100% Renewable Energy Systems in the Scandinavian Region

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Synopsis:

Denmark has set an ambitious goal to become 100% renewable by 2050, and this study aims to investigate further how Denmark could achieve this goal. Specifically the study aims to help understand the implications for Denmark when it is interconnected in a Scandinavian system in a 100% renewable energy system in 2050. This study compares three energy system types (supergrid, smart grid and smart energy system) for Denmark within in a Scandinavian context. In this study two extreme situations were developed being a fully interconnected and fully Disconnected Scandinavian system, using the energy systems of Denmark, Sweden and Norway from 2009. A range of technological solutions that represented each energy system type (e.g. EVs, biofuels, heat pumps, district heating) were modelled in sequential implementation steps and were assessed within the context of the two extreme Scandinavian systems to determine wind integration ability, fossil fuel and biomass demand, socio-economic costs and CO_2 emissions for each step.

It was found that the fully Connected Scandinavian system has lower fuel demand, and improved wind integration compared to the Disconnected Scandinavian system in all steps. However the ideal level of interconnection was not identified in this study. The benefits for Denmark are incalculable using the methodology applied in this study however it is expected that some of the benefits from having a Connected Scandinavian system would likely be allocated to Denmark for wind integration and fuel savings. This area needs further investigation.

All energy system types will be able to meet the future renewable energy policy targets, but with large differences in terms of fuel demand in the form of biomass. A combination of the three energy systems is the ideal situation, and there are no technological fixes that alone would allow a conversion towards a realistic 100% renewable society in the future. Measures should relate to energy conservation technologies, renewable energy sources and improved efficiency of supply systems. Further research should be focused on policy development that supports a level playing field between the different energy system types in the future.

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Abstract

Denmark has set an ambitious goal to become 100% renewable by 2050, and this study aims to investigate further how Denmark could achieve this goal. Specifically the study aims to help understand the implications for Denmark when it is interconnected in a Scandinavian system in a 100% renewable energy system in 2050. This study compares three energy system types (supergrid, smart grid and smart energy system) for Denmark within in a Scandinavian context. In this study two extreme situations were developed being a fully interconnected and fully Disconnected Scandinavian system, using the energy systems of Denmark, Sweden and Norway from 2009. A range of technological solutions that represented each energy system type (e.g. EVs, biofuels, heat pumps, district heating) were modelled in sequential implementation steps and were assessed within the context of the two extreme Scandinavian systems to determine wind integration ability, fossil fuel and biomass demand, socio-economic costs and CO_2 emissions for each step.

It was found that the fully Connected Scandinavian system has lower fuel demand, and improved wind integration compared to the Disconnected Scandinavian system in all steps. However the ideal level of interconnection was not identified in this study. The benefits for Denmark are incalculable using the methodology applied in this study however it is expected that some of the benefits from having a Connected Scandinavian system would likely be allocated to Denmark for wind integration and fuel savings. This area needs further investigation.

All energy system types will be able to meet the future renewable energy policy targets, but with large differences in terms of fuel demand in the form of biomass. A combination of the three energy systems is the ideal situation, and there are no technological fixes that alone would allow a conversion towards a realistic 100% renewable society in the future. Measures should relate to energy conservation technologies, renewable energy sources and improved efficiency of supply systems. Further research should be focused on policy development that supports a level playing field between the different energy system types in the future.

Preface

This report is the result of a Master Thesis project carried out between February 3rd 2014 and June 4th 2014 in the master programme Sustainable Cities at Aalborg University Copenhagen, Denmark.

The supervisor of the project was Brian Vad Mathiesen, Professor with Specific Responsibilities, Department of Development and Planning, Aalborg University Copenhagen.

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Glossary

CCS - Carbon capture and storage. A technology for collecting and storing carbon so it is not released into the atmosphere.

CHP - Combined Heat and power plant. A technology using cogeneration operation to produce electricity and heat at the same time.

Connected Scandinavia - An interconnected energy system analysed in this report where the Danish, Swedish and Norwegian energy systems act as if they were one combined system.

CO_2 - Carbon dioxide. Is a chemical compound contributing to the greenhouse effect and the climate change when released in large quantities into the atmosphere.

Disconnected Scandinavia - A disconnected energy system analysed in this report where the Danish, Swedish and Norwegian energy systems do not import or export electricity between each other, but are aggregated in a Scandinavian energy system in this study.

