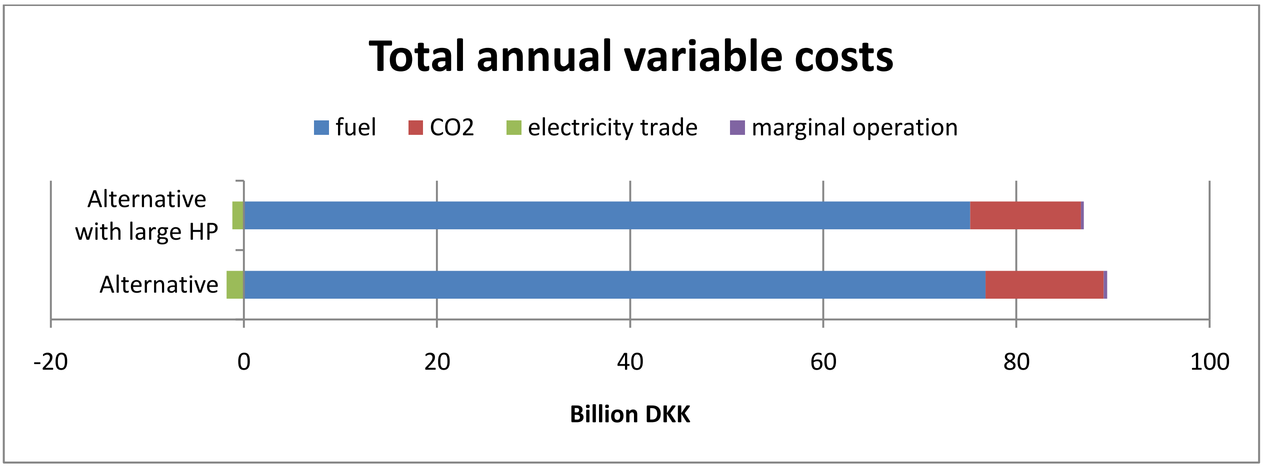

Figure 6.10: Total annual variable costs of the Alternative energy system before and after the implementation of large HPs

An overall **socio-economic profit** of around **1.1 billion DKK per year or 1.2%** is observed even if the **investment** costs as well as the fixed O&M costs of **large heat pumps** are included in the total annual costs of the **Alternative** energy system (see Figure 6.11).

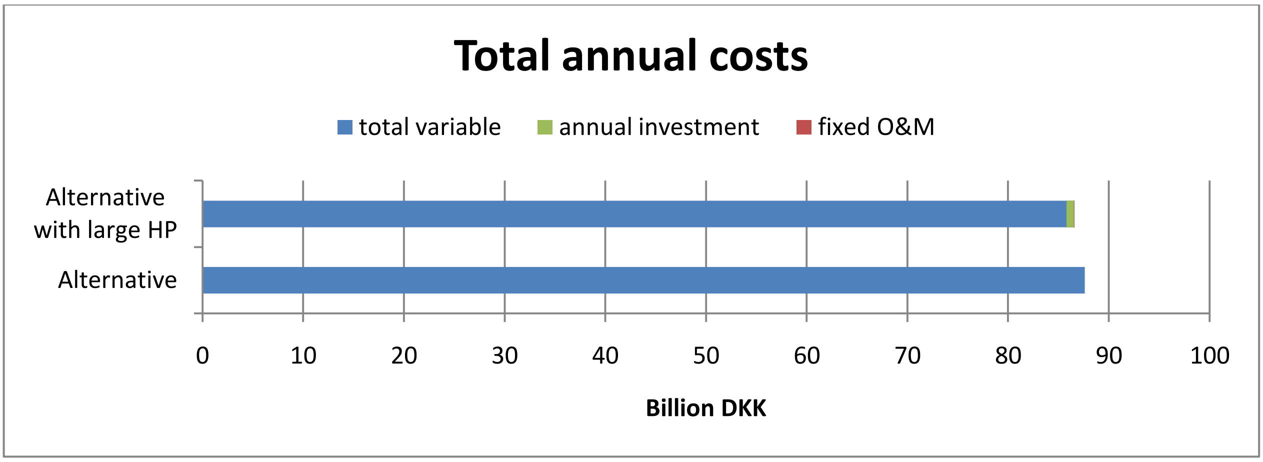

Figure 6.11: Total annual costs of the Alternative energy system before and after the implementation of large HPs

7 Techno-Economic Analysis of Electric Vehicles

In this Chapter the techno-economic effects of introducing Electric Vehicles (EVs) both in the BAU and in the Alternative energy system, in reference to 2030, are analysed. The impacts of converting EVs to Vehicle-to-Grid (V2G) cars on the two energy systems are also investigated with the EnergyPLAN model.

7.1 Inputs and assumptions

In this section all the assumptions that are used to build the scenario which is related to the introduction of electric vehicles in both the BAU and the Alternative energy system are described. Moreover, the way that these assumptions are utilised in order to define the inputs needed to conduct the analysis of EVs with the EnergyPLAN model is presented. The first part of this section refers to the technical data, the second to the economic data while the third to some important considerations that the reader needs to take into account when reading the analysis of EVs.

7.1.1 Technical inputs and assumptions

According to official data from Danish Statistics, the total number of vehicles in Demark is approximately 4 million[1] for 2011, of which around 2.5 million are passenger and commercial freight vehicles (0 – 3.5 tons) (Statistics Denmark n.d.). As it has been assumed in IDA Climate Plan 2050, the number of passenger and commercial freight vehicles will remain the same in 2030 (IDA 2009). This assumption is also adopted in this study, since the fuel distribution in the transport sector that is used in the BAU and the Alternative energy system is founded on the reconstruction of DEA's projection in IDA's Plan.

In the framework of the present study, in order to analyse the effect of electric vehicles in both the BAU and the Alternative energy system, it is assumed that 50% of passenger and commercial freight vehicles (1.25 million) are replaced by EVs. Particularly, it is considered that EVs are substituting diesel cars at 60% and petrol cars at 40%. Based on official actual data from Danish Statistics, it can be observed that there has been a tendency to increase of the share of diesel vehicles in passenger and commercial freight vehicles during the years 1993-2011 (Statistics Denmark n.d.). By following the same increase rate, it can be concluded that the share of diesel and petrol vehicles will be 60% and 40% respectively by 2030. This is probably due to the fact that the size of diesel cars tends to grow smaller and their efficiency higher during the last few years.

An efficiency of 1.5 km/kWh is assumed for conventional diesel and petrol vehicles as proposed in (P. Koustrup 2009) while an efficiency of 6 km/kWh for electric vehicles according to (W. K. Henrik Lund 2008). The two-seated EV Tesla Roadster is supposed to have an efficiency of 9km/kWh (Tesla Motors n.d.). However, an efficiency of 6 km/kWh is considered as more realistic for a four-passenger light-weight sedan, according to tests conducted at the University of Delaware (W. K. Henrik Lund 2008).

In this way it can be estimated that 10.27 TWh/year of diesel and 6.87 TWh/year of petrol can be substituted by 4.28 TWh/year of electricity. For a more detailed description of the calculations concerning the fuel substitution due to the introduction of electric vehicles please see Appendix II. Apart from the

[1] Including: *passenger cars, vans (0 - 3.5 tons)*, buses, lorries (3.5 - 6+ tons), road tractors, trailers, semi-trailers, motorcycles, 45-mopeds, agricultural tractors, caravans, vans and lorries for rescue

electricity demand of electric cars (demand from the grid), which is equal to 4.28 TWh/year, a number of other parameters should be defined for the modelling of EVs in EnergyPLAN.

The power capacity of the grid connection to the vehicle is assumed to be 17.3 kW considering a new house in Denmark[1], as proposed in (P. Koustrup 2009). Such a high power line connection provides operational benefits such as flexibility in the charging of the vehicle and fast recharging e.g. during lunch breaks on trips (W. K. Henrik Lund 2008). Therefore, the total charging capacity that corresponds to 1.25 million EVs is 21,625 MW. In the case of V2G cars the total discharging capacity is considered to be equal to the total charging capacity, such a selection implies that all EVs are converted to V2G cars.

As for the capacity of the battery storage of EVs it is assumed to be up to 22 kWh, which corresponds to a range of 200 km as it is proposed in (P. Koustrup 2009) for a battery electric vehicle in 2025. The total battery storage for 1.25 million vehicles is equal to 27.5 GWh. It should be also noted that the efficiency of both the grid to battery and the battery to grid connection is considered to be 0.9 (P. Koustrup 2009).

Moreover, it is assumed that 70% of the parked EV/V2G cars are connected to the grid (connection share) and that 20% of EV/V2G cars are driving (not parked) during rush hours (driving share). In (W. K. Henrik Lund 2008) it is even suggested that this 20% could be characterised as a conservative assumption, if looking at figures based on actual data, which could slightly underestimate the power capacity of the grid connection (considered by the model as lower than it is actually). (W. K. Henrik Lund 2008)

Another quite important input that should be defined for modelling EVs is the distribution of the transport demand. By setting a certain distribution, the number of EV/V2G cars that are driving and so they are not connected to the grid can be defined. Furthermore, through the distribution profile along with the connection share and the driving share the number of EV/V2G cars available to the electricity system at any given hour can be determined. Another purpose of defining the transport demand is to determine the discharging of the battery storage caused by driving (Lund, EnergyPLAN 2011).

The hour distribution of the transportation demand is based on actual time specific driving data from the US for 2001 (US Department of Transportation 2003). Despite the fact that the transportation pattern in Denmark can be somewhat different from that of the US, in (W. K. Henrik Lund 2008) it is considered better to use actual data than a distribution based on a series of assumptions.

7.1.2 Economic inputs and assumptions

The investment costs for EVs are calculated based on a socio-economic cost of 87,000 DKK/unit excluding the cost of the battery. Therefore, the investment costs for 1.25 million EVs will be up to 108,750 million DKK. On the top of that, O&M costs are calculated equal to 11.2% of the investment in (IDA 2009) based on a battery price of 250 $/kWh for an EV with 200 km range as suggested in (P. Koustrup 2009). The price of battery refers to 2025 and it is in agreement with the recommendations of Danish Energy Authority (Danish Energy Authority 2008). However, it should be stated that this price is only indicative since it is very hard to predict precisely the prices of Li-ion batteries in the future, due to uncertainties related to material consumption and price, production rate, module and battery pack design etc. The lifetime of both the

[1] 3-phased, 400V, 25Amp

electric vehicles and the batteries is considered to be 13 years in reference to the year 2025. (P. Koustrup 2009)

Given that battery Electric Vehicles already have the necessary grid connections for charging, the extra costs as well as the operational adjustments for V2G cars are minimal (Willett Kempton 2004). Actually the extra equipment that should be reflected to the investment costs for V2G refers to the control connection of the car for communication with the system operator and on-board power meters (W. K. Henrik Lund 2008). Particularly the on-board incremental costs for a V2G car comparing to a battery EV are estimated by (Willett Kempton 2004) at up to 400 US$. Therefore, the socio-economic cost of a V2G car is considered to be 89,000 DKK/unit and the total investment costs for introducing 1.25 million V2G cars is 111,250 million DKK.

The installation of charging stations is required both in the case of EVs and V2G cars. Two charging stations are considered for every EV/V2G (one at home one at work) with a cost of 5,000 DKK/unit and a lifetime up to 10 years (P. Koustrup 2009). The total investment for charging stations is estimated to 12,500 million DKK.

The investment for replacing the same amount of vehicles that were replaced by EVs/V2G with new conventional diesel and petrol cars should be also estimated. In this way whenever the total annual costs of each energy system are presented, the figure that arises by considering only the marginal costs of introducing EVs/V2G can be provided. By considering the replacement of 0.75 million diesel cars and 0.5 million petrol cars and based on a cost of 98,000 DKK/unit for conventional diesel vehicles and 77,000 DKK/unit for petrol vehicles a total investment of 112,000 million DKK is required (Danish Energy Authority 2008). With a lifetime of 13 years for conventional cars as proposed in (P. Koustrup 2009) and given that the interest rate is 6% the above mentioned total investment corresponds to annual investment costs of 12,652 million DKK per year. The O&M costs for conventional cars considered to be up to 7.12% of the investment costs (weighted average for diesel and petrol cars based on data retrieved from (P. Koustrup 2009)). Therefore, the annual fixed O&M costs are estimated up to 7,974 million DKK per year. As a consequence the total annual costs for replacing 1.25 million existing conventional vehicles with new conventional vehicles is equal to **20,626 million DKK per year**.

7.1.3 Other considerations about EVs/V2G cars

A smart way of charging has been selected for battery electric vehicles. This means that the model is using the battery storage of EVs in order to achieve lower prices for the electricity that they consume comparing to the price that it would get if it was following a fixed electricity demand as determined by a fixed charging profile. In this way, the model can meet the electricity demand of EVs while aiming at minimising the costs of buying electricity. Furthermore, in the case of V2G, the battery storage is utilised so that considering the external market prices the profit from buying and selling electricity to the grid is optimised.

After introducing EVs/V2G and optimising the operation of both the BAU and the Alternative energy system without setting any limitations in the charging of EVs/V2G, it is observed that the specified electricity demand for EVs/V2G can not be covered by the available power plant capacity in combination with the available import capacity. If the charging of EVs/V2G is limited so that it can not exceed the sum of power plant capacity and transmission line capacity reduced by the rest of the electricity demands, the problem is solved. This is achieved by changing the way that the vehicles are charging since the model takes into account the PP and import capacity that is available at any hour when the limitation is set. As a result, during an hour that the model was selecting to charge the vehicle at a certain level without having any limitation, by setting the limitation the vehicle is now charged at a higher level if the available PP/import capacity is enough to do so. This means that by selecting to set the limitation the charging of EVs/V2G is not done on the optimal way from an economic perspective. On the one hand the costs related to the electricity trade are higher when the limitation is applied on the other hand the impact on the total annual costs is not significant and what is more important the PP/import capacity problem is solved. Otherwise the option of investing in new power plant and/or import capacity needs to be considered in order to face the challenge. However, according to the outputs of the model this option does not seem to be advantageous. Indicatively, the existing power plant capacity should be increased by approximately 7000 MW in order to be enough to cover the electricity demand for EVs/V2G. Adding 7000 MW in central power plants (comparing to 8552 MW that already exist) requires an investment up to 56,000 million DKK (based on a cost of 8 million DKK/MW as it is proposed in (IDA 2009)). Considering 1.25 million vehicles, this investment is equal to 44,800 DKK per car. Moreover, such an investment would add 5,188 million DKK in the total annual costs of the Alternative energy system, which has total annual costs of 87,614 million DKK. In contrast, by selecting to set limitations to the operation of EVs/V2G, there is not a high impact on the system in terms of total annual costs, total fuel consumption, total CO_2, and Critical Excess Electricity Production. Consequently, the option of limiting the operation of EVs/V2G is selected to deal with the lack of the required power plant/import capacity.

Something more that is worth discussing in the framework of the analyses of V2G systems is their contribution to the stabilisation of the grid. As it is stated in (Jayakrishnan R. Pillai 2011), V2G systems are able to provide major grid ancillary services in the long term. This means that a stabilisation share should be defined for V2G systems in EnergyPLAN. However, in the present study, there is no requirement for a minimum production coming from stabilising units. The stabilisation of the grid both in the BAU and the Alternative energy system is considered to be ensured by the large CHP plants, which are always producing above a technical minimum production that has been set. Therefore, even if a stabilisation share is allocated to V2G systems it would not change anything in the operation of the system. Consequently, in this study V2G systems are not used for providing stabilisation to the grid.

In connection with the type of services that V2G provides to the system, an issue about whether there is a need to set a degradation cost due to extra use for discharging arises. Such a cost represents the cost related to the degradation of the battery because of the V2G operation. The degradation cost for a battery vehicle is determined by the cost of a reinvestment in a new battery (incl. replacement labour) split out over the lifetime of the battery expressed in produced energy for a certain cycling regime. Therefore, the lifetime of the battery in a degradation cost calculation is determined by the lifetime of the battery in cycles at a specific depth-of-discharge (DoD) and the total energy storage of the battery. (Willett Kempton 2004) After that, it is considered as necessary to investigate the frequency and the depth of discharges for both the BAU and the Alternative energy system. In this way the level of the degradation cost can be identified.

For the needs of this analysis the BAU and the Alternative energy system are optimised without setting any degradation cost due to V2G discharging. By looking at the hourly values expressing the amount of electricity supplied from the V2G cars to the grid (V2G discharge), it can be observed that V2G are discharging for 32 and 34 hours out of 8784 per year for the BAU and the Alternative energy system respectively. Whenever V2G are discharging, this happens step-by-step for 2 to 4 hours continuously starting with a low level of discharge. The level of discharge for the next hours is increasing until the battery storage is completely empty.

Two important conclusions can be inferred from the above mentioned observations. The first one is that the batteries of V2G cars are seldom used for discharging in the case of both the BAU and the Alternative energy system. The second one is that when a discharge occurs then the battery is emptied entirely, the reason why this happens is explained at a later stage.

After all it could be argued that the actual number of hours that the batteries of V2G cars are discharging, both in the case of the BAU and the Alternative energy system, is really low so that there is no need to define a degradation cost. This is because such an utilisation of the battery due to V2G discharge can not excuse a reinvestment in a new battery. In other words, it is considered that the lifetime of the battery is not reduced due to V2G degradation significantly.

Of course an analysis of the way that batteries in V2G systems are used for load balancing would be quite interesting to conduct. However, for the needs of this project it was considered as sufficient to make a screening of the certain operation of V2G systems under the conditions that apply to the BAU and the Alternative energy system.

7.2 EVs and V2G in the BAU energy system

The introduction of electric vehicles in the BAU energy system has caused on the one hand a decrease in the oil consumption (petrol and diesel) of the transportation sector while on the other hand an increase of the electricity demand of the system. Given that a smart way of charging has been selected for EVs, the model is going to regulate the operation of the energy generating units of the system so that the annual electricity demand required by EVs can be met and the socio-economic costs of buying electricity are minimised, at the same time. In the framework of this procedure, a balance production is identified for each unit of the system, in which the resulting market price becomes equal to the marginal production price (Lund, EnergyPLAN 2011). It should be also reminded that the charging of EVs is limited by available power plant and import capacity.