Energy system type - The name for the energy systems that are analysed in the report, i.e. supergrid, smart grid and smart energy system

EVs - electric vehicles. A transport technology for example cars and light vans using electricity as a propellant

IEA - International Energy Agency. An intergovernmental energy organisation conducting research and collecting statistical data for energy sectors worldwide

Lock-in - A situation where certain technologies, institutions, actors or other aspects due to stabilising mechanisms have more or less locked the system

Path-dependency - Explains why decisions are made based on previous decisions that follow the same path, as it seems easier or cheaper

PP - Power plants. Condensing power plants produce electricity only, but with a higher electricity efficiency than for example CHP plants

Synfuel - Transport fuel produced through chemical synthesis, usually using biomass and hydrogen, that can be used as a replacement for fossil fuels in the transport sector

Technological solution - The term used in this report for technologies that are part of the energy system types

Unused electricity - Electricity that cannot be used within the country and has to be exported or which forces technologies to shut down

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1 Summary of findings

This study is carried out to analyse the Danish energy system in the context of the Scandinavian countries (Denmark, Sweden and Norway) when different technological solutions and energy systems types are modelled for 2050. Hence, the findings for the Scandinavian countries and systems are presented as well as the findings for the Danish energy system.

This section provides a summary of the findings from the five energy systems assessed in the study (Sweden, Denmark, Norway, Disconnected Scandinavia and Connected Scandinavia) and how the future energy system types and technological solutions impact the integration of wind, fuel demand (biomass), socio-economic costs and CO_2. The technological solutions are compared with each other by modelling different amounts of wind integration from 0-100% of electricity demand. In addition, different future energy system types which include A (supergrid), B (smart grid) and C (smart energy system) are analysed for wind integration abilities. The point where unused electricity begins to be produced above a 5% curtailment threshold is the point plotted on the figures below for each step.

Note: Electric vehicles (EVs) are included in steps 2b and 5b to finalise energy system type A and Energy system type B but since the steps build on top of each other these b steps are removed before the next steps continue being step 3 and step 6. Therefore the results for the steps should be read from step 2 to 3 and step 5 to 6.

The findings are described in more detail in chapter 5 Results and Appendix E – Supplementary results while the methodology is described in chapter 4 Methodology.

1.1 Scandinavian energy systems

The main findings for the Scandinavian countries and energy systems are presented below.

1.1.1 Wind integration potential

The ability for the different countries and the Scandinavian systems to integrate wind is presented below in Figure 1 and Figure 2.

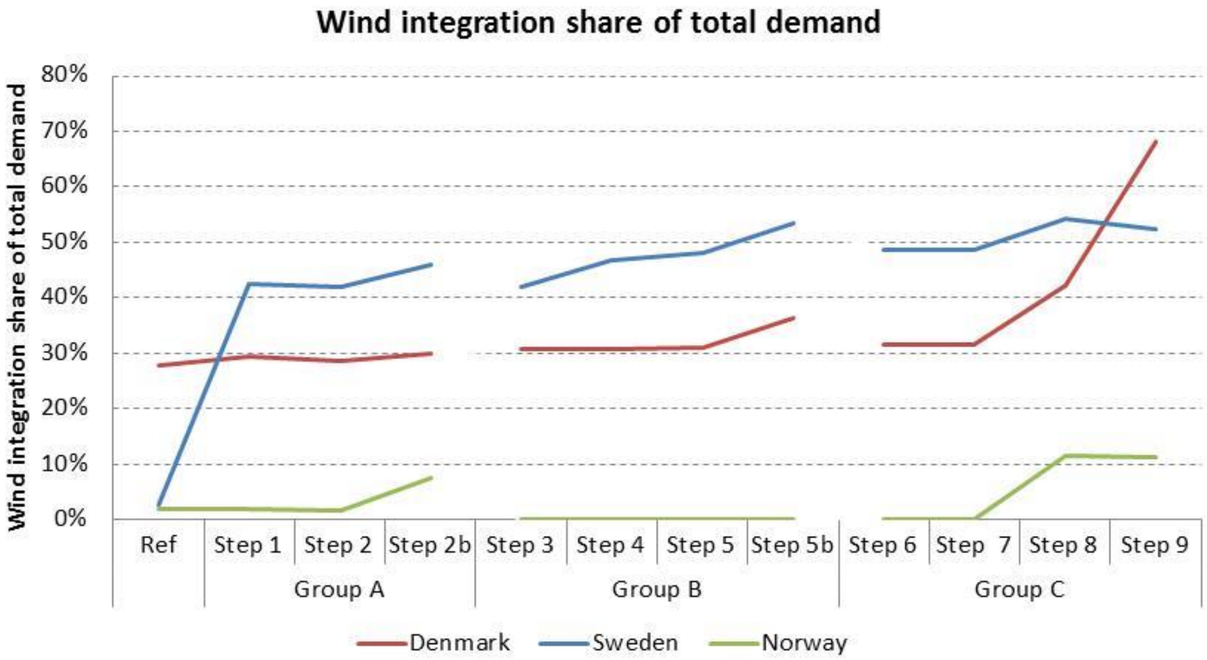

Figure 1: Wind integration share of total demand for the Danish, Swedish and Norwegian energy systems

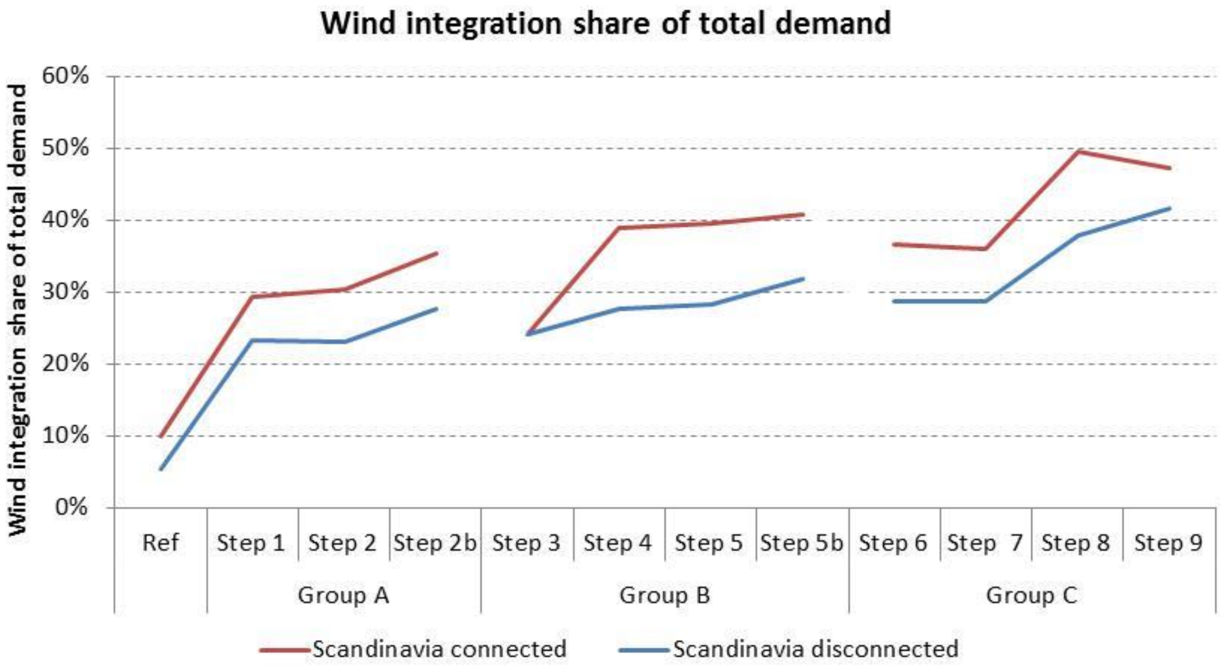

Figure 2: Wind integration share of total demand for the Connected and Disconnected Scandinavian energy systems

- Step 1 shows the greatest increase in wind integration, due to the removal of nuclear power in Sweden which affects the overall Scandinavian systems. The transition from fossil fuels to biomass in industry and the heating and power sector in step 1 has little influence on wind integration.

- All the steps where electric vehicles are integrated in the system show improvements for the integration of wind, i.e. steps 2b, 5b and 8. The system with the largest improvement is step 8 due to a large increase in electricity demand as both electric vehicles and electrolysers for synfuel production are introduced to the system.