The annual electricity demand that is introduced into the system due to EVs is equal to 4.28 TWh. After the optimisation of the system, a share of this increase in the electricity demand is met by condensing power plants (2.6 TWh) while the rest is covered by increasing the imports and slightly decreasing the exports of electricity, comparing to the case of the BAU energy system without any EVs.

The increase in the electricity production of condensing power plants stimulates a quite significant increase in the coal consumption and a minor increase in the NG consumption. Hence, the total annual fuel consumption of power plants becomes higher. However, this is counterbalanced by the drop of the oil consumption in the transportation sector. As a result the **total annual fuel consumption of the system is reduced by 4.7% or 11 TWh** out of 234 TWh, which is the total annual fuel consumption of the BAU energy system before the introduction of EVs (see Figure 7.1). It is also observed that the share of renewable energy in the primary energy is increased by 1.5%, given that the amount of wind as a resource remains the same before and after the introduction of EVs. Moreover, the resulting reduction in the consumption of fossil fuels in the system leads to **5.8% or 2.52 million tons less CO_2** emissions in the BAU energy system after the introduction of EVs (see Figure 7.2).

Concerning the effect of EVs in the annual costs of the system, it is observed that the fuel costs are subjected to a major reduction which is mainly related to diesel and petrol costs. As it is expected the total CO_2 emissions costs are also lower after the introduction of EVs. In contrary, the marginal operation costs increase, mostly because of the operation of condensing power plants. Moreover, the costs related to electricity trading in the external market increase. This is linked with the higher imports and lower exports that EVs have caused, which affect also the electricity price on the market. All in all, **annual socio-economic benefits of approx. 10.5 billion DKK out of 93.4 billion DKK (11.2% reduction)** are observed when considering the **total variable costs** of the system before and after the replacement of 1.25 million diesel and petrol cars with electric vehicles (see Figure 7.3).

This figure is reversed by taking into account the fixed O&M costs as well as the annual investment costs that correspond to 1.25 million EVs. Actually, the **total annual costs** of the system **increase by 17%** leading to **annual socio-economic loss of 15.7 billion DKK out of 93.4 billion DKK** (see Figure 7.4).

Assuming that the cars which are replaced by electric vehicles would have anyway to be replaced by new conventional petrol and diesel cars the total annual costs of the system are lower comparing to the reference situation (before EVs). Therefore, if only the marginal fixed O&M and annual investment costs of electric vehicles are considered, the **total annual costs** of the BAU system **decrease by 4.3%** and the annual **socio-economic benefits** are estimated around **4.94 billion DKK** (see Figure 7.5).

EVs operating as V2G systems

In this part of the analysis it is considered that all the electric vehicles that are introduced to the BAU energy system have also the ability of sending electricity back to the grid (discharging) and so they are able to operate as V2G cars. In this case, the model aims at optimising the economic profit from buying and selling electricity to the grid by taking into account the external market prices. (Lund, EnergyPLAN 2011) It should be also considered that the charging is limited by the available power plant and import capacity.

Similarly with EVs, when V2G cars are introduced in the BAU energy system they cause an increase in the electricity demand. This increase is higher than the one stimulated by EVs. The reason is that V2G charge more comparing to EVs on an annual basis (4.46 TWh and 4.28 TWh respectively), so that they can take advantage of their ability to discharge to the grid and maximise in this way the profit from buying and selling electricity to the grid. In general the different operation of V2G cars comparing to EVs requires a different optimisation of the units of the system. Particularly, comparing to the BAU energy system, in the case of V2G the increase in the electricity demand, due to the charging of V2G, stimulates an increase in the electricity production of condensing power plants. In addition to this, the imports of electricity become higher while the exports a bit lower comparing to the BAU energy system before V2G. Comparing to the case of EVs, the charging of V2G is higher and even if the discharge of V2G is considered, the electricity demand becomes a bit higher. In the case of V2G, the increased electricity demand is covered at a higher rate by condensing power plants and CHP plants than by imports, comparing to the case of EVs.

These changes after the introduction of **V2G** cars are reflected to the **total annual fuel consumption** of the system which becomes **9 TWh or 3.9% lower comparing to the BAU energy system without any EVs/V2G** but a bit higher comparing to the case of EVs (see Figure 7.1).

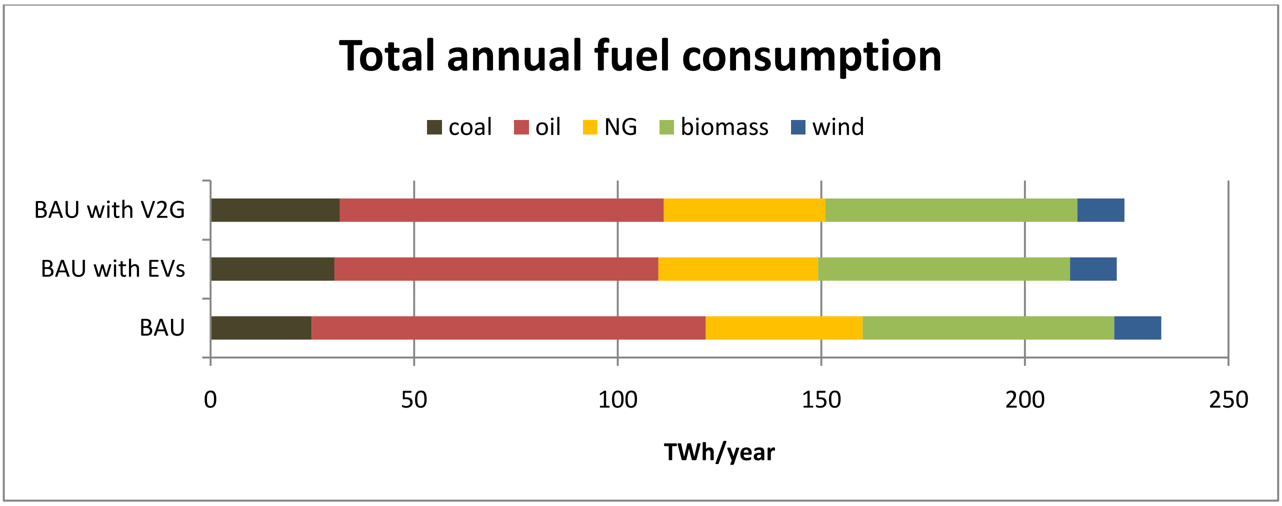

Figure 7.1: Total annual fuel consumption of BAU energy system after introducing EVs and V2G cars

The total annual fuel consumption is lower both in the case of EVs and V2G comparing to the BAU energy system with petrol and diesel cars because of the significant reduction in the oil consumption. This reduction counterbalances the increase in the coal and NG consumed in condensing power plants and CHP plants for the production of the electricity required by EVs/V2G cars. The total annual fuel consumption in the case of V2G cars appears to be 1.84 TWh or 0.8% higher comparing to the case of EVs according to Figure 7.1. This happens because V2G systems are attempting to maximise the profit from buying and selling electricity to the grid which could result in storing electricity (charging) produced in coal-fired and NG-fired condensing power plants and CHP plants.

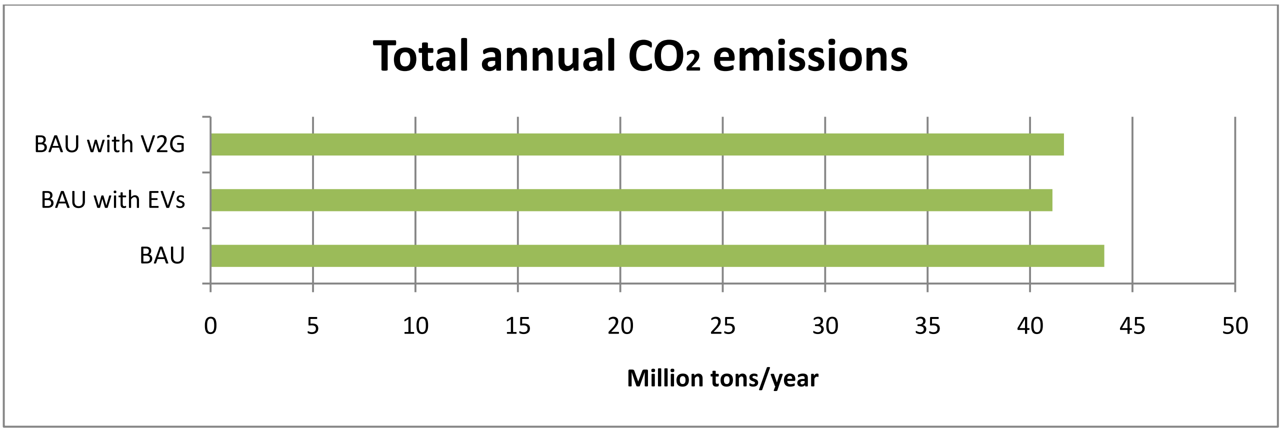

Figure 7.2: Total annual CO_2 emissions of BAU energy system after introducing EVs and V2G cars

The changes caused by the introduction of EVs and V2G cars in the total annual fuel consumption are reflected in the total annual CO_2 emissions of the BAU energy system. Both **EVs and V2G cars** lead to **2.52 Mt/year or 5.8% and 1.96 Mt/year or 4.5% lower CO_2 emissions** respectively, comparing to the **BAU** energy system **with petrol and diesel cars**. In the comparison between V2G and EVs the former appear to result in higher CO_2 emissions due to the higher consumption of fossil fuels in condensing power plants and CHP plants (see Figure 7.2).

The **total annual variable costs** of the BAU energy system appears to be **lower by 11.2% and 11% after the replacement of petrol and diesel cars with EVs and V2G cars respectively**. This reduction in the total variable costs of the system mainly stems from the reduction in fuel costs and in CO_2 costs stimulated by EVs/V2G cars (see Figure 7.3). As for the comparison of EVs and V2G systems, it seems that the former lead to slightly lower total annual variable costs. Although V2G systems achieve to reduce the electricity trade costs compared to EVs, the fuel and so the CO_2 costs as well as the marginal operation costs are higher compared to EVs. This is due to the increased electricity production of condensing power plants stimulated by V2G systems, as it was explained above.

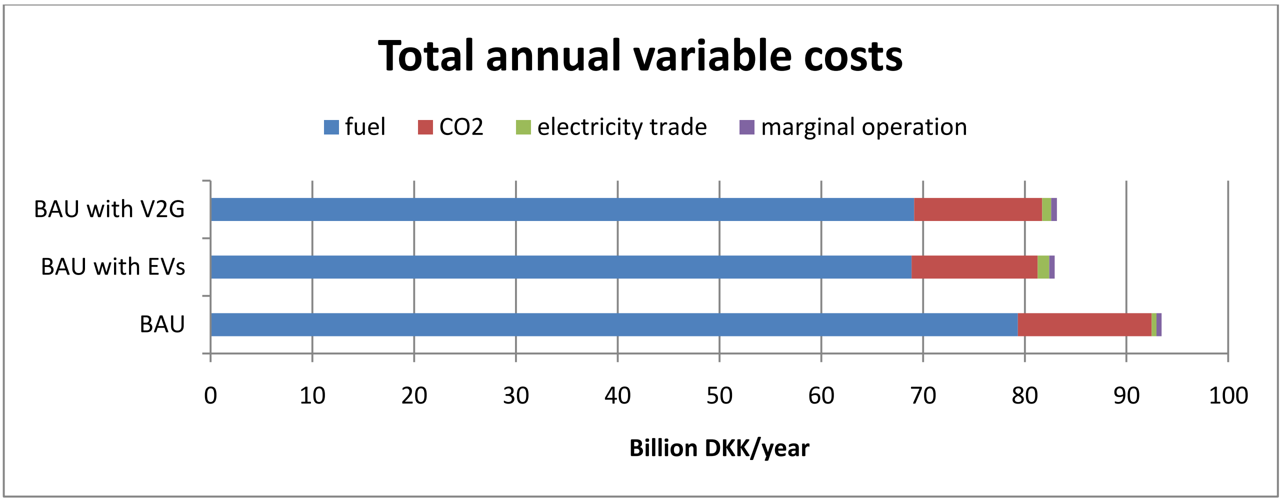

Figure 7.3: Total annual variable costs of BAU energy system after introducing EVs and V2G cars

If the annual investment costs as well as the corresponding fixed O&M costs of EVs/V2G are included, then the **total annual costs** of the BAU energy system become **higher by 15.7 billion DKK or 16.8% and 16.4 billion DKK or 17.6% after the introduction of EVs and V2G respectively** (see Figure 7.4). The annual investment costs as well as the fixed O&M costs of V2G are higher than these of EVs. In addition to this, as it was explained before, the total variable costs in the case of V2G are also higher compared to the case of EVs. As a consequence, the total annual costs of the BAU energy system with V2G are higher than that with EVs.

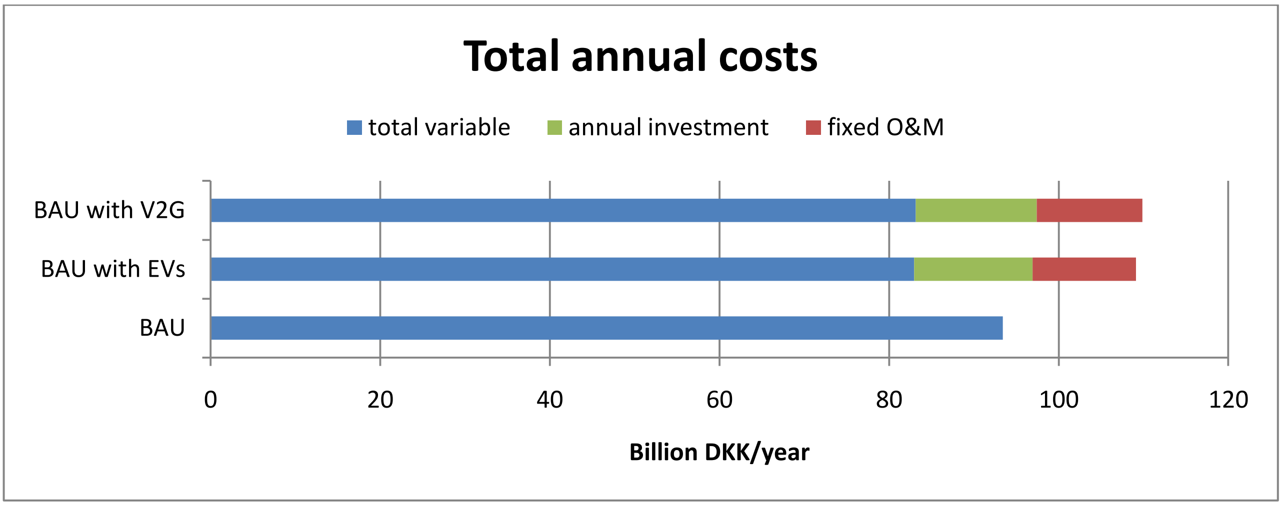

Figure 7.4: Total annual costs of BAU energy system after introducing EVs and V2G cars

In the case of BAU energy system before the introduction of EVs/V2G the total annual variable costs are identical with the total annual costs, since no investment has been included. If it is assumed that the same number of cars that is replaced by EVs/V2G cars is replaced by new conventional diesel and petrol cars then the situation in terms of total annual costs changes (see Figure7.5). Now the total annual costs of the BAU energy system after the introduction of EVs/V2G cars appear to decrease. In other words, if 1.25 million conventional cars are replaced by **EVs instead of new conventional cars** in the BAU energy system, there is a **socio-economic profit** of approximately **4.94 billion DKK per year** corresponding to **4.3% reduction** in terms of total annual costs. In case that the **conventional cars are replaced by V2G cars instead of new conventional cars then the socio-economic profit** is around **4.2 billion DKK per year or 3.7%**.

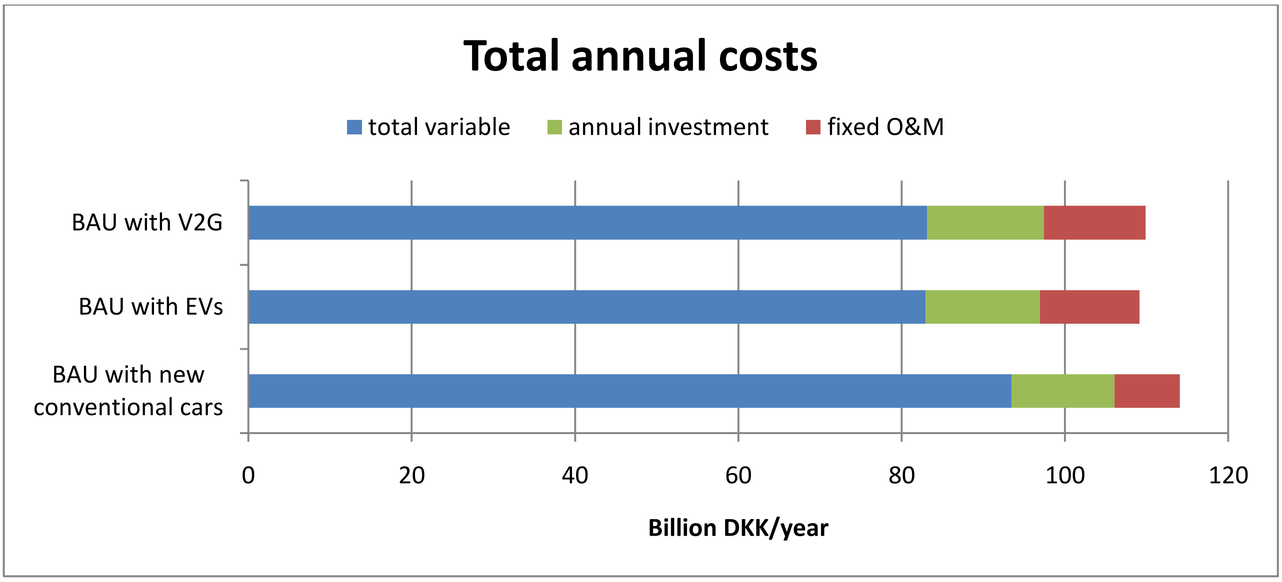

Figure 7.5: Total annual costs of BAU energy system after introducing new conventional cars, EVs and V2G cars

Another quite important parameter of the BAU energy system that is worth mentioning how it is affected by the introduction of EVs and V2G cars is the Critical Excess Electricity Production (CEEP) of the system. It should be reminded that in the BAU energy system there is no CEEP initially. The situation is the same after the introduction of EVs to the system but this is not the case with V2G cars in the system. Actually, the annual CEEP is equal to 0.032 TWh when V2G are introduced. An attempt to explain the way that this critical excess electricity is produced will be made by analysing the operation of V2G systems under a Market-Economic optimisation strategy.