- In step 4 where the industry is electrified this improves the wind integration especially for the Connected Scandinavia system. For the Danish system step 9 causes the largest improvement due to the removal of grid stabilisation regulation on power plants since grid stabilisation is delivered by other technologies.

- Only a few steps worsen the wind integration and one of these is step 3 where heat pumps replace individual boilers and electric heating, thereby reducing the electricity demand for Sweden and Norway. This reduction in electricity demand decreases the ability to integrate further wind.

- In energy system type A the Swedish system changes from 3% wind integration in the reference system to 46% in energy system type A while the Disconnected Scandinavia increases from 5% to 28%. The Connected Scandinavia system increases from 11% to 34%. Small improvements are also gained in Denmark and Norway.

- In energy system type B the wind integration is improved by between 4-7% compared with energy system type A for all the energy systems in the countries, except for Norway that cannot integrate any wind power in energy system type B. This is because some of the steps cause a reduced electricity demand that gets lower than the hydropower production.

- In energy system type C the wind integration is improved further compared to the other energy system types. The Danish energy system increases the amount of wind that can be integrated significantly from 36% to 68%, especially when the grid stabilisation regulation for power plants is removed in step 9. For Norway the electricity demand increases which allows for wind to be integrated again.

- The Connected Scandinavia system is able to integrate more wind for all steps and energy system types compared to the Disconnected Scandinavia system. The maximum wind that can be integrated in all the steps for the countries are: Sweden = 54%, Norway = 12%, Denmark = 68%, Disconnected Scandinavia = 42% and the Connected Scandinavia = 50%.

1.1.2 Fossil fuel and biomass demand

The fuel demand for the different countries and the Scandinavian systems are presented below in Figure 3 and Figure 4.

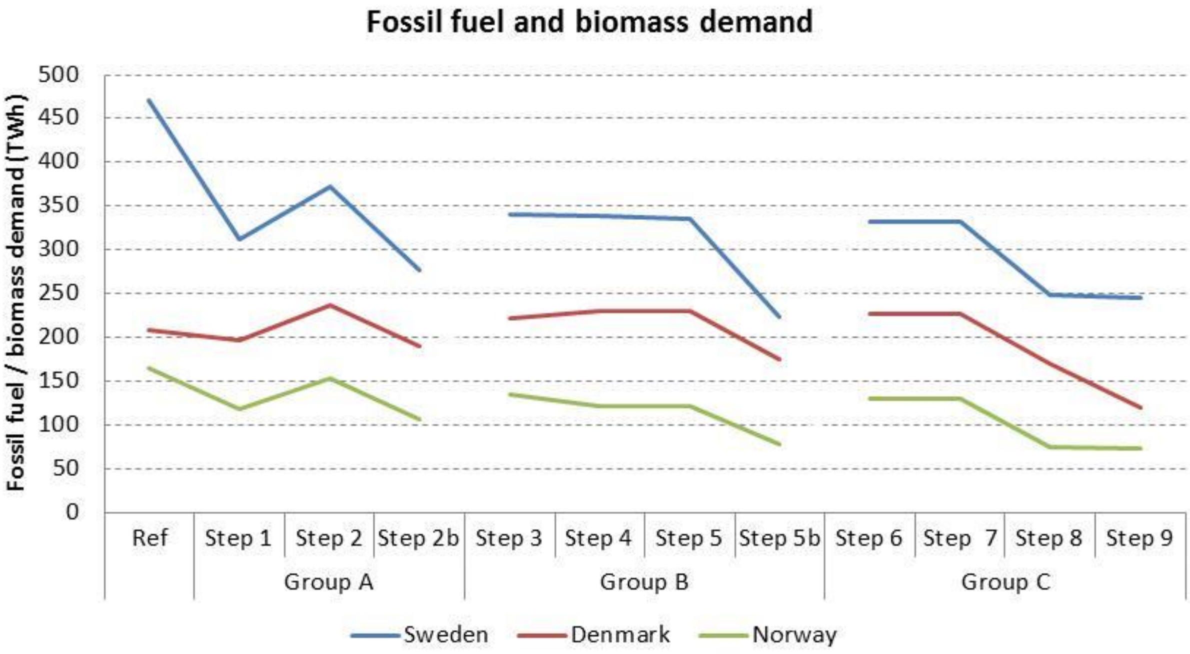

Figure 3: Fossil fuel and biomass demand for the Danish, Swedish and Norwegian energy systems

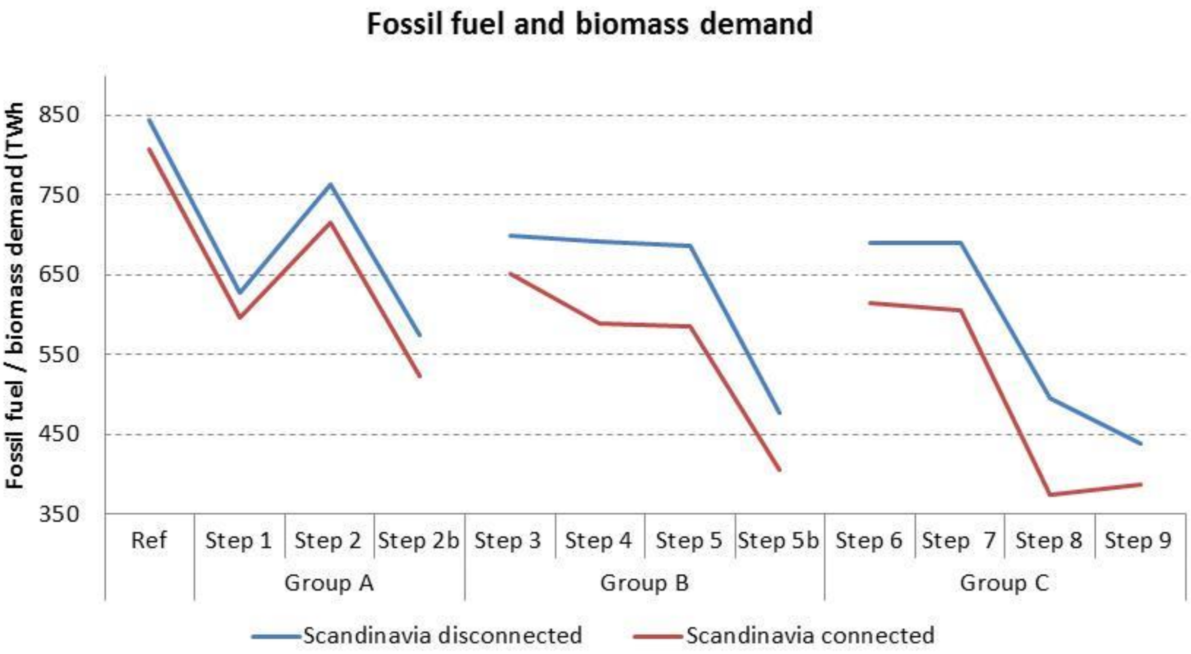

Figure 4: Fossil fuel and biomass demand for the Connected and Disconnected Scandinavian energy systems

- Step 1 improves the energy efficiency in terms of fuel demand as the nuclear power in Sweden is removed and replaced by wind power and power plants, and natural gas flaring is removed in Denmark and Norway. The Scandinavian energy systems are also improved significantly due to the removal of nuclear power and natural gas flaring.

- For all the steps where electric vehicles are implemented large fuel savings occur, which includes steps 2b, 5b and 8.

- Step 2 increases the fuel demand for all countries because of lower efficiency in the system from producing biofuels, especially biopetrol and biojetfuel. When liquid fuels are produced from biomass a larger fuel demand is needed for the same fuel requirement.

- In step 3 replacing electric heating and individual boilers with individual heat pumps improves the fuel efficiency. This is because the heat pumps are more efficient than the existing technologies.

- Step 6 causes an increased fuel demand for some of the systems as the electricity demand decreases when district heating replaces some heat pumps and hence less wind can be integrated.

- The largest fuel savings are in energy system type C, which are slightly better savings than in energy system type B. The fuel savings in energy system type C for Sweden reach 44% compared to the reference fuel demand, for Denmark the savings are 31%, for Norway 55%, for the Disconnected Scandinavia system it is 43% while the fuel demand is reduced by 45% for the Connected Scandinavia system compared to the reference system.

- The biomass demand for all Scandinavian systems and individual countries is higher than the domestic biomass potentials in each country.