As a starting point, V2G cars are charging according to a fixed charging profile so that the hourly transport demand can be met. Apart from that, during hours when the electricity required by the V2G cars according to the fixed profile is low and the electricity price in the Nord Pool market is equal to zero, V2G cars that are available to the electric system are charging so that they can store cheap electricity in their batteries. The batteries can be discharged later either for transport purposes or for selling electricity to the market if the price is advantageous. In case that the battery should be discharged in order to meet the electricity demand for transport then this happens (at high depth of discharge) until the battery is empty. In case that there is still some energy left in the battery, after the electricity demand for transport has been covered, this maybe discharged to the grid so that profit is made through the export of electricity. However, in this last case there is a possibility of having critical excess electricity production. This can happen if the total electricity that can be potentially exported (incl. the electricity discharged to the grid from V2G) is higher than the electricity that it is actually exportable (determined by the capacity of the transmission lines). This is the explanation why there is some CEEP in the BAU energy system when V2G are introduced while following a Market-Economic optimisation strategy. Although the discharging of V2G cars is limited (V2G discharge for 32 hours over a year) it is enough to create 0.032 TWh/year of CEEP in the BAU energy system. The maximisation of the profit is the main priority and the model attempts to achieve it compromising the production of some excess electricity.

All in all, the batteries of V2G cars are charged so that they can meet the transport demand, which follows a fixed profile, but they are also charged when the market price is low so that they can store cheap electricity, which can be later discharged to the grid at a high price. In this way V2G cars act as electricity storage for the grid and contribute to the optimisation of the profit from buying and selling electricity from and to the grid.

7.3 EVs and V2G in the Alternative energy system

The operation of electric vehicles in the Alternative energy system has some similarities with that in the BAU energy system. Here as well the electricity production of condensing power plants (PP) and CHP plants increases so that the electricity required by EVs can be met. However, the difference in the Alternative energy system is that the extra electricity needed is produced in biomass-fired power plants. In the case of the BAU energy system this electricity was produced in coal/NG-fired power plants since there were no more biomass resources available to be consumed in condensing PP. This is not the case in the Alternative energy system in which the increased electricity production of wind turbines contributes to a more rational use of biomass resources. Therefore, in the Alternative system it is possible that the extra electricity demand can be met by consuming more biomass in PP, given that the resulting biomass consumption does not exceed the share of biomass that was initially set as fixed in the fuel distribution of PP. It should also be noted that the imported electricity appears to be increased after the introduction of EVs while the exports of electricity become lower, as in the case of the BAU energy system.

The above mentioned changes are also reflected in the **total fuel consumption** of the **Alternative system with EVs**, which is **reduced by 13.21 TWh/year or 5.6%** compared to the system with petrol and diesel cars (see Figure 7.6). This reduction is mainly due to the reduction in the oil consumption in the transportation sector which counterbalances the increase in the biomass and coal consumption. A significant **reduction** equal to **4.28 Mt/year or 10.6%** can be observed in the **CO_2 emissions of the Alternative energy system with EVs** which is in accordance with the fuel balance as described above (see Figure 7.7).

Electric Vehicles are charging primarily in order to cover the electricity required for transport. In addition to this, EVs are charging during hours when the price of electricity is cheap so that they can minimise the costs of the system. When the charging takes place during hours in which there was some CEEP in the Alternative energy system before the introduction of EVs, they can be charged by consuming this critical excess electricity. In this way, the total annual CEEP of the Alternative energy system is reduced substantially due to the operation of EVs. Particularly, the **CEEP of the Alternative energy system** before the introduction of EVs is 1.88 TWh/year and it reduces down to 1 TWh/year which corresponds to a **reduction of 0.88 TWh or 47% after the introduction of EVs** (see Figure 7.8).

As for the effect of EVs to the costs of the Alternative system, as it is expected, both the fuel and the CO_2 emissions costs are reduced. In contrary, the net revenue from the electricity trade appears to be reduced in the Alternative system with EVs. In the Alternative energy system the high electricity production of wind turbines leads to quite high exports of electricity with a relatively low average price. When EVs are introduced in the Alternative system, the electricity demand becomes higher and so the exports of electricity reduce by 1.8 TWh and the imports increase by 0.56 TWh. This leads to a proportional increase in both the average price of exported electricity and in the average price of imported electricity. As a result, both the total annual cost of imports and the total annual profit from exports increase. However, the extra profit is not enough to cover the extra costs that occur after the introduction of EVs. Consequently, EVs lead to a reduction of the net profit from the electricity trade in the Alternative energy system. All in all the reduction in fuel and CO_2 emissions costs counterbalance the loss in the net profit from the trade of electricity. Therefore, the **total annual variable costs** appear to be **lower by 11.6 billion DKK or 13% with EVs** in the **Alternative** system (see Figure 7.9).

By **including the investment** as well as the fixed O&M costs of EVs, the **total annual costs** of the system after the introduction of EVs are much **higher** (**16.6%**) than they were before, leading to a **socio-economic loss of 14.6 billion DKK per year** (see Figure 7.10).

In case that an investment in new conventional cars is considered in the Alternative energy system, then the total annual costs of the system become higher than they are when investing in EVs. Therefore, it can be stated that if existing conventional cars are replaced by **EVs instead of new conventional cars** an **annual socio-economic profit of 6 billion DKK or 5.6%** is created to the **Alternative** energy system (see Figure 7.11).

EVs operating as V2G systems

As it was also mentioned when the analysis of V2G systems in the BAU energy system was conducted, the model optimises the system in order to meet the electricity demand of V2G cars while it seeks to maximise the profit from the electricity trade through controlling the charging and discharging of V2G systems.

The electricity required by V2G is mainly met by biomass-fired condensing power plants and CHP plants run on coal and NG. In addition, the imports of electricity are increased while the exports are reduced in order to meet the increased electricity demand due to V2G charging.

The fuel consumption for the production of electricity is higher after the introduction of V2G cars but it is counterbalanced by the reduction of the oil consumed in the transport sector. As a consequence, the **total annual fuel consumption** of the **Alternative** system after the introduction of **V2G cars** is **lower by 12 TWh or 5%**, as it also happens with EVs (see Figure 7.6).

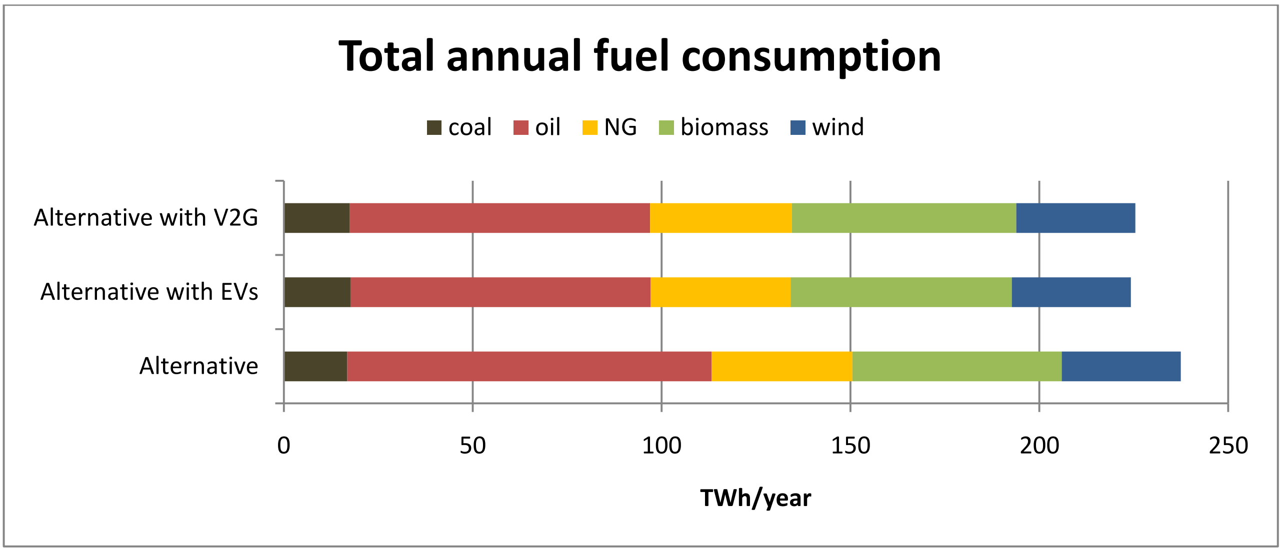

Figure 7.6: Total annual fuel consumption of Alternative energy system per type of fuel after introducing EVs and V2G cars

The changes in the fuel consumption of the Alternative system affect also the CO_2 emissions of the system. The CO_2 emissions of the Alternative system are almost the same in the case of EVs (36.25 Mt/year) and in the case of V2G cars (36.29 Mt/year) and significantly lower comparing to the Alternative system before EVs/V2G (40.53 Mt/year). The **decrease** in the **total annual CO_2 emissions** of the **Alternative** energy system is equal to **4.24 Mt or 10.5%** after replacing conventional cars with **V2G cars** (see Figure 7.7)

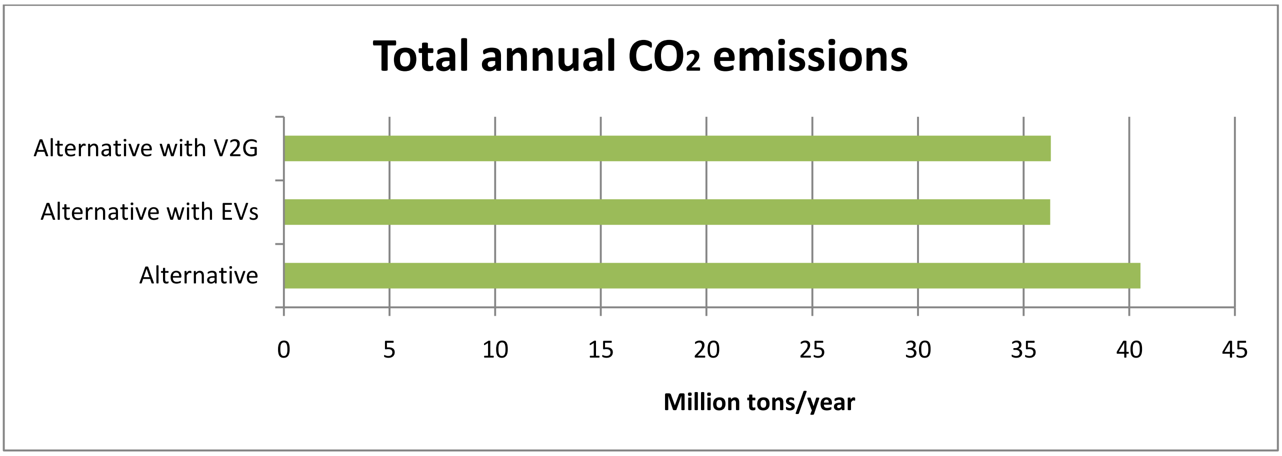

Figure 7.7: Total annual CO_2 emissions of Alternative energy system after introducing EVs and V2G cars

The **CEEP** of the **Alternative** energy system is reduced by **0.45 TWh/year or 24%** after the introduction of **V2G** cars to the system. This is mainly because V2G cars are charged during hours with low electricity prices when the electricity production coming from wind is usually high and critical excess electricity is produced. In this way V2G cars contribute to the integration of wind power. However, the reduction in CEEP in the case of V2G cars is less than the reduction achieved in the case of EVs. This happens because, as it was also explained for the BAU energy system, V2G cars are discharging electricity to the grid aiming at selling electricity to the market at a high price even though they may contribute to the production of critical excess electricity. Although the discharging of V2G cars in the Alternative energy system is limited and happens during 34 hours per year, it is enough to create some CEEP and thus lead to a lower reduction compared to EVs (see Figure 7.8).

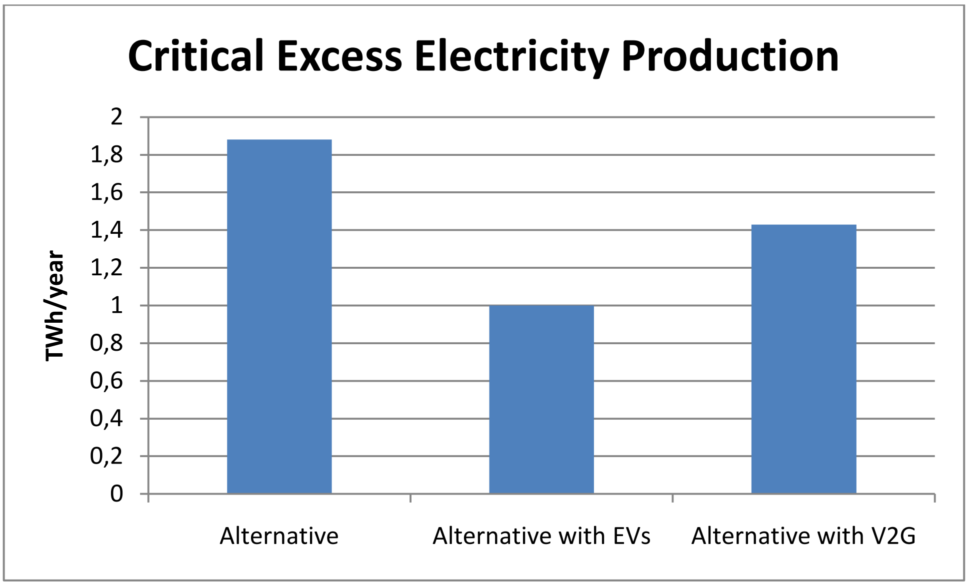

Figure 7.8: CEEP in the Alternative energy system before and after the introduction of EVs and V2G cars

Comparing EVs with V2G in the Alternative energy system, V2G systems charge more in order to store electricity that can be later discharged to the grid aiming at optimising the profit from the electricity trade. Also in the case of V2G cars, the exports of electricity are higher than in the case of EVs. This reduces the average price of the exported electricity which is already relatively low in the Alternative energy system (due to the already high exports stimulated by the high electricity production of wind turbines). Therefore, V2G systems maybe achieve to maximise their profit at an hourly basis but the overall income from exports decreases and so does the profit from electricity trade compared to the case of EVs.

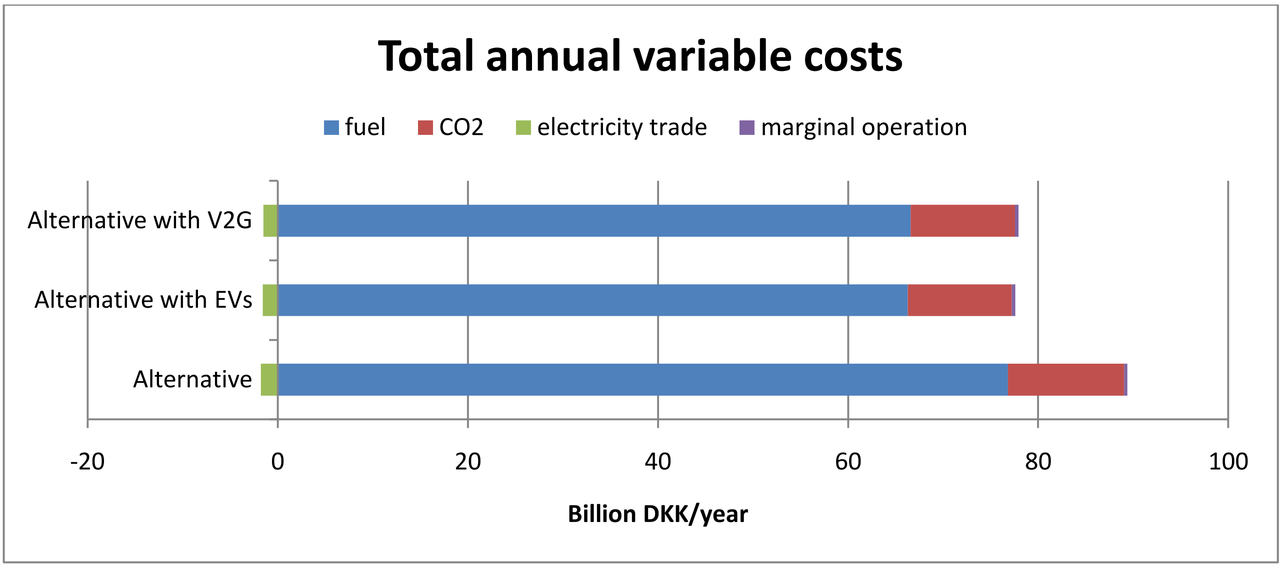

Figure 7.9: Total annual variable costs of the Alternative energy system after introducing EVs and V2G cars

As for the effect of V2G systems to the other costs of the Alternative energy system, it can be observed that both the fuel costs and the CO_2 emissions costs are quite lower with V2G in the energy system. However, they are slightly higher comparing to the case of EVs mainly due to the increased charging of V2G systems. As a result, the **total annual variable costs** of the **Alternative** energy system become lower after the introduction of **V2G** cars leading to a **socio-economic profit of 11.2 billion DKK per year or 12.8%** (see Figure 7.9).

If the annual **investment costs** and the fixed O&M costs that correspond to EVs and V2G are considered then the total annual costs of the **Alternative** system are higher **after the introduction of EVs and V2G** cars leading to **socio-economic loss** of **14.6 billion DKK or 16.6% and 15.5 billion DKK or 17.7% respectively** (see Figure 7.10). As it can be seen in Figure 7.10 the total annual costs in the case of V2G are higher compared to the case of EVs, since both the annual investment costs and so the fixed O&M costs as well as the total variable costs are a bit higher.

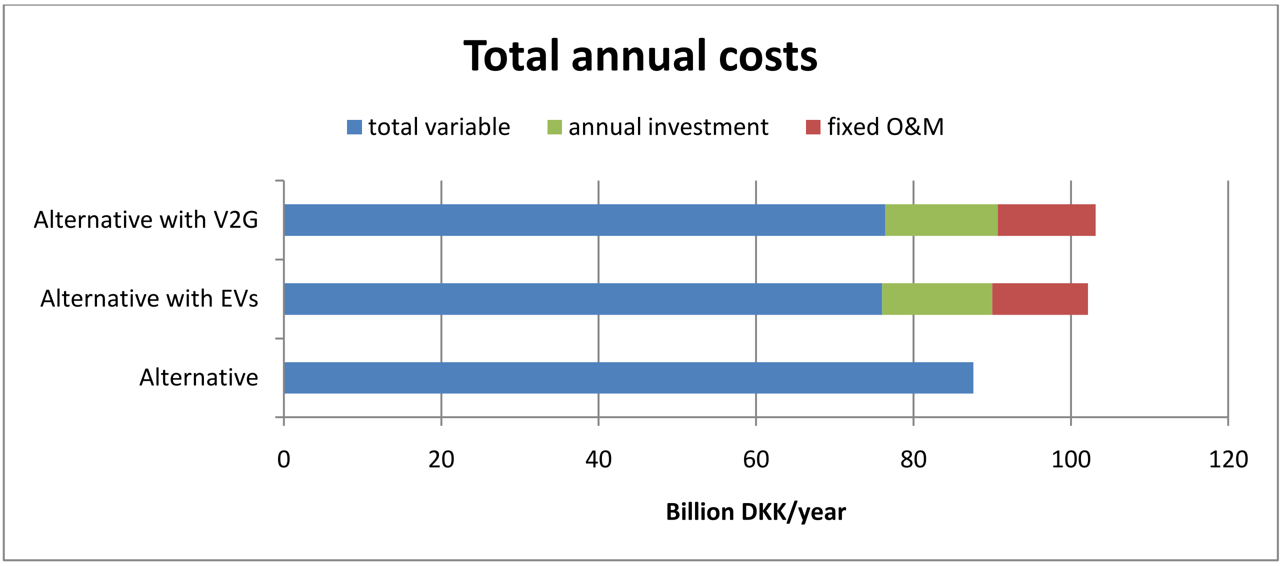

Figure 7.10: Total annual costs of the Alternative energy system after introducing EVs and V2G cars

The total annual costs of the Alternative energy system become higher if an investment in new conventional cars is made instead of EVs or V2G cars (see Figure 7.11). In this case it can be stated that both **EVs and V2G** lead to annual **socio-economic profit of 6 billion DKK or 5.6% and 5.1 billion DKK or 4.7% respectively** (see Figure 7.11)

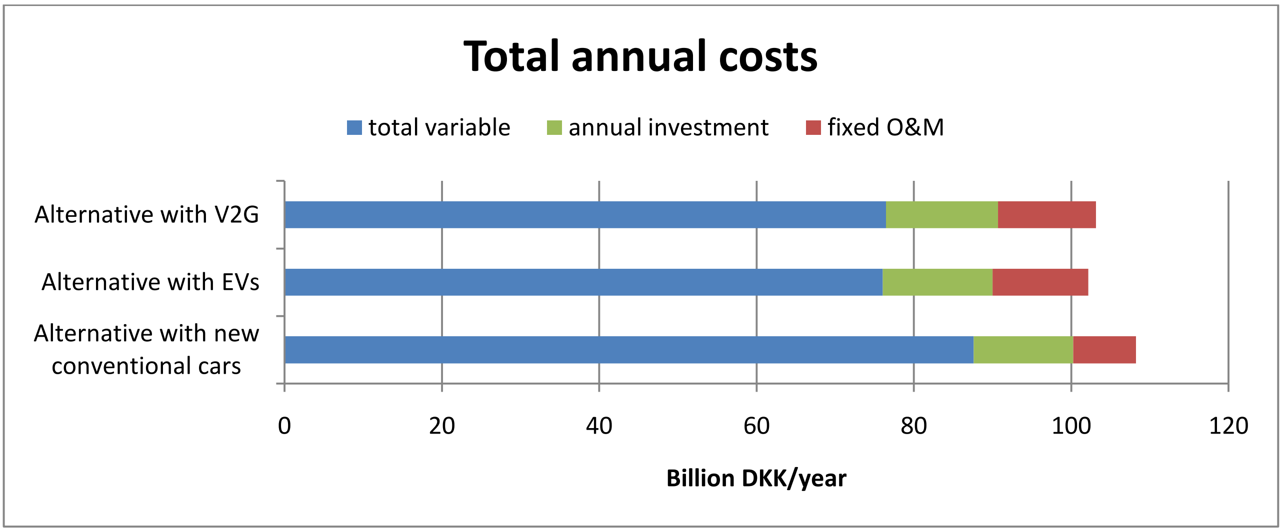

Figure 7.11: Total annual costs of the Alternative energy system after introducing new conventional cars, EVs and V2G cars

The socio-economic savings that can be achieved by introducing EVs and V2G in the Alternative energy system are higher than the savings in the BAU energy system. This is mainly connected with the higher utilisation of biomass in the Alternative system instead of coal and NG which are consumed more in the BAU for covering the electricity demand of EVs/V2G. This leads to lower fuel and CO_2 emissions costs in the Alternative system compared to the BAU. Moreover, in the Alternative system the electricity of wind turbines can be used to charge EVs and V2G cars while in the BAU this electricity is imported. As a consequence better trading can be achieved in the case of the Alternative system. Hence, the socio-economic profit is higher in the Alternative energy system comparing to the BAU system either with EVs or with V2G, given that the investment and the fixed O&M costs are the same in both systems.

8 Conclusions

The conclusions of this project will be drawn at two levels aiming at providing a profound answer to the research question of this project: ***"How can wind power be integrated into the heat and transport sector and what are the technical and socio-economic effects of introducing individual heat pumps, large heat pumps as well as electric vehicles, in reference to the future energy system of Denmark?"***

At the first level, the focus will be on summarising the effects of the technical means studied within the individual heating, the district heating and the transport sector separately. In this way the impacts both to the BAU and the Alternative energy system of the basic technologies that have been analysed (i.e. individual heat pumps, large heat pumps and electric vehicles) along with all the different versions of them (i.e. adding heat storage, V2G option) will be compared.

At the second level, the different groups of technologies will be evaluated on their ability to integrate wind power in terms of fuel consumption, CO_2 emissions, Critical Excess Electricity Production (CEEP) and socio-economic costs.

8.1 Individual heating sector

Having the focus on the individual heating sector, the effects of individual heat pumps with and without the option of heat storage in the BAU and the Alternative energy system are summarised in the following graphs (see Figures 8.1-8.4).

It should be reminded that the existing heat pumps in the two systems are able to cover 16.7% of the total annual individual heat demand (or 189 MW_e) and an expansion of individual heat pumps is considered so that heat pumps can meet 50% of the total annual individual heat demand (or 567 MW_e). As a result the total number of heat pumps becomes equal to 500,000 after the expansion. The same number of heat storage units i.e. 500,000 with a capacity equal to 1 day of average heat demand is used.

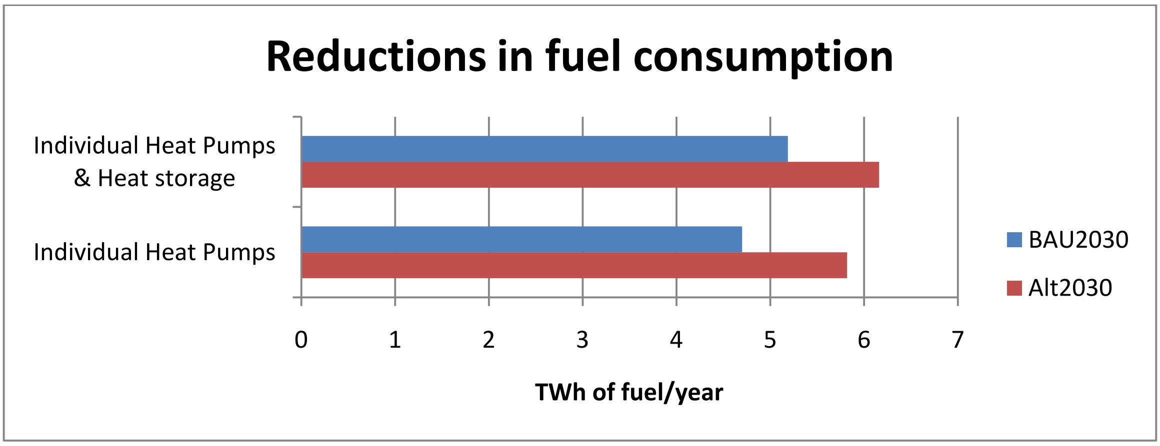

Figure 8.1: Effect of individual heat pumps on the fuel consumption of the future energy system

A reduction of 4.7 TWh or 2% (2.1% excl. RES) can be achieved in the total annual fuel consumption by the expansion of individual heat pumps in the BAU energy system. This reduction can go up to 5.2 TWh or 2.2% (2.3% excl. RES) if there is an option for storing the heat produced by heat pumps.

As for the Alternative system, 5.8 TWh or 2.5% (2.8%) of fuel can be saved by expanding individual heat pumps and 6.16 TWh of fuel or 2.6% (3% excl. RES) by adding heat storages. Therefore, the effect of both the expansion of individual heat pumps and the addition of heat storage on the top of the expansion is stronger in an energy system with higher wind penetration such as the Alternative 2030.

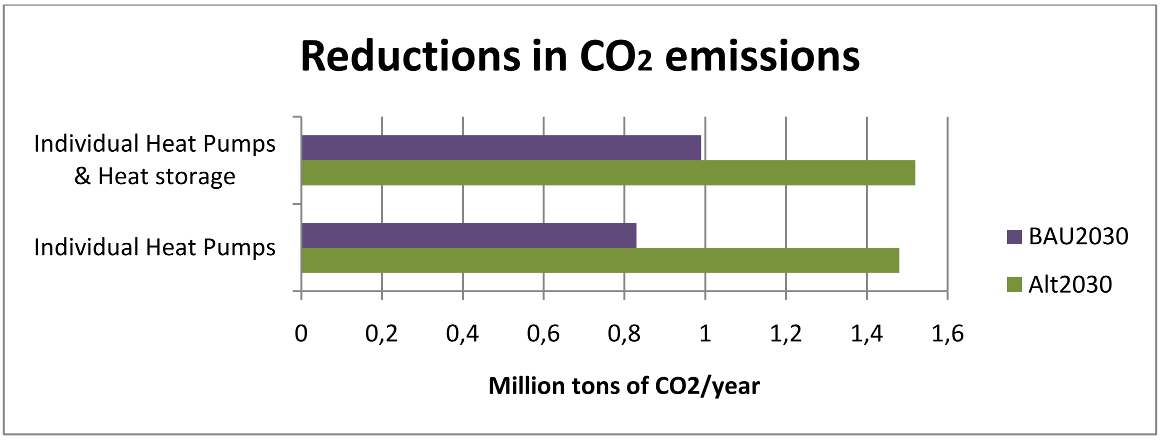

Figure 8.2: Effect of individual heat pumps on the CO_2 emissions of the future energy system

Similarly with the effect of individual heat pumps on the fuel consumption, the 0.83 Mt or 1.9% of CO_2 emissions that can be saved annually by expanding individual heat pumps can be 1 Mt or 2.3% if heat storages are also introduced into the BAU energy system. These CO_2 savings become equal to 1.5 Mt or 3.7% and 1.52 Mt or 3.8% in the case of the Alternative energy system. This means that individual heat pumps can contribute to the reduction of the CO_2 emissions of the future energy system more effectively when they are combined with heat storages and even more if they are installed in a system with substantially increased wind penetration.

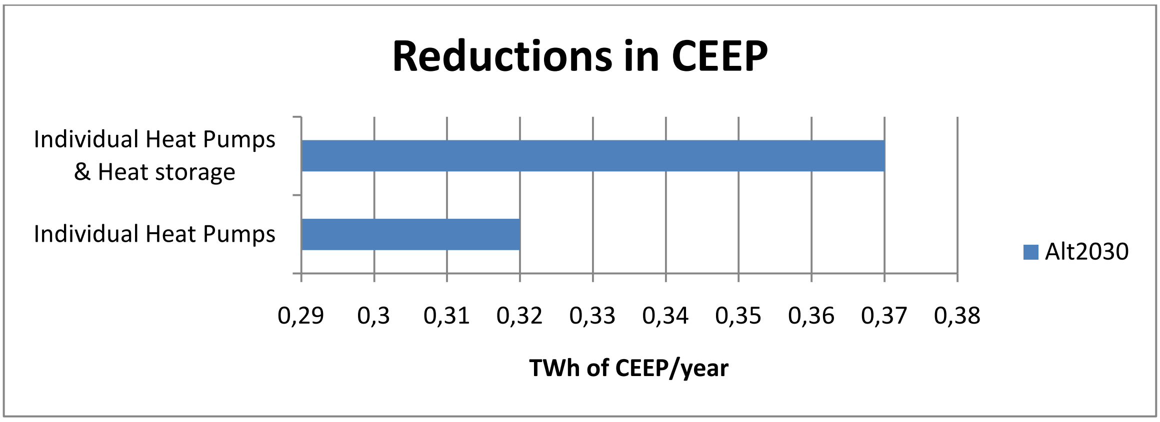

Figure 8.3: Effect of individual heat pumps on the critical excess electricity production of the future energy system

The effect of individual heat pumps on the critical excess electricity production of the future energy system can be identified only in the case of the Alternative energy system where the high wind power leads to the production of excess electricity that can not be exported. By expanding heat pumps in the individual heating sector the annual CEEP can be reduced by 0.32 TWh which corresponds to 17%. The addition of heat storages operating in conjunction with individual heat pumps can further reduce the CEEP by 0.37 TWh or almost 20% in total.

In terms of costs, the expansion of individual heat pumps contributes to the reduction of the total annual socio-economic costs of the BAU energy system by 0.5%, leading to an annual socio-economic profit of 500 million DKK. The addition of heat storages reduces the total variable costs of the BAU system but this reduction can not compensate for the investment costs of heat storages. As a result, there is an annual socio-economic loss of 140 million DKK or 0.15% for the BAU energy system.

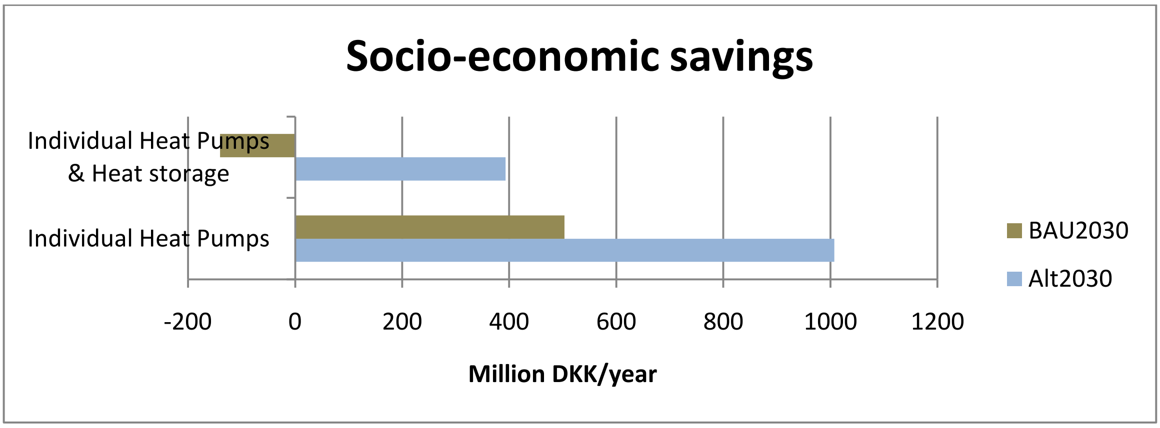

Figure 8.4: Effect of individual heat pumps on the total socio-economic costs of the future energy system

In a future energy system with higher wind power than in the BAU, as it is in the Alternative system, the expansion of individual heat pumps is really beneficial for the economics of the system since a socio-economic profit of 1 billion DKK or 1.1% is achieved. This means that the profit is doubled since heat pumps can consume relatively cheap electricity, which is possible to be produced in a system with high wind penetration. Therefore, even when the extra investment costs of heat storages are considered there is a socio-economic profit of 393 million DKK or 0.45% for the Alternative energy system.

Overall assessment

The expansion of individual heat pumps has a positive effect both on the fuel consumption and the CO_2 emissions of the future energy system, in reference to 2030. This positive effect becomes more intense when heat pumps can store the heat that they produce and even more intense if a system with significantly higher wind penetration is considered. Quite important is also the contribution of individual heat pumps to the decrease of the critical excess electricity that maybe produced in the future energy system if the wind capacity is increased significantly (as happens in the case of the Alternative 2030 energy system). Especially if there is an option of storing the produced heat, then the CEEP can be further reduced.

Concerning the socio-economic costs of the future energy system, an expansion of individual heat pumps would create a socio-economic profit to the system, which can be higher if the wind penetration is higher. As for the option of storing the heat produced on heat pumps, it seems that it is not feasible to add heat storages to the system since when the investment costs of heat storages are considered the socio-economic profit that was achieved by the expansion of heat pumps is converted to socio-economic loss. However, in a future energy system with relatively high wind penetration the socio-economic profit that is created by the expansion of heat pumps is enough to cover the investment required for adding heat storages. Therefore, in a system with the configuration of the Alternative 2030 it is feasible to make an expansion of the individual heat pumps and add also heat storages so that the positive effects in terms of fuel consumption, CO_2 emissions and CEEP created when the heat produced by heat pumps can be stored are fully exploited.

All in all, it can be concluded that individual heat pumps combined with individual heat storages constitute a technical mean that can contribute substantially to the integration of wind power to the future energy system of Denmark.