1.1.3 Socio-economic costs

The socio-economic costs for the different countries and the Scandinavian systems are presented below in Figure 5 and Figure 6.

Note: the socio-economic costs can vary in the future leading to uncertainty and therefore these results should be investigated further over the next few years.

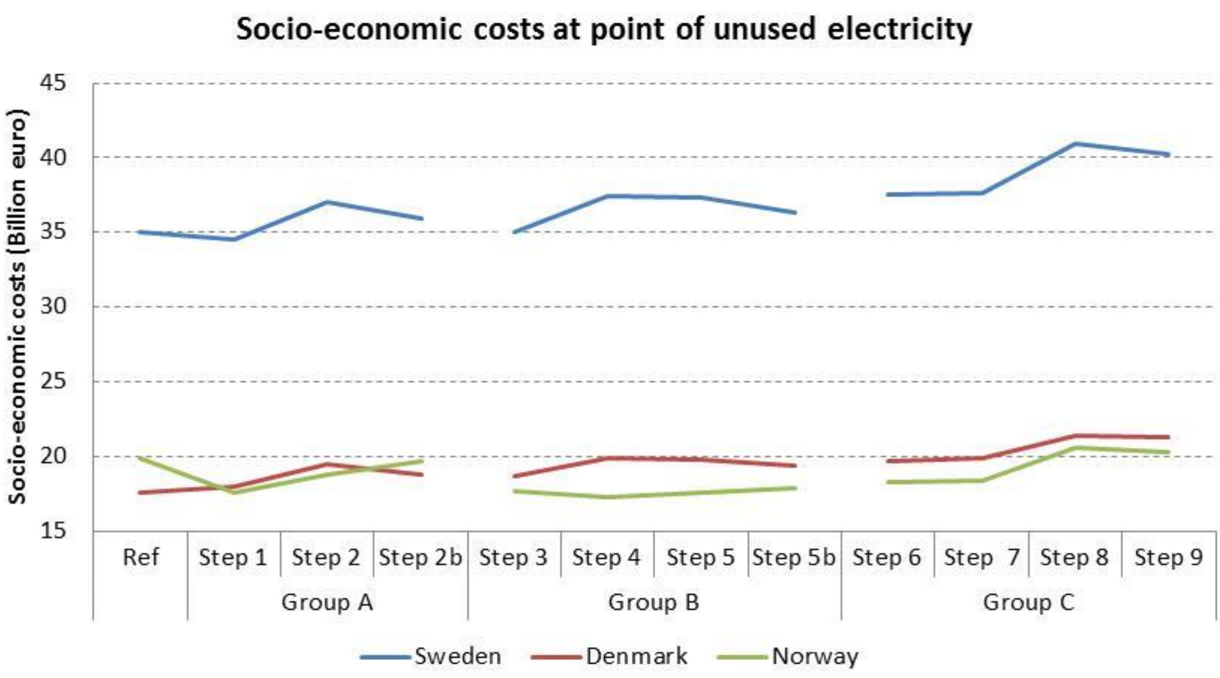

Figure 5: Socio-economic costs for the Danish, Swedish and Norwegian energy systems