8.2 District heating sector

The effects of large heat pumps in the BAU and the Alternative energy system are compared in terms of fuel savings, reductions in CO_2 emissions and CEEP as well as socio-economic savings (see Figures 8.5 – 8.7). The capacity of the large heat pumps that are introduced in the two energy systems is equal to 570 MW_e corresponding to 1,000 large heat pumps installed in the DH system.

The introduction of large heat pumps can decrease the total annual fuel consumption of the BAU energy system by 3.72 TWh or 1.6% (or 1.7% excl. RES). This reduction is up to 7.65 TWh or 3.2% (3.7% excl. RES) in the case of the Alternative energy system. This means that the impact of large heat pumps on the fuel consumption of the future energy system can be doubled (more than doubled if the impact only on fossil fuels is considered) if significantly more wind power is introduced to the system. This is mainly related to the higher utilisation of large heat pumps over CHP units in a system with quite high wind penetration.

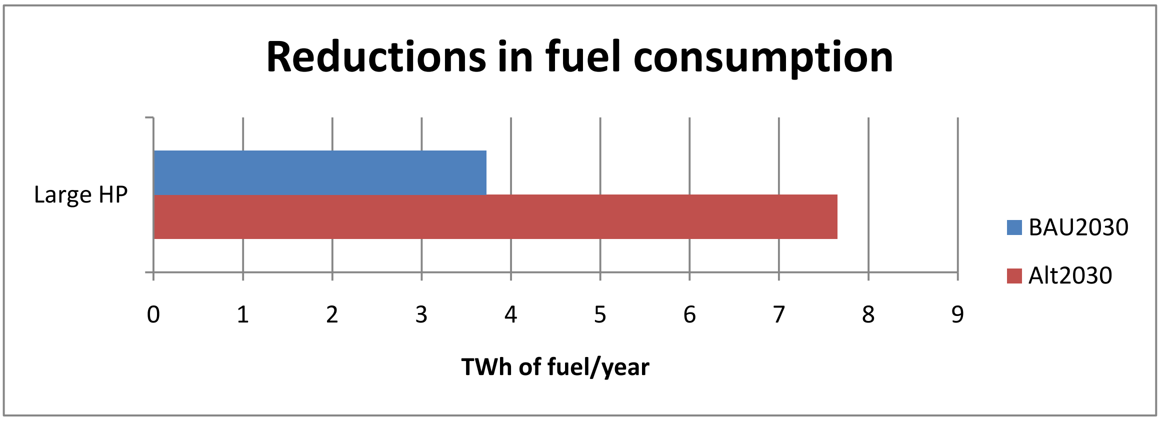

Figure 8.5: Effect of large heat pumps on the fuel consumption of the future energy system

The CO_2 emissions that can be avoided by implementing large heat pumps in the BAU energy system are equal to 0.77 million tons corresponding to a reduction of 1.8%. In the case of the Alternative, 2.57 million tons or 6.3% of CO_2 emission can be saved if large heat pumps are installed in the DH systems. This means that the higher the wind penetration in the future energy system the higher the utilisation of large heat pumps consuming wind-produced electricity and saving the consumption of fossil fuels for the production of DH.

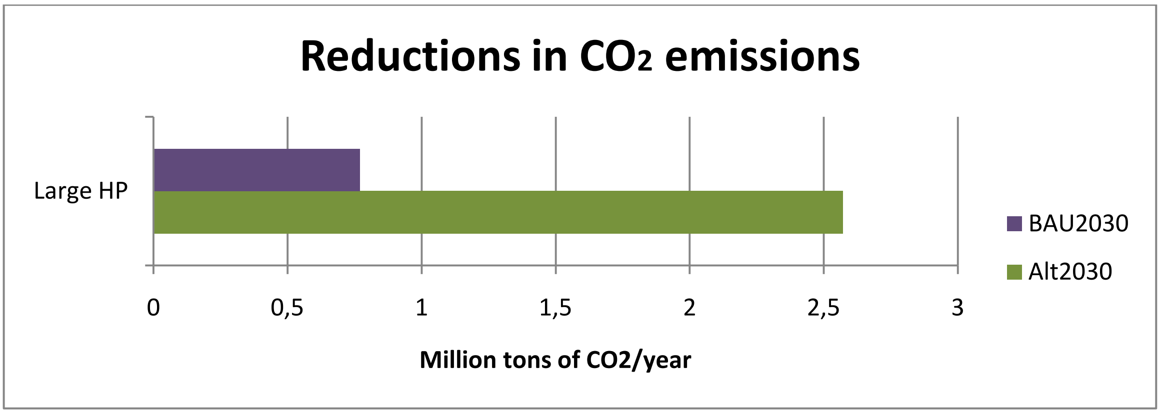

Figure 8.6: Effect of large heat pumps on the CO_2 emissions of the future energy system

The contribution of large heat pumps to the reduction of the critical excess electricity that is produced in the case of the Alternative energy system is significant. The annual CEEP is decreased by 0.42 TWh or 22% after the introduction of large heat pumps. Furthermore, the production of excess electricity that can not be exported constitutes a problem for 210 hours per year less when large heat pumps are implemented (from 1,459 hours to 1,249 hours).

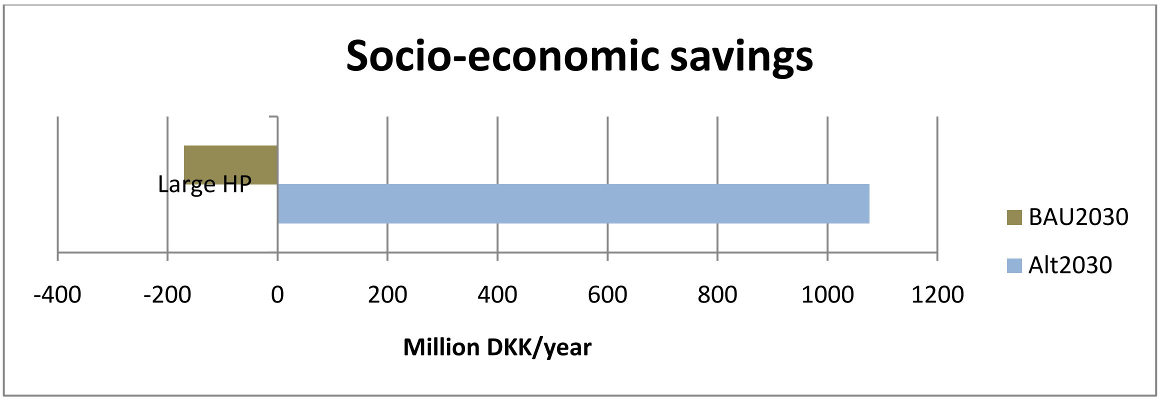

Figure 8.7: Effect of individual heat pumps on the total socio-economic costs of the future energy system

The total annual socio-economic costs of the BAU energy system increase by 0.2% after the introduction of large heat pumps into the BAU energy system leading to a socio-economic loss of 170 million DKK, although the variable costs of the system decrease by 571 million DKK or 0.6%. The feasibility of large heat pumps seems to be much better in the Alternative system since the variable costs are reduced by 1.8 billion DKK or 2.1%. As a result, the profit related to the variable costs of the system is enough to cover the investment costs for large heat pumps and lead the Alternative energy system to an annual socio-economic profit of 1.1 billion DKK or 1.2%.

Overall assessment

To sum up, the effects of large scale heat pumps are beneficial for the operation of the future energy system in terms of fuel and CO_2 emissions savings. These benefits are higher if a system with higher share of wind power is considered, like the Alternative 2030. Furthermore, the introduction of large heat pumps can contribute to the minimisation of critical excess electricity which is produced when the penetration of fluctuating wind power is quite high.

Concerning the socio-economic costs of the future energy system, large heat pumps are able to decrease the variable costs of the system independently of wind penetration. This is not the case if the total annual costs of a future energy system similar to the BAU 2030 are considered, since a socio-economic loss is observed. However, the increased wind-produced electricity can convert this socio-economic loss to significant socio-economic profit.

All in all, the installation of large-scale electric heat pumps have only positive impacts to the operation of a future energy system with quite high wind penetration and thus can contribute substantially to the integration of wind power in the future energy system of Denmark.

8.3 Transport sector

In this section, the effects of introducing EVs and V2G cars both in the BAU and in the Alternative energy system in terms of fuel consumption, CO_2 emissions, CEEP and socio-economic costs are summarised, based on the following graphs (see Figures 8.8 – 8.11).

It is assumed that 50% of passenger and commercial freight vehicles are replaced by EVs. This corresponds to 1.25 million vehicles. In the case of V2G cars, it is considered that all the EVs are converted to V2G cars.

The introduction of electric vehicles in the BAU energy system can save 11 TWh or 4.7% (4.9% excl. RES) of fuel annually while if V2G cars are considered instead, the annual fuel savings are 9 TWh or 3.9% (or 4.1% excl. RES).

Both EVs and V2G cars can achieve higher fuel savings in the Alternative than in the BAU energy system (see Figure 8.8). In the case of EVs, the fuel consumption of the Alternative system is reduced by 13.2 TWh or 5.6% (6.4% excl. RES) annually and by 12 TWh or 5% (5.8% excl. RES) in the case of V2G cars. Hence, it can be concluded that the effect of EVs/V2G cars is more intense in a future energy system with significantly high wind power.

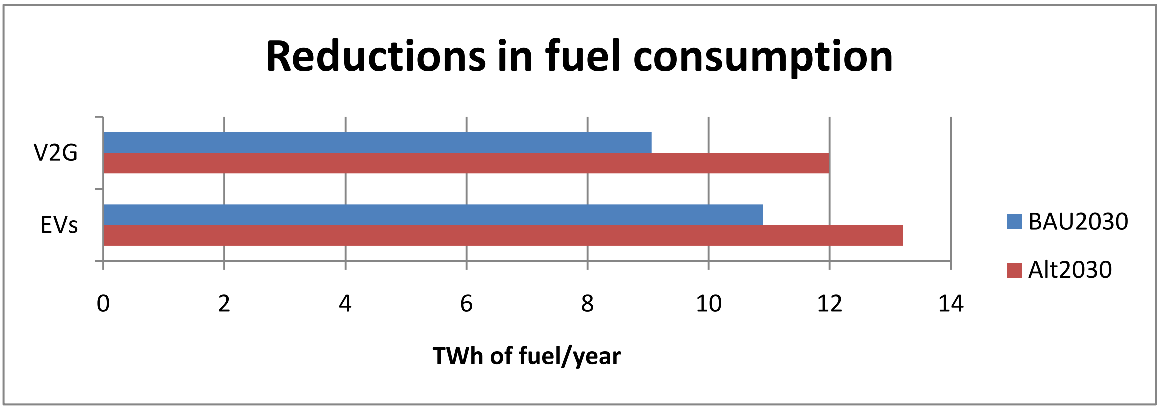

Figure 8.8: Effect of EVs and V2G cars on the fuel consumption of the future energy system

Similarly with the fuel savings, the CO_2 reduction is higher in the Alternative energy system comparing to the BAU both for EVs and V2G cars. After the introduction of EVs the CO_2 emissions of the BAU energy system decrease by 2.52 Mt or 5.8% annually while the corresponding reduction for V2G cars is 1.96 Mt or 4.5%.

The CO_2 emissions savings in the Alternative system are almost doubled for EVs since they decrease by 4.28 Mt or 10.6% per year. As for V2G cars the CO_2 emissions savings are more than double in the Alternative energy system leading to an annual reduction of 4.24 Mt or 10.5% annually.

This means that the increased wind power can be utilised by EVs/V2G cars replacing petrol and diesel cars, leading in this way to significant CO_2 emissions savings in the transportation sector.

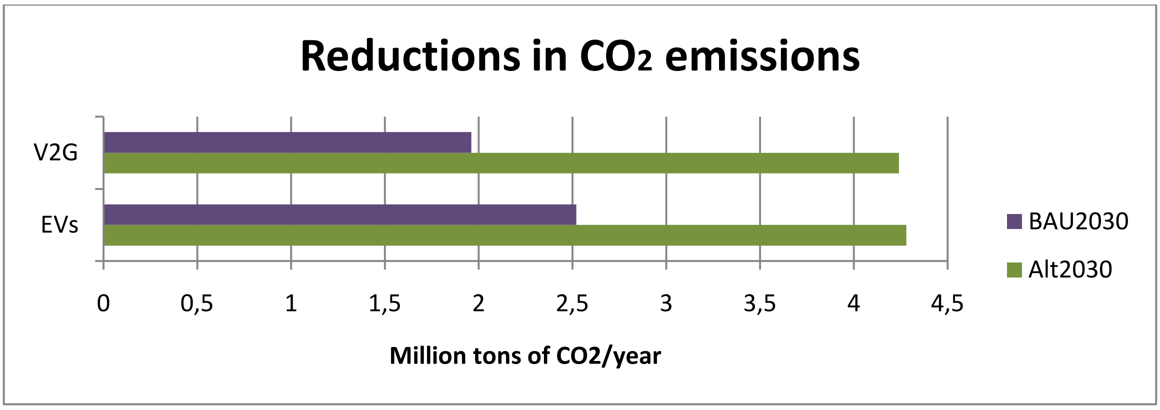

Figure 8.9: Effect of EVs and V2G cars on the CO_2 emissions of the future energy system

Concerning the effects on the CEEP, an annual reduction of 0.88 TWh or 47% can be achieved if electric vehicles are introduced in a system where CEEP is a problem such as the Alternative energy system; this is a quite significant reduction. In the case of V2G cars CEEP is decreased by 0.45 TWh or 24% annually. The lower reduction comparing to EVs is due to the fact that the maximisation of the profit that V2G can make is the top priority when their operation is optimised and not the reduction of CEEP. Therefore, it can be also explained why in the BAU energy system, in which CEEP is not a problem, the introduction of V2G cars lead to 0.032 TWh of CEEP, although when EVs are introduced the CEEP remains to be zero.

The interesting thing is that in a future energy system with high electricity production coming from fluctuating sources such as wind power both EVs and V2G can contribute to the substantial reduction of the excess electricity that is produced and can not be exported.

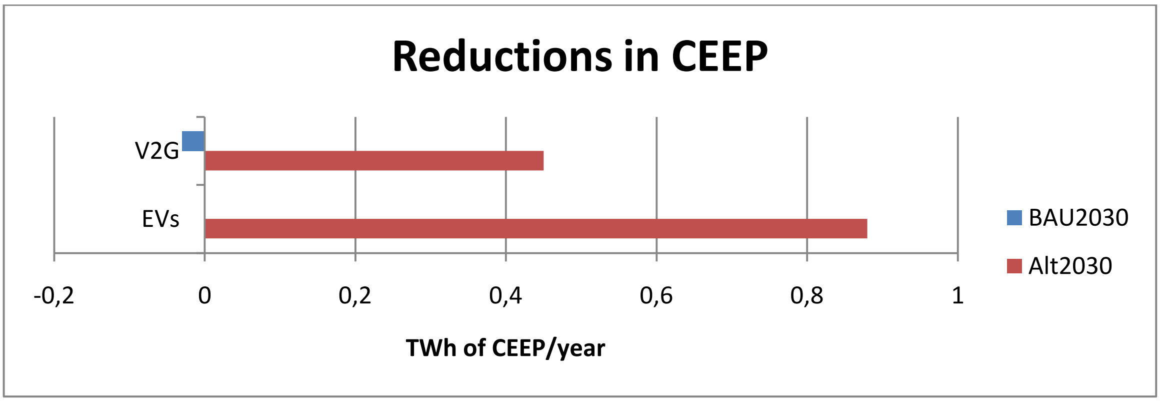

Figure 8.10: Effect of EVs and V2G cars on the critical excess electricity production of the future energy system

Both EVs and V2G cars lead the BAU energy system to annual socio-economic profits of 4.9 billion DKK or 4.3% and 4.2 billion DKK or 3.7% respectively, when it is considered that existing conventional cars are replaced by EVs and V2G cars instead of new conventional cars.

The annual socio-economic profit becomes higher in the case of the Alternative energy system since it goes up to 6 billion DKK or 5.6% for EVs and 5.1 billion DKK or 4.7% for V2G cars. This means that the introduction of EVs/V2G in a future energy system with quite high shares of wind power will be beneficial in economic terms. The wind-produced electricity in a future energy system with significantly high wind penetration can be utilised by EVs/V2G saving fuel costs and reducing the costs for importing electricity.

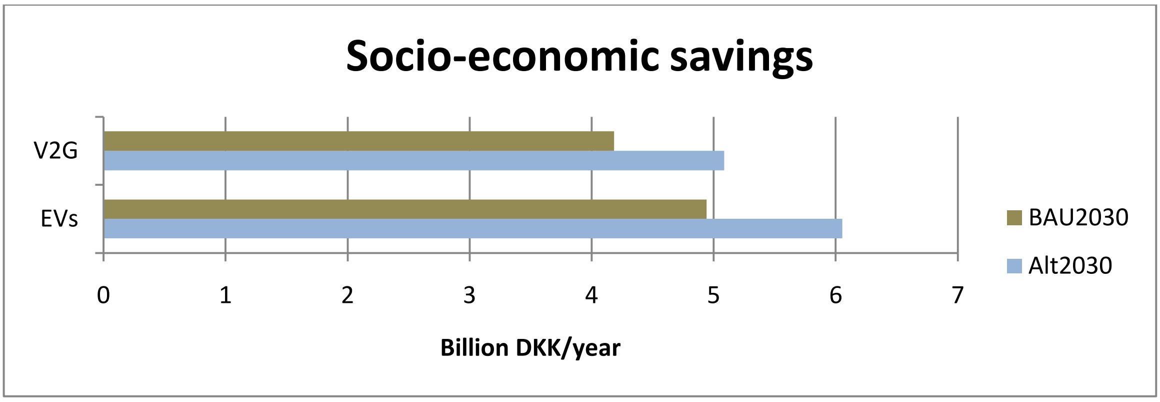

Figure 8.11: Effect of EVs and V2G cars on the total socio-economic costs of the future energy system

Overall assessment

It can be concluded that EVs/V2G can improve the performance of the future energy system. Their effects are even more beneficial in case that the wind penetration is substantially increased in the future energy system. In such a system, EVs/V2G can take advantage of the high wind-based electricity production and improve the performance of the system in terms of fuel consumption, CO_2 emissions and CEEP. In reference to the socio-economic costs of the future energy system, the high shares of wind power can be utilised by EVs/V2G, so that the transportation demand can be covered with lower socio-economic costs. It is concluded that investing in EVs/V2G is feasible, since a socio-economic profit is created in the future energy system if it is assumed that existing conventional cars would anyway be replaced by new conventional cars. The feasibility of EVs/V2G is further improved with the increase of wind penetration.

The introduction of V2G cars can improve the performance of the future energy system but the benefits are less intense compared to EVs. This happens if a market-economic optimisation strategy is followed according to which the operation of V2G cars is optimised so that the profit from buying and selling electricity to the grid can be maximised at an hourly basis. This is maybe achieved and V2G can improve their economics related to the electricity trade occasionally. However, this is not reflected in the overall socio-economic costs of the system, since it can not compensate for the higher investment, fuel and CO_2 emissions costs related to the operation of V2G cars. Consequently, it can be concluded that it is really important how V2G cars will be regulated in the future energy system in order to take advantage of their technical characteristics (their ability to discharge electricity to the grid and operate as electricity storage for the system).

8.4 Overview of technical means of wind integration

In this part of the conclusions the groups of technologies analysed in this study are evaluated on their ability to integrate wind power in terms of fuel consumption, CO_2 emissions, Critical Excess Electricity Production (CEEP) and socio-economic costs.

In the following paragraphs the different assumptions that are related to the introduction of the technical means should always be taken into account. The detailed assumptions can be found in Chapters 5, 6 and 7 for individual heat pumps, large heat pumps and EVs respectively. However, the penetration of the different technical means is briefly described here:

- **Expansion of Individual heat pumps**: 50% of the total annual individual heat demand (16.7% already covered by HPs before the expansion) / 567 MW_e (189 MW_e capacity of the existing heat pumps) / 500,000 units
- **Introduction of heat storages**: 500,000 units (each one with a capacity equal to 1 day of average heat demand)
- **Introduction of Large heat pumps in DH systems**: 570 MW_e / 1,000 units
- **Introduction of EVs/V2G:** 50% of passenger and commercial freight vehicles / 1.25 million vehicles

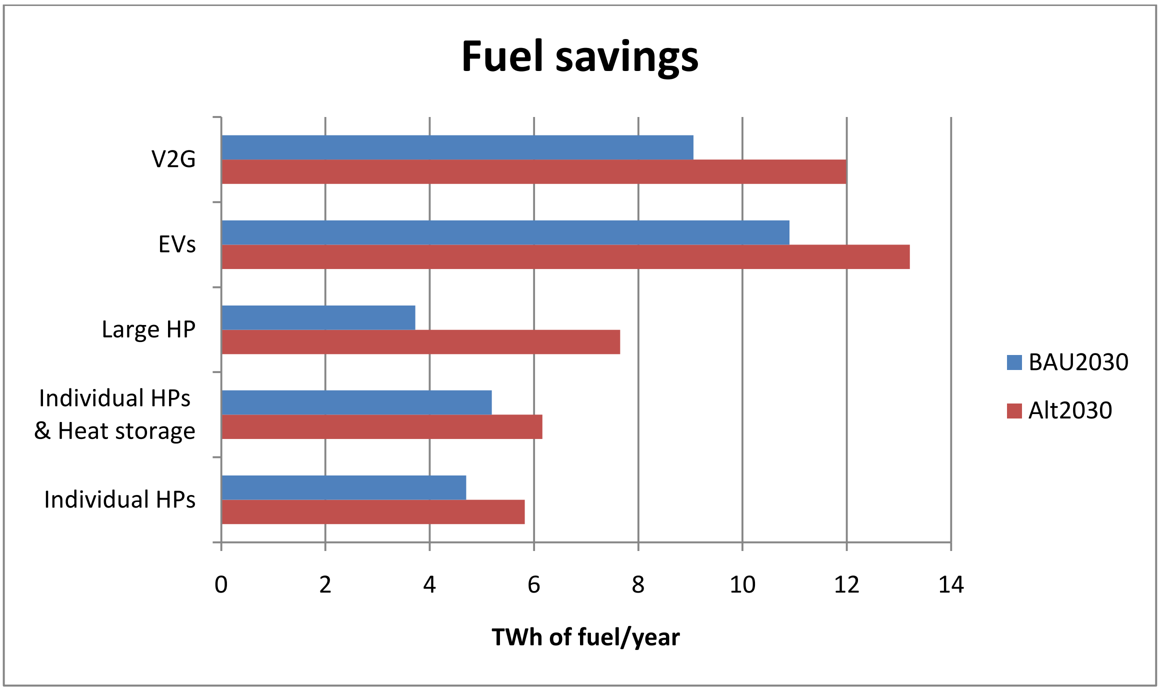

Figure 8.12: Fuel savings in the future energy system

All the technical means that have been studied appear to lead the future energy system, in reference to 2030, to significant fuel savings. Of course each mean corresponds to different amount of fuel savings. This is not necessarily indicative of the ability of the means to reduce the fuel consumption of the future energy system, since different assumptions lie behind the introduction of each technology. Therefore a direct comparison would be dicey. However, it should be noted that all the means lead to higher fuel savings when introduced in a future energy system with significantly high wind penetration (around 70%). This demonstrates the ability of all the means analysed to contribute to the integration of wind power to the future energy system of Denmark in terms of fuel savings.

Moreover, it is worth mentioning that the increase of the wind penetration in the future energy system appears to affect more extensively the fuel savings that can be achieved with the introduction of large heat pumps to the system. This is quite important in reference to the ability of large heat pumps to integrate wind power in terms of fuel consumption, although it is not the mean with the highest fuel savings (see Figure 8.12).

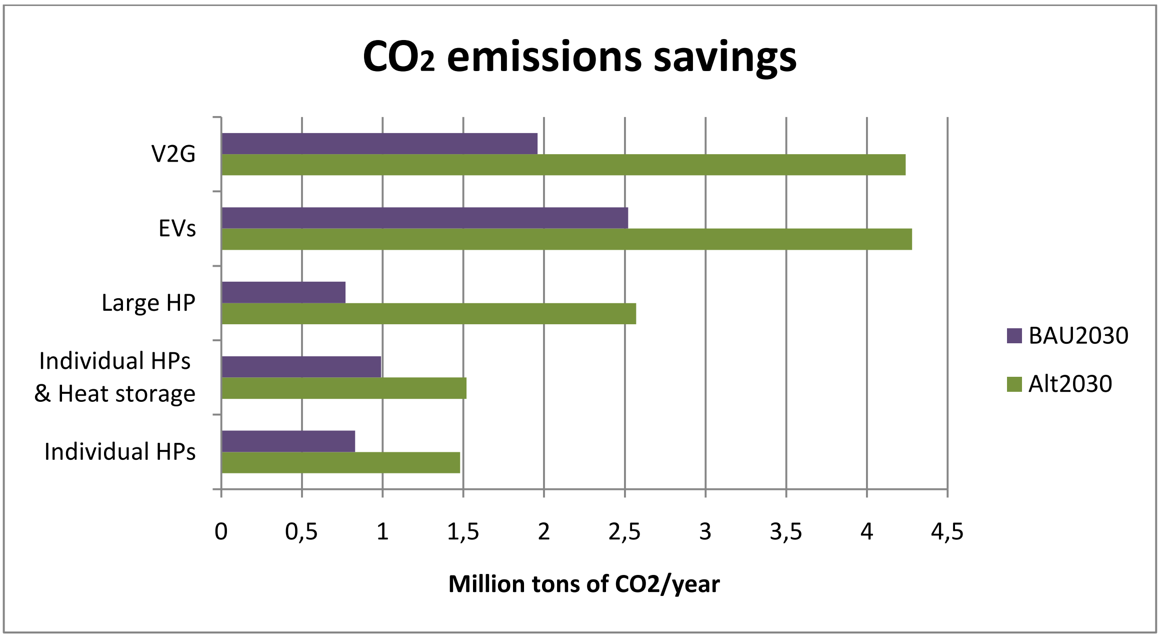

Figure 8.13: CO_2 emissions savings in the future energy system

Concerning the CO_2 emissions, firstly it should be observed that all the technical means lead the system to significant savings. Exceptional is the ability of all the means to integrate high shares of wind-produced electricity in terms of CO_2 emissions, since the reductions in the emissions of the future energy system are at least doubled when the wind penetration appears to be substantially increased (from 28% to 74%). Particularly noticeable is the difference in the CO_2 emissions savings that is achieved with the introduction of large heat pumps as well as V2G cars when the wind capacity is increased. In the case of large heat pumps, the CO_2 emissions savings are more than tripled and in the case of V2G cars more than doubled.

If Figures 8.12 and 8.13 are looked at carefully, it can be observed that the ratio between the CO_2 emissions savings achieved by each technical mean in the BAU 2030 and in the Alternative 2030 is higher than the corresponding ratio in reference to fuel savings. Based on that, it can be concluded that the extra wind power of the Alternative energy system is exploited by the analysed technologies, leading in this way to reductions in the fossil fuels' consumption of the future energy system. This is an indication of the ability of the technical means presented in this study to contribute to the integration of wind power.

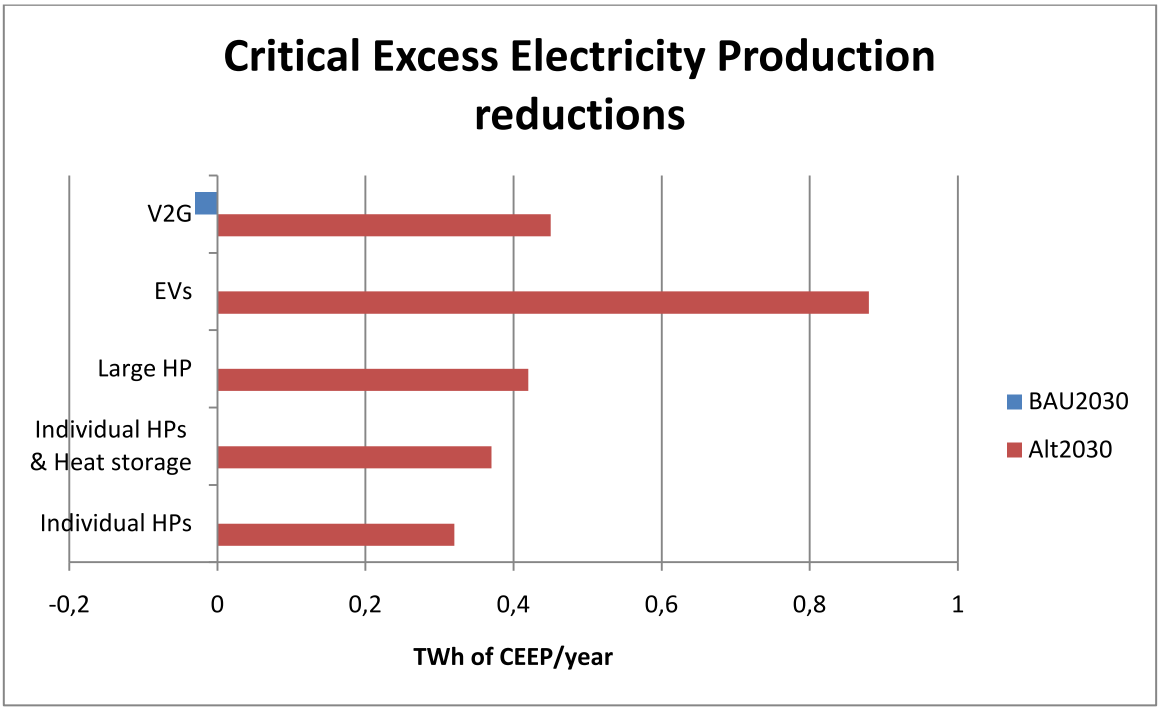

Figure 8.14: Critical Excess Electricity Production reductions in the future energy system

By looking at Figure 8.14, it can be stated that the ability of electric vehicles to reduce the critical excess electricity that is produced in the future energy system is remarkable. Of course, the different penetration of the analysed technologies should be taken into account when making a direct comparison of their effects.

It is also worth noting that when a Business-as-Usual development is considered for the future energy system in reference to 2030, there is no CEEP and the situation remains the same after the introduction of heat pumps and EVs. This is not the case when V2G cars are implemented in the future energy system. The ability of V2G cars to deliver electricity back to the grid leads to the production of some critical excess electricity to the system, when they are optimised in order to maximise the profit from the electricity exchange. As a result, the way that the operation of V2G is regulated is determinant for their effects on CEEP and this should be deliberated before the introduction of this technology to the future energy system.

Generally speaking, all the technical means, when implemented in a future energy system with considerably high wind penetration in which CEEP constitutes a problem, can contribute to the reduction of CEEP substantially. The operation of means such as heat pumps and electric vehicles in the future energy system equals to much less hours with excess electricity production that can not be exported. In this way the curtailment of wind power can be avoided and the wind-produced electricity can be fully exploited. Therefore, the introduction of the technologies analysed in this project is really crucial for the smooth integration of wind power in the future energy system.

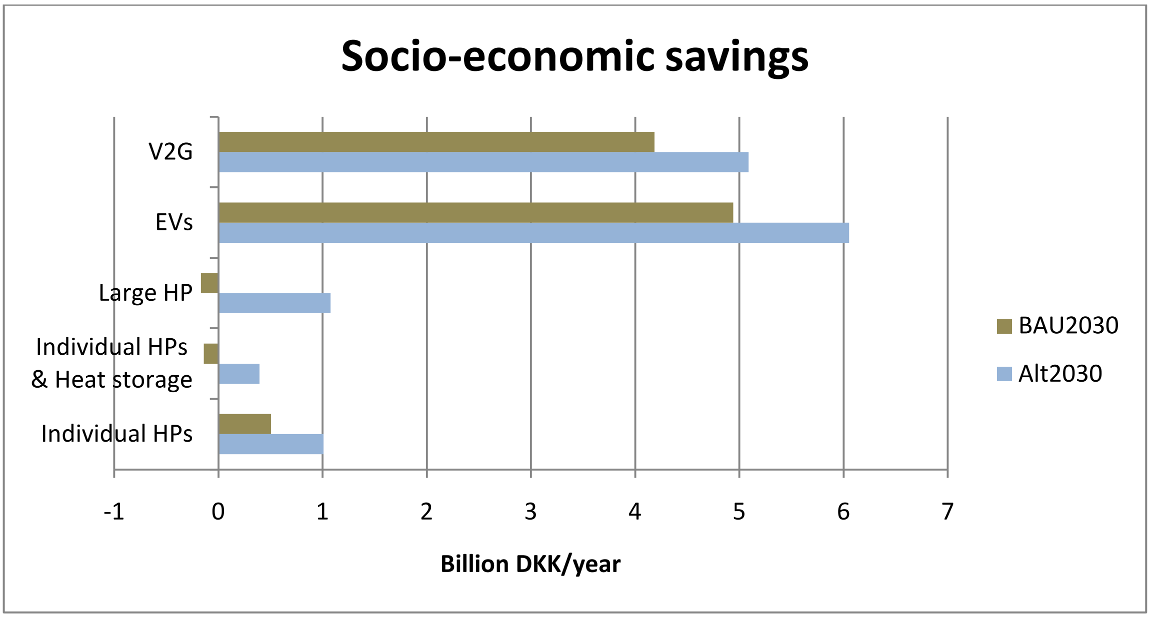

Figure 8.15: Socio-economic savings in the future energy system

In Figure 8.15 the socio-economic savings that can be achieved by the introduction of heat pumps and electric vehicles in the future energy system are presented. In these estimations the investment and fixed O&M costs that correspond to the implemented technical means are considered.

The socio-economic profit that can be achieved after the introduction of EVs/V2G appears to be significant. However, one should be aware that these estimations are based on the assumption that a share of the conventional cars of the future energy system is replaced by EVs/V2G instead of new conventional cars. Otherwise, electric vehicles would lead the future energy system to socio-economic losses. These are mentioned in order to avoid giving a misleading picture for the socio-economic effects of the analysed means, although it has already mentioned that a direct comparison is dicey.

The increased wind-based electricity production in reference to the future energy system of 2030 can be considerably beneficial for the operation of large heat pumps and individual heat pumps with heat storages in terms of socio-economic costs. The socio-economic loss that these technologies bring to the BAU system of 2030 is converted to socio-economic profit when the wind penetration is increased. This is indicative of the ability of heat pumps to utilise the wind power.

Finally, it is clear that both heat pumps and electric vehicles can contribute to the integration of wind power to the future energy system of Denmark and improve the economics of the system, given that they are leading to significant socio-economic profits under high wind penetration.

In conclusion, based on the analysis of the technical as well as the socio-economic effects of both the heat pumps and the electric vehicles, it is clear that the interaction of the heat and the transport sector with the electric system is crucial for the integration of wind power to the future energy system of Denmark. Moreover, it can be concluded that heat pumps as well as electric vehicles should have a central role in the future energy system of Denmark in order to ensure a smooth integration of high shares of wind power in the long-term.

Future Perspectives

As a future expansion of the analysis conducted in this project, it would be interesting to analyse the techno-economic effects of introducing the use of hydrogen both in the heat and the transport sector. The implementation of hydrogen micro CHP units in the individual heat sector as well as the introduction of hydrogen fuel cell vehicles in the transport sector, both combined with electrolysis units, could probably contribute to the integration of wind power in the future energy system of Denmark. Therefore, the effects of such technologies that utilise hydrogen as the energy carrier could be investigated in a future study.

Another future perspective would be to analyse the effects of combining different technical means of wind integration. In this way, more synergy effects could possibly be created both in the heat and the transport sector. This would maybe increase the ability of the future energy system to integrate large volumes of wind power.

Finally, this study could be expanded by analysing the effects of various technical means of wind integration by applying a Technical Optimisation strategy in the EnergyPLAN model. This would mean that the least fuel consuming solution instead of the lowest-cost solution would be indentified by the model and the minimisation of Critical Excess Electricity Production would be a top priority. Hence, it would be interesting to know how a different optimisation strategy can affect the fuel consumption, the CO_2 emissions, the CEEP and the socio-economic costs of a future energy system in Denmark.