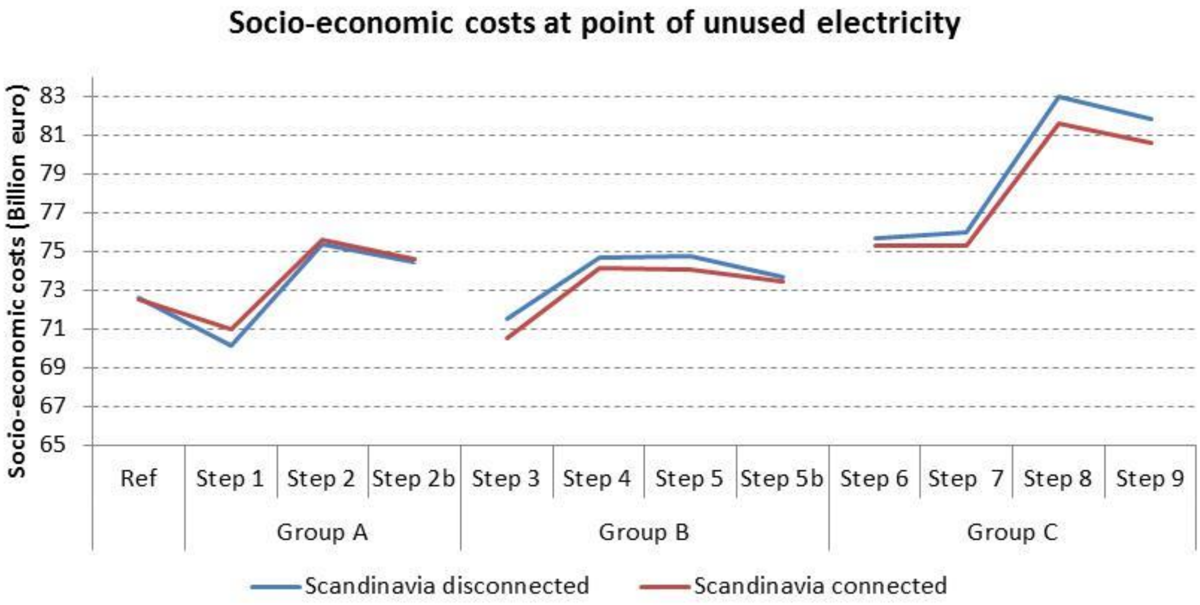

Figure 6: Socio-economic costs for the Danish, Swedish and Norwegian energy systems

- In Sweden the costs increase by 4% in energy system type B and 15% in energy system type C while the Norwegian costs decrease by 10% in energy system type B and increase by 2% in energy system type C compared to the reference system.

- When comparing the two Scandinavia systems the costs are highest for the Connected Scandinavia system in energy system type A by a very small amount, while the Disconnected Scandinavia system has the higher costs in energy system types B and C. This is without including transmission cable costs. The Disconnected Scandinavia system has higher costs by around 13% in energy system type C while the Connected Scandinavia system increases by 11% in energy system type C.

1.1.4 Carbon dioxide emissions

- The CO_2-emissions only exist in the reference system and step 1 as all the fuels after the implementation of step 2 are renewable. Reductions are therefore only carried out in step 1 and 2. The reductions between the two steps are rather similar for most of the systems, except for Denmark where the reduction is largest in step 1 due to a larger share of CO_2 emissions from thermal production than in the other systems.

1.2 Denmark main findings

This report is conducted with a main focus on the Danish society within the Scandinavian context and hence this chapter describes the main findings for the Danish energy system for the different energy system types and technological solutions.

1.2.1 Denmark connected to the Scandinavian system

No clear conclusions can be drawn about the level of connection the Danish system should have in the Scandinavian system. However, it is clear that when the Scandinavian energy system is connected it can integrate more wind and has lower fuel demands than when it is not connected. Hence, the difference between the Connected and Disconnected systems is where Denmark could experience benefits. Part of the improvements and savings of the Connected Scandinavia system might be allocated to Denmark along with Sweden and Norway.

The results for the Danish energy system are presented below for the different energy system types and technological solutions.

1.2.2 Wind integration potential

The ability for Denmark to integrate wind is presented below in Figure 7 and Figure 8.