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Appendix I

The Table I.1 presents the data of the baseline projection of DEA (Danish Energy Agency 2010) as they were converted to EnergyPLAN inputs for the ‘Reference 2030’ scenario in IDA’s Climate Plan 2050 (IDA 2009). In the framework of this project, these data are used for the construction of the BAU energy system, which is further described in Chapter 4.

Table I.1: Input from the Danish Energy Authority converted to input to the EnergyPLAN (IDA 2009)

EnergyPLAN Inputs (TWh/year)												
	Efficiency		Fuel						Production		Demand	
	Electric	Thermal	Coal	Oil	NG	Biomass	Waste	Solar th.	Electr.	DH	Electr.	DH
Power plant	42.36%		19.39	0.73	2.07	17.17			16.68			
Onshore wind									11.51			
Hydro power												
CHP central	35.43%	54.76%	9.63	0.27	1.25	9.51			7.32	11.31		
CHP decentralised	37.25%	48.02%	0.17	0.05	2.66	3.11			2.23	2.88		
District heating boilers		94.62%	0.00	2.60	4.22	3.81		0.01		10.07		
Industrial CHP	33.15%	57.10%										
Waste CHP	22.50%	62.40%	0.00	0.00	0.00	0.00	12.26		2.76	7.65		
Waste district heating		79.76%	0.00	0.00	0.00	0.00	0.07			0.06		
Industry sum (gr 3)			3.02	20.48	13.00	3.46			1.22	2.09		
Transport Diesel etc.				32.30		0.00						
Transport Petrol etc.				18.86		2.91						
Transport jet fuel				10.87		0.00						
Households			0.00	2.62	4.79	11.54		0.50				
Households/heatpumps											1.13	
Elec. Demand											40.59	
District heating Gr 1												2.64
District heating Gr2												9.90
District heating Gr 3												21.52
District heating demand												*34.06*
Geothermal (COP)		1.00								0.00	0.00	
NG grid losses												
Non energy												
Refinery												
North see												
Household gas												
Net-export											0.00	
Sum various			0.00	8.38	9.23	0.00						
Sum			32.21	97.16	37.22	51.50	12.33	0.51	41.72	34.06	41.72	34.06
Control (PJ/year)			115.97	349.79	134.01	185.42	44.40	1.84	150.19	122.62	150.19	122.62

Appendix II

Fuel substitution by introducing EVs/V2G cars

- Total vehicle fleet in Denmark for 2011: 4 million vehicles of all types (Statistics Denmark n.d.) covering a total distance of 82 billion km/year (IDA 2009)

  Average distance covered by each vehicle: 20,500 km/vehicle per year

  Total number of passenger and commercial freight vehicles for 2011: 2.5 million (Statistics Denmark n.d.). It is assumed that the number remains the same for 2030 (IDA 2009).

- Conventional vehicles to be replaced by EVs: 50% of passenger and commercial freight vehicles or else 1.25 million vehicles

  EVs are replacing by 60% diesel cars and by 40% petrol cars (assumption based on data from (Statistics Denmark n.d.))

  Diesel cars replaced: 60% x 1.25 million vehicles = 0.75 million diesel cars

  Petrol cars replaced: 40% x 1.25 million vehicles = 0.5 million petrol cars

- Reduction in km covered by diesel cars: 0.75 million diesel vehicles x 20,500 km/vehicle per year = 15.4 billion km/year

  Reduction in diesel fuel consumption: (15.4 billion km/year) / (1.5 km/kWh) = 10.27 TWh/year

  Reduction in km covered by petrol cars: 0.5 million petrol vehicles x 20,500 km/vehicle per year = 10.3 billion km/year

  Reduction in petrol fuel consumption: (10.3 billion km/year) / (1.5 km/kWh) = 6.87 TWh/year

  Source for efficiencies: (P. Koustrup 2009)

- Distance covered by EVs: (15.4 + 10.3) billion km/year = 25.7 billion km/year

  Electricity consumption by EVs: (25.7 billion km/year) / (6 km/kWh) = 4.28 TWh/year

  Source for efficiencies: (W. K. Henrik Lund 2008)

Considering the reductions in diesel and petrol consumption and the corresponding reduction in the distance covered by diesel and petrol vehicles the values of the Table II.1 below arise. In Table II.1 the inputs of the EnergyPLAN model concerning the fuel distribution before and after the introduction of EVs are summarised.

Table II.1: Inputs of EnergyPLAN before and after introducing EVs

		Before EVs		After EVs	
	Vehicle's Efficiency (km/kWh)	Fuel consumption (TWh/year)	Distance covered (Billion km/year)	Fuel consumption (TWh/year)	Distance covered (Billion km/year)
Diesel	1.5	32.3	48	22	33
Petrol	1.5	18.86	28	12	18
Biomass	1.5	3.78	6	3.78	6
Electricity	6	0	0	4.28	26
		Total	**82**	**Total**	**82**

Investment in conventional cars

- 0.75 million diesel cars x 98,000 DKK/unit = 73,500 million DKK

  0.5 million petrol cars x 77,000 DKK/unit = 38,500 million DKK

  Source for costs: (P. Koustrup 2009)

  Total investment: 112,000 million DKK

  By considering a lifetime of 13 years for conventional cars according to (P. Koustrup 2009) and given that the interest rate is 6% (Danish Energy Agency 2010), the above mentioned total investment can be annualised.

  Annual investment costs: 12,652 million DKK/year

- The O&M costs for conventional cars considered to be up to 7.12% of the investment costs (weighted average based on data retrieved from (P. Koustrup 2009)). Therefore, the annual fixed O&M costs can be also estimated.

  Annual fixed O&M costs: 7,974 million DKK/year

- Total annual costs for replacing 1.25 million existing conventional vehicles with new conventional vehicles:

20,626 million DKK/year

Appendix III

In this Appendix all the data in which the analyses of 'Large Heat Pumps' have been based are stated. Moreover, the way that they have been transformed in order to be inserted in EnergyPLAN is presented.

Table III.1: Technical and economic specifications of large electric heat pumps for DH systems for year 2030. Data retrieved from: (Technology Data for Energy Plants 2010)

Technology	**Large heat pumps, electric (heat source: ambient temperature)**	**Large heat pumps, electric (heat source: 35°C)**
Generation capacity for one unit (MJ/s heat)	1 - 10	1 - 10
COP	3	3.8
Technical Lifetime (years)	20	20
Specific investment (M€ per MJ/s heat out)	0.4 - 0.7	0.35 - 0.75
Fixed O&M (€/year)	2,000 - 3,000	2,000 - 3,000
Variable O&M (€ per MJ/s heat out for every 10,000 hours of operation)	1,500	1,500

As it is mentioned in (Technology Data for Energy Plants 2010), in relation to the specifications of large heat pumps, it is assumed that CO_2 is used as refrigerant and the supply temperature is about 80 °C. These costs include pipes, electrical system, installation etc. but they do not include any costs for buildings or storage tanks.

Investment costs:

The average of the two ranges in Table III.1 referring to the specific investment of the two types of heat pumps is equal to 0.55 M€/MW_{th}. Using an exchange rate of 7.456 DKK/€, the specific investment is equal to 4.1 MDKK/MW_{th} and based on an average COP of 3.4 the investment cost becomes 13.94 MDKK/MW_e. However, in this study all the costs have been inserted to the EnergyPLAN in 2011 prices and this value is in 2008 price levels, since all the data from the report (Technology Data for Energy Plants 2010) are in 2008 price levels. Therefore, the investment cost needs to be multiplied by a factor of 1.0429 in order to be moved in 2011 price levels as proposed in (Forudsætninger for samfundsøkonomiske analyser på energiområdet 2010). Finally, the investment cost that is inserted in EnergyPLAN for large heat pumps is equal to **14.54 million DKK/MW_e**. The same investment cost is considered for heat pumps installed in decentralised and central areas.

Fixed O&M costs:

As it is stated in (Technology Data for Energy Plants 2010), a typical service contract for large heat pumps is estimated up to 2,000 - 3,000 €/year, for the larger sizes. In this study an average of 2,500 €/year or 18,640 DKK/year is used for each heat pump installed.

The generation capacity for one unit varies from 1 to 10 MJ/s heat and it is the same for both of the two types of heat pumps. In this study it is considered that each heat pump has an average capacity of 2 MW_{th}.

According to estimations of the Danish Energy Association, the potential for installing heat pumps in district heating system is equal to an overall capacity of 2,000 MW_{th}, in reference to the year 2025 (Danish Energy Association 2009). Therefore, the total number of heat pumps introduced both in the BAU and the Alternative energy system is equal to 1,000.

As a result, the total fixed O&M costs for all the heat pumps that are introduced are equal to 18.64 MDKK per year (2008 prices).

The total investment costs are: 4.1 MDKK/MW_{th} x 2000 MW_{th} = 8,200 MDKK (2008 prices).

The fixed O&M costs as a percentage of the investment become equal to: (18.64 MDKK/year) / 8,200 MDKK = 0.002273 or approximately **0.23%.**

Variable O&M costs:

As it is mentioned in the (Technology Data for Energy Plants 2010) an overall check is necessary every 10,000 hours of operation for large heat pumps, costing approx. 1,500 €/MW_{th}. This is translated to 0.51 €/MWh_e, given that the COP is 3.4. By using an exchange rate of 7.456 DKK/€ the variable O&M costs are equal to 3.8 DKK/MWh_e in 2008 prices or **3.96 DKK/MWh_e** in 2011 prices (based on a factor of 1.0429 to move from 2008 to 2011 prices).

Appendix IV

This Appendix includes a CD-ROM with all the EnergyPLAN data sets that have been utilised in the project and the corresponding outputs' sheets of the model. It also includes the sheets with the outputs from the optimisation of the BAU 2030 and the Alternative 2030 energy system.

Input BAU2030

The EnergyPLAN model 9.0

Electricity demand (TWh/year):		Flexible demand	0,00
Fixed demand	40,59	Fixed imp/exp.	0,00
Electric heating	0,00	Transportation	0,00
Electric cooling	0,00	Total	40,59

District heating (TWh/year)	Gr.1	Gr.2	Gr.3	Sum
District heating demand	2,64	9,90	21,52	34,06
Solar Thermal	0,01	0,00	0,00	0,01
Industrial CHP (CSHP)	0,00	0,00	2,65	2,65
Demand after solar and CSHP	2,63	9,90	18,87	31,40

Wind	2350	MW	6,58	TWh/year	0,00	Grid
Offshore Wind	1239	MW	4,93	TWh/year	0,00	stabili-
River Hydro	0	MW	0	TWh/year	0,00	sation
Photo Voltaic	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	1945	2507	0,37	0,48	
Heat Pump	0	0			3,50
Boiler		3484		0,95	
Group 3:					
CHP	2500	3864	0,35	0,55	
Heat Pump	0	0			3,50
Boiler		7574		0,95	
Condensing	8552		0,42		

Heatstorage: gr.2: 40 GWh gr.3: 10 GWh
Fixed Boiler: gr.2: 2,5 Per cent gr.3: 1,0 Per cent

Electricity prod. from	CSHP	Waste (TWh/year)
Gr.1:	0,00	0,00
Gr.2:	0,00	0,97
Gr.3:	1,93	1,79

Regulation Strategy:	Market regulation NEW	
KEOL regulation	00000	
Minimum Stabilisation share	0,00	
Stabilisation share of CHP	0,00	
Minimum CHP gr 3 load	450	MW
Minimum PP	0	MW
Heat Pump maximum share	0,00	
Maximum import/export	2500	MW
Distr. Name :	Price_DKV_2008.txt	
Addition factor	0,00	DKK/MWh
Multiplication factor	1,12	
Dependency factor	0,02	DKK/MWh pr. MW
Average Market Price	473	DKK/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	0,85	
Hydro Turbine:	0		0,85	
Electrol. Gr.2:	0	0	0,73	0,07
Electrol. Gr.3:	0	0	0,73	0,07
Electrol. trans.:	0	0	0,73	
Ely. MicroCHP:	0	0	0,73	
CAES fuel ratio:		0,000		

(TWh/year)	Coal	Oil	Ngas	Biomass
Transport	0,00	62,03	0,00	3,78
Household	0,00	2,62	4,79	12,17
Industry	3,02	20,48	13,00	3,46
Various	0,00	8,38	9,23	0,00

Output

District Heating

	Demand: Distr. heating MW	Production: Solar MW	Waste+ CSHP MW	DHP MW	CHP MW	HP MW	ELT MW	Boiler MW	EH MW	Ba-lance MW
January	6239	0	1179	477	3921	0	0	663	0	0
February	6384	0	1179	488	3802	0	0	914	0	0
March	5439	1	1179	415	3097	0	0	740	0	9
April	4358	2	1179	330	2724	0	0	170	0	-46
May	3419	2	1179	257	1886	0	0	53	0	43
June	1550	3	1179	111	825	0	0	53	0	-621
July	1550	2	1179	112	826	0	0	53	0	-622
August	1550	2	1179	112	811	0	0	53	0	-607
September	2379	1	1179	177	1157	0	0	53	0	-188
October	3543	1	1179	268	2054	0	0	53	0	-11
November	4648	0	1179	354	2975	0	0	119	0	21
December	5550	0	1179	424	3288	0	0	644	0	16
Average	3878	1	1179	293	2276	0	0	296	0	-168
Maximum	10897	14	1179	838	6371	0	0	2707	0	4202
Minimum	1357	0	1179	98	696	0	0	53	0	-5987
Total for the whole year TWh/year	34,06	0,01	10,36	2,57	19,99	0,00	0,00	2,60	0,00	-1,47

Electricity

	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	Balance: Stab-Load %	Imp MW	Exp MW	CEEP MW	EEP MW
January	5223	0	182	0	71	0	0	1192	0	0	534	2651	250	100	1091	241	0	241
February	5167	0	182	0	88	0	0	1632	0	0	534	2545	196	100	835	304	0	304
March	4973	0	167	0	23	0	0	1372	0	0	534	2076	231	100	1118	168	0	168
April	4383	0	133	0	2	0	0	1182	0	0	534	1873	394	100	765	230	0	230
May	4276	0	99	0	0	0	0	1175	0	0	534	1300	1078	100	710	421	0	421
June	4156	0	29	0	0	0	0	1267	0	0	534	550	2256	100	439	862	0	862
July	3789	0	29	0	0	0	0	868	0	0	534	550	2257	100	407	798	0	798
August	4360	0	29	0	0	0	0	1165	0	0	534	539	2463	100	426	739	0	739
September	4474	0	60	0	0	0	0	1173	0	0	534	797	3205	100	69	1244	0	1244
October	4641	0	103	0	0	0	0	1789	0	0	534	1417	1030	100	419	445	0	445
November	5015	0	143	0	5	0	0	1714	0	0	534	2044	240	100	804	173	0	173
December	5016	0	166	0	39	0	0	1214	0	0	534	2214	305	100	1154	199	0	199
Average	4621	0	110	0	19	0	0	1310	0	0	534	1544	1160	100	687	485	0	485
Maximum	7127	0	189	0	605	0	0	3589	0	0	534	4445	7229	100	2500	2500	0	2500
Minimum	2315	0	22	0	0	0	0	0	0	0	534	450	0	100	0	0	0	0
Total for the whole year TWh/year	40,59	0,00	0,97	0,00	0,17	0,00	0,00	11,51	0,00	0,00	4,69	13,56	10,19		6,04	4,26	0,00	4,26

Exchange

	Payment Imp Million DKK	Exp Million DKK
January	385	79
February	251	89
March	347	55
April	255	85
May	221	160
June	143	328
July	130	312
August	143	288
September	26	475
October	155	163
November	280	51
December	404	57
Average price (DKK/MWh)	453	503
Total for the whole year (Million DKK)	2738	2143

FUEL BALANCE (TWh/year):

	DHP	CHP2	CHP3	Boiler2	Boiler3	PP	Geo/Nu.	Hydro	Elc./gas	Waste	CAES	Wind	Offsh.	Hydro	PV	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	-	0,42	15,83	-	-	5,56	-	-	-	-	-	-	-	-	-	-	-	-	3,02	-	24,83	2,07	26,90	8,49	9,20
Oil	1,98	0,05	0,27	0,10	0,10	0,73	-	-	-	-	-	-	-	-	-	-	62,03	2,62	20,48	8,38	96,74	0,08	96,82	25,77	25,79
N.Gas	-	6,51	2,06	2,30	0,04	0,59	-	-	-	-	-	-	-	-	-	-	-	4,79	13,00	9,23	38,52	0,22	38,74	7,90	7,95
Biomass	0,74	3,11	9,51	0,10	0,10	17,17	-	-	-	12,33	-	-	-	-	-	-	3,78	11,54	3,46	-	61,85	1,83	63,68	1,44	0,00
Renewable	-	-	-	-	-	-	-	-	-	-	-	6,58	4,93	-	-	0,51	-	-	-	-	12,02	0,00	12,02	0,00	0,00
H2 etc.	-	0,00	0,00	0,00	0,00	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0,00	0,00	0,00	0,00	0,00
Nuclear	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0,00	0,00	0,00	0,00	0,00
Total	2,72	10,08	27,67	2,50	0,24	24,06	-	-	-	12,33	-	6,58	4,93	-	-	0,51	65,81	18,95	39,96	17,61	233,96	4,20	238,16	43,61	42,94

Output specifications BAU2030 The EnergyPLAN model 9.0

District Heating Production

Gr.1

	District heating MW	Solar MW	CSHP MW	DHP MW
January	484	0	6	477
February	495	0	6	488
March	422	1	6	415
April	338	2	6	330
May	265	2	6	257
June	120	3	6	111
July	120	2	6	112
August	120	2	6	112
September	184	1	6	177
October	275	1	6	268
November	360	0	6	354
December	430	0	6	424
Average	301	1	6	293
Maximum	845	14	6	838
Minimum	105	0	6	98
Total for the whole year TWh/year	2,64	0,01	0,06	2,57

Gr.2

	District heating MW	Solar MW	CSHP MW	CHP MW	HP MW	ELT MW	Boiler MW	EH MW	Storage MW	Balance MW
January	1814	0	306	885	0	0	622	0	3161	0
February	1856	0	306	665	0	0	884	0	2853	0
March	1581	0	306	560	0	0	715	0	2021	0
April	1267	0	306	857	0	0	146	0	13247	-42
May	994	0	306	621	0	0	28	0	17642	39
June	450	0	306	129	0	0	28	0	4538	-13
July	450	0	306	126	0	0	28	0	19357	-10
August	450	0	306	115	0	0	28	0	16769	1
September	691	0	306	379	0	0	28	0	25036	-22
October	1030	0	306	686	0	0	28	0	30633	9
November	1351	0	306	929	0	0	95	0	19403	21
December	1613	0	306	672	0	0	619	0	9006	16
Average	1127	0	306	551	0	0	270	0	13677	0
Maximum	3167	0	306	2507	0	0	2658	0	40000	1864
Minimum	395	0	306	0	0	0	28	0	0	-2413
Total for the whole year TWh/year	9,90	0,00	2,69	4,84	0,00	0,00	2,37	0,00		0,00

Gr.3

	District heating MW	Solar MW	CSHP MW	CHP MW	HP MW	ELT MW	Boiler MW	EH MW	Storage MW	Balance MW
January	3942	0	866	3036	0	0	40	0	5321	0
February	4033	0	866	3137	0	0	30	0	5084	0
March	3436	0	866	2537	0	0	24	0	5595	9
April	2754	0	866	1867	0	0	24	0	5953	-4
May	2160	0	866	1265	0	0	24	0	3271	5
June	979	0	866	696	0	0	24	0	2422	-608
July	979	0	866	700	0	0	24	0	5347	-612
August	979	0	866	696	0	0	24	0	5598	-607
September	1503	0	866	777	0	0	24	0	5598	-165
October	2239	0	866	1368	0	0	24	0	5876	-20
November	2937	0	866	2046	0	0	24	0	7518	0
December	3507	0	866	2616	0	0	24	0	6217	0
Average	2450	0	866	1725	0	0	26	0	5317	-168
Maximum	6885	0	866	3864	0	0	1713	0	10000	3877
Minimum	858	0	866	696	0	0	24	0	0	-3652
Total for the whole year TWh/year	21,52	0,00	7,61	15,15	0,00	0,00	0,23	0,00		-1,47

RES specification

	RES1 Wind MW	RES2 Offshoı MW	RES3 River H MW	RES4 Photo \ MW	Total aic MW
January	679	513	0	0	1192
February	962	670	0	0	1632
March	786	586	0	0	1372
April	661	521	0	0	1182
May	661	514	0	0	1175
June	705	562	0	0	1267
July	477	391	0	0	868
August	660	505	0	0	1165
September	658	515	0	0	1173
October	1051	738	0	0	1789
November	1008	706	0	0	1714
December	694	520	0	0	1214
Average	749	561	0	0	1310
Maximum	2350	1239	0	0	3589
Minimum	0	0	0	0	0
Total for the whole year TWh/year	6,58	4,93	0,00	0,00	11,51

ANNUAL COSTS (Million DKK)

Total Fuel =		79313
Coal =	2393	
FuelOil =	10865	
Gasoil/Diesel=	21843	
Petrol/JP =	19457	
Ngas =	12255	
Biomass =	12500	
Food income =	0	
Waste =	0	
Marginal operation costs =		490
Total Electricity exchange =		457
Import =	2738	
Export =	-2143	
Bottleneck =	-138	
Fixed imp/ex=	0	
Total CO2 emission costs =		13170
Total variable costs =		93431
Fixed operation costs =		0
Annual Investment costs =		0
TOTAL ANNUAL COSTS =		93431

	DHP aı Boilers MW	CHP2 CHP3 MW	PP CAES MW	Individual MW	Transport MW	Indu. Var. MW	Demanı Sum MW	Biogas MW	Syngas MW	Storage MW	Sum MW	Import MW	Export MW
January	613	1601	15	961	0	2531	5720	0	0	0	5720	5720	0
February	866	1319	11	986	0	2531	5713	0	0	0	5713	5713	0
March	700	1096	13	820	0	2531	5160	0	0	0	5160	5160	0
April	146	1405	23	630	0	2531	4735	0	0	0	4735	4735	0
May	32	1006	63	465	0	2531	4096	0	0	0	4096	4096	0
June	32	268	131	136	0	2531	3098	0	0	0	3098	3098	0
July	32	264	132	136	0	2531	3095	0	0	0	3095	3095	0
August	32	249	144	136	0	2531	3092	0	0	0	3092	3092	0
September	32	615	187	282	0	2531	3647	0	0	0	3647	3647	0
October	32	1108	60	487	0	2531	4217	0	0	0	4217	4217	0
November	97	1526	14	681	0	2531	4848	0	0	0	4848	4848	0
December	607	1258	18	839	0	2531	5253	0	0	0	5253	5253	0
Average	267	975	68	545	0	2531	4386	0	0	0	4386	4386	0
Maximum	2590	3894	421	1779	0	2531	8595	0	0	0	8595	8595	0
Minimum	32	94	0	102	0	2531	2759	0	0	0	2759	2759	0
Total for the whole year TWh/year	2,35	8,56	0,59	4,79	0,00	22,23	38,52	0,00	0,00	0,00	38,52	38,52	0,00

RES Share: 31,6 Percent of Primary Energy 64,0 Percent of Electricity 26,1 TWh electricity from RES

Input Alternative 2030 — The EnergyPLAN model 9.0

Electricity demand (TWh/year):		Flexible demand	0,00
Fixed demand	40,59	Fixed imp/exp.	0,00
Electric heating	0,00	Transportation	0,00
Electric cooling	0,00	Total	40,59

District heating (TWh/year)	Gr.1	Gr.2	Gr.3	Sum
District heating demand	2,64	9,90	21,52	34,06
Solar Thermal	0,01	0,00	0,00	0,01
Industrial CHP (CSHP)	0,00	0,00	2,65	2,65
Demand after solar and CSHP	2,63	9,90	18,87	31,40

Wind	4500	MW	12,60	TWh/year	0,00	Grid
Offshore Wind	4600	MW	18,42	TWh/year	0,00	stabili-
River Hydro	0	MW	0	TWh/year	0,00	sation
Photo Voltaic	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	1945	2507	0,37	0,48	
Heat Pump	0	0			3,50
Boiler		3484		0,95	
Group 3:					
CHP	2500	3864	0,35	0,55	
Heat Pump	0	0			3,50
Boiler		7574		0,95	
Condensing	8552		0,42		

Heatstorage: gr.2: 40 GWh gr.3: 10 GWh
Fixed Boiler: gr.2: 2,5 Per cent gr.3: 1,0 Per cent

Electricity prod. from	CSHP	Waste (TWh/year)
Gr.1:	0,00	0,00
Gr.2:	0,00	0,97
Gr.3:	1,93	1,79

Regulation Strategy:	Market regulation NEW	
KEOL regulation	00000	
Minimum Stabilisation share	0,00	
Stabilisation share of CHP	0,00	
Minimum CHP gr 3 load	450	MW
Minimum PP	0	MW
Heat Pump maximum share	0,00	
Maximum import/export	2500	MW

Distr. Name :	Price_DKV_2008.txt	
Addition factor	0,00	DKK/MWh
Multiplication factor	1,12	
Dependency factor	0,02	DKK/MWh pr. MW
Average Market Price	473	DKK/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	0,85	
Hydro Turbine:	0		0,85	
Electrol. Gr.2:	0	0	0,73	0,07
Electrol. Gr.3:	0	0	0,73	0,07
Electrol. trans.:	0	0	0,73	
Ely. MicroCHP:	0	0	0,73	
CAES fuel ratio:	0,000			

(TWh/year)	Coal	Oil	Ngas	Biomass
Transport	0,00	62,03	0,00	3,78
Household	0,00	2,62	4,79	12,17
Industry	3,02	20,48	13,00	3,46
Various	0,00	8,38	9,23	0,00

Output WARNING!!: (1) Critical Excess;

	District Heating										Electricity																		Exchange	
	Demand	Production									Consumption						Production							Balance					Payment	
	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	Imp Million DKK	Exp Million DKK
January	6239	0	1179	477	3245	0	0	1339	0	0	5223	0	182	0	71	0	0	3218	0	0	534	2161	118	100	591	1146	124	1022	203	120
February	6384	0	1179	488	2773	0	0	1943	0	0	5167	0	182	0	88	0	0	4342	0	0	534	1824	77	100	333	1673	293	1380	96	97
March	5439	1	1179	415	2531	0	0	1300	0	13	4973	0	167	0	23	0	0	3696	0	0	534	1667	84	100	472	1290	162	1128	146	90
April	4358	2	1179	330	2250	0	0	613	0	-16	4383	0	133	0	2	0	0	3214	0	0	534	1516	91	100	323	1160	54	1106	106	134
May	3419	2	1179	257	1791	0	0	181	0	10	4276	0	99	0	0	0	0	3189	0	0	534	1231	314	100	381	1275	245	1030	114	156
June	1550	3	1179	111	829	0	0	53	0	-624	4156	0	29	0	0	0	0	3452	0	0	534	553	989	100	195	1538	205	1333	62	306
July	1550	2	1179	112	836	0	0	53	0	-632	3789	0	29	0	0	0	0	2378	0	0	534	558	1338	100	261	1252	150	1101	81	281
August	1550	2	1179	112	797	0	0	53	0	-593	4360	0	29	0	0	0	0	3152	0	0	534	529	1435	100	178	1440	187	1253	61	303
September	2379	1	1179	177	1169	0	0	53	0	-200	4474	0	60	0	0	0	0	3187	0	0	534	807	1640	100	40	1674	176	1498	15	395
October	3543	1	1179	268	1605	0	0	440	0	50	4641	0	103	0	0	0	0	4769	0	0	534	1088	147	100	98	1891	429	1462	36	157
November	4648	0	1179	354	2094	0	0	1021	0	0	5015	0	143	0	5	0	0	4566	0	0	534	1397	61	100	317	1712	350	1362	109	93
December	5550	0	1179	424	2753	0	0	1208	0	-13	5016	0	166	0	39	0	0	3272	0	0	534	1832	145	100	595	1157	197	959	205	95
Average	3878	1	1179	293	1888	0	0	684	0	-168	4621	0	110	0	19	0	0	3531	0	0	534	1263	538	100	316	1432	214	1218	Average price (DKK/MWh)	
Maximum	10897	14	1179	838	6371	0	0	6735	0	3950	7127	0	189	0	605	0	0	9100	0	0	534	4445	7371	100	2500	6603	4103	2500		
Minimum	1357	0	1179	98	696	0	0	53	0	-5987	2315	0	22	0	0	0	0	0	0	0	534	450	0	100	0	0	0	0	444	177
Total for the whole year																													Million DKK	
TWh/year	34,06	0,01	10,36	2,57	16,58	0,00	0,00	6,01	0,00	-1,47	40,59	0,00	0,97	0,00	0,17	0,00	0,00	31,02	0,00	0,00	4,69	11,09	4,72		2,78	12,58	1,88	10,69	1234	2227

FUEL BALANCE (TWh/year):

	DHP	CHP2	CHP3	Boiler2	Boiler3	PP	Geo/Nu.	Hydro	Elc./gas	Waste	CAES	Wind	Offsh.	Hydro	PV	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	-	0,16	13,60	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	3,02	-	16,79	-11,39	5,39	5,74	1,84
Oil	1,98	0,05	0,27	0,10	0,10	0,45	-	-	-	-	-	-	-	-	-	-	62,03	2,62	20,48	8,38	96,46	-0,43	96,03	25,70	25,58
N.Gas	-	2,54	1,77	4,45	1,50	-	-	-	-	-	-	-	-	-	-	-	-	4,79	13,00	9,23	37,27	-1,22	36,05	7,65	7,40
Biomass	0,74	3,11	9,51	0,10	0,10	10,69	-	-	-	12,33	-	-	-	-	-	-	3,78	11,54	3,46	-	55,37	-10,09	45,28	1,44	0,00
Renewable	-	-	-	-	-	-	-	-	-	-	-	12,60	18,42	-	-	0,51	-	-	-	-	31,53	0,00	31,53	0,00	0,00
H2 etc.	-	0,00	0,00	0,00	0,00	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0,00	0,00	0,00	0,00	0,00
Nuclear	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0,00	0,00	0,00	0,00	0,00
Total	2,72	5,86	25,15	4,65	1,70	11,15	-	-	-	12,33	-	12,60	18,42	-	-	0,51	65,81	18,95	39,96	17,61	237,42	-23,13	214,29	40,53	34,83

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Output specifications — Alternative 2030 — The EnergyPLAN model 9.0

District Heating Production

	Gr.1				Gr.2										Gr.3										RES specification				
	District heating MW	Solar MW	CSHP MW	DHP MW	District heating MW	Solar MW	CSHP MW	CHP MW	HP MW	ELT MW	Boiler MW	EH MW	Stor-age MW	Ba-lance MW	District heating MW	Solar MW	CSHP MW	CHP MW	HP MW	ELT MW	Boiler MW	EH MW	Stor-age MW	Ba-lance MW	RES1 Wind MW	RES2 Offshoı MW	RES3 River H MW	RES4 Photo \ MW	Total aic MW
January	484	0	6	477	1814	0	306	481	0	0	1027	0	1615	0	3942	0	866	2764	0	0	312	0	4025	0	1300	1917	0	0	3218
February	495	0	6	488	1856	0	306	231	0	0	1318	0	640	0	4033	0	866	2542	0	0	625	0	3759	0	1842	2501	0	0	4342
March	422	1	6	415	1581	0	306	230	0	0	1044	0	622	0	3436	0	866	2301	0	0	256	0	4577	13	1506	2190	0	0	3696
April	338	2	6	330	1267	0	306	467	0	0	495	0	3925	-2	2754	0	866	1783	0	0	118	0	5520	-14	1266	1948	0	0	3214
May	265	2	6	257	994	0	306	561	0	0	129	0	14607	-2	2160	0	866	1230	0	0	52	0	4527	12	1266	1923	0	0	3189
June	120	3	6	111	450	0	306	133	0	0	28	0	5237	-17	979	0	866	696	0	0	24	0	110	-608	1351	2101	0	0	3452
July	120	2	6	112	450	0	306	132	0	0	28	0	28513	-16	979	0	866	704	0	0	24	0	6178	-616	913	1465	0	0	2378
August	120	2	6	112	450	0	306	102	0	0	28	0	19268	14	979	0	866	696	0	0	24	0	6744	-608	1264	1888	0	0	3152
September	184	1	6	177	691	0	306	388	0	0	28	0	23118	-31	1503	0	866	782	0	0	24	0	7518	-170	1260	1927	0	0	3187
October	275	1	6	268	1030	0	306	383	0	0	289	0	11082	51	2239	0	866	1222	0	0	151	0	5135	-1	2013	2755	0	0	4769
November	360	0	6	354	1351	0	306	329	0	0	716	0	2494	0	2937	0	866	1765	0	0	305	0	4741	0	1930	2635	0	0	4566
December	430	0	6	424	1613	0	306	400	0	0	907	0	5133	0	3507	0	866	2352	0	0	301	0	5719	-13	1330	1943	0	0	3272
Average	301	1	6	293	1127	0	306	320	0	0	501	0	9748	0	2450	0	866	1568	0	0	183	0	4890	-168	1434	2097	0	0	3531
Maximum	845	14	6	838	3167	0	306	2507	0	0	2658	0	40000	1864	6885	0	866	3864	0	0	4224	0	10000	3314	4500	4600	0	0	9100
Minimum	105	0	6	98	395	0	306	0	0	0	28	0	0	-2413	858	0	866	696	0	0	24	0	0	-3652	0	0	0	0	0
Total for the whole year TWh/year	2,64	0,01	0,06	2,57	9,90	0,00	2,69	2,81	0,00	0,00	4,40	0,00		0,00	21,52	0,00	7,61	13,77	0,00	0,00	1,61	0,00		-1,47	12,60	18,42	0,00	0,00	31,02

ANNUAL COSTS (Million DKK)

Total Fuel =		76811
Coal =	1618	
FuelOil =	10781	
Gasoil/Diesel=	21843	
Petrol/JP =	19457	
Ngas =	11841	
Biomass =	11272	
Food income =	0	
Waste =	0	
Marginal operation costs =		344
Total Electricity exchange =		-1781
Import =	1234	
Export =	-2227	
Bottleneck =	-788	
Fixed imp/ex=	0	
Total CO2 emission costs =		12240
Total variable costs =		87614
Fixed operation costs =		0
Annual Investment costs =		0
TOTAL ANNUAL COSTS =		87614

	DHP aı 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	Stor-age MW	Sum MW	Im-port MW	Ex-port MW
January	1329	788	0	961	0	2531	5608	0	0	0	5608	5608	0
February	1916	535	0	986	0	2531	5967	0	0	0	5967	5967	0
March	1295	503	0	820	0	2531	5148	0	0	0	5148	5148	0
April	611	650	0	630	0	2531	4421	0	0	0	4421	4421	0
May	179	663	0	465	0	2531	3838	0	0	0	3838	3838	0
June	51	209	0	136	0	2531	2927	0	0	0	2927	2927	0
July	51	209	0	136	0	2531	2927	0	0	0	2927	2927	0
August	51	181	0	136	0	2531	2899	0	0	0	2899	2899	0
September	51	450	0	282	0	2531	3314	0	0	0	3314	3314	0
October	433	502	0	487	0	2531	3953	0	0	0	3953	3953	0
November	1009	523	0	681	0	2531	4743	0	0	0	4743	4743	0
December	1198	662	0	839	0	2531	5231	0	0	0	5231	5231	0
Average	677	490	0	545	0	2531	4243	0	0	0	4243	4243	0
Maximum	6479	2755	0	1779	0	2531	10711	0	0	0	10711	10711	0
Minimum	51	89	0	102	0	2531	2774	0	0	0	2774	2774	0
Total for the whole year TWh/year	5,95	4,30	0,00	4,79	0,00	22,23	37,27	0,00	0,00	0,00	37,27	37,27	0,00

RES Share: 36,6 Percent of Primary Energy 105,1 Percent of Electricity 42,8 TWh electricity from RES

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