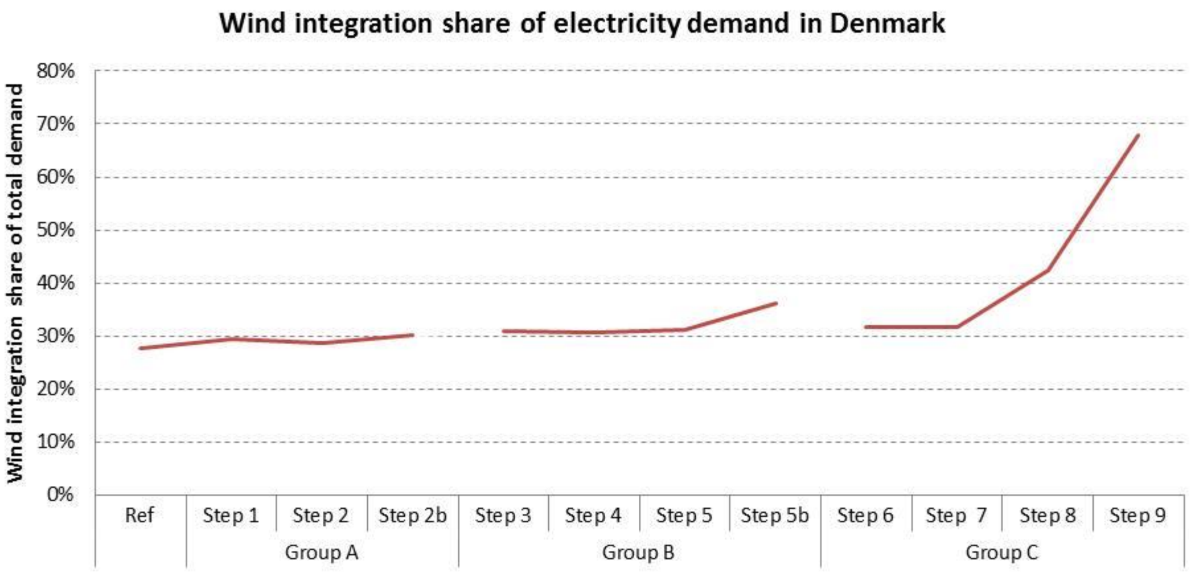

Figure 7: Wind integration share of electricity demand in Denmark for energy system types and steps

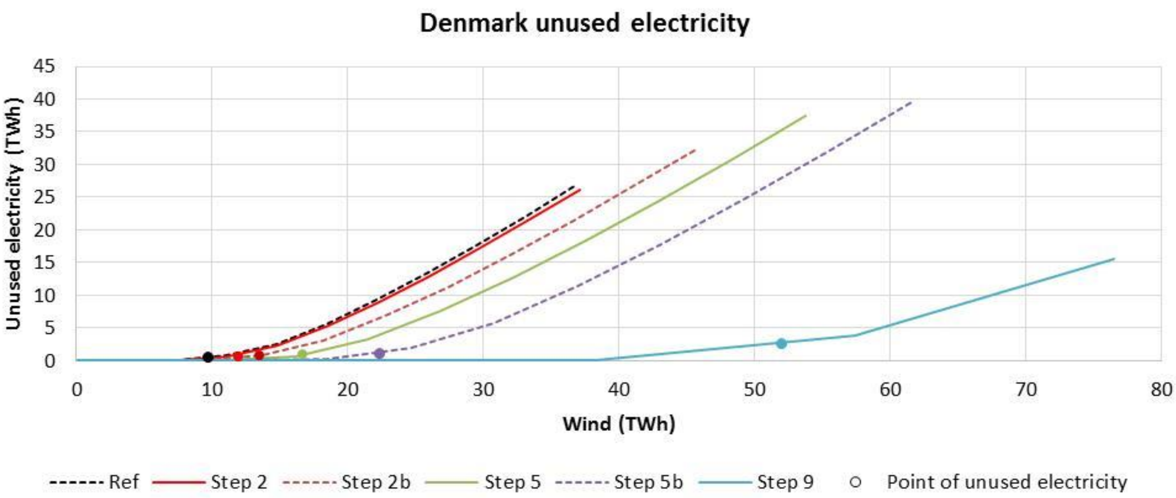

Figure 8: Unused electricity curves for Denmark for selected steps with integration of wind from 0-100% of electricity demand

- The wind integration for all the energy system types continuously improves, with energy system type C being able to integrate the most wind (68%) before unused electricity is produced.

- Even though the system can integrate more wind when integrating electric vehicles in step 2b the increasing electricity demand means that the percentage share of wind changes very little.

- Individual heat pumps and electrification of industry in step 3 and 4 improves the amount of wind integration, but as both of them also cause higher electricity demand, the share of wind that can be integrated remains almost the same.

- Electric vehicles in step 5b improve the integration of wind due to a smart charging strategy instead of dump charge such as in step 2b.
- Electric vehicles and synfuels for heavy transport in step 8 improve the integration of wind electricity due to higher electricity demand and electric vehicles using smart charge.
- In step 9 the gasification of biomass improved the integration of wind significantly. The difference between the reference system and step 9 in terms of wind integration improves from 27% to 68% of the electricity demand. Due to removal of grid stabilisation regulation from thermal technologies it is possible to integrate further wind.

1.2.3 Fossil fuel and biomass demand

The fossil fuel and biomass demand for Denmark is presented below in Figure 9 and Figure 10.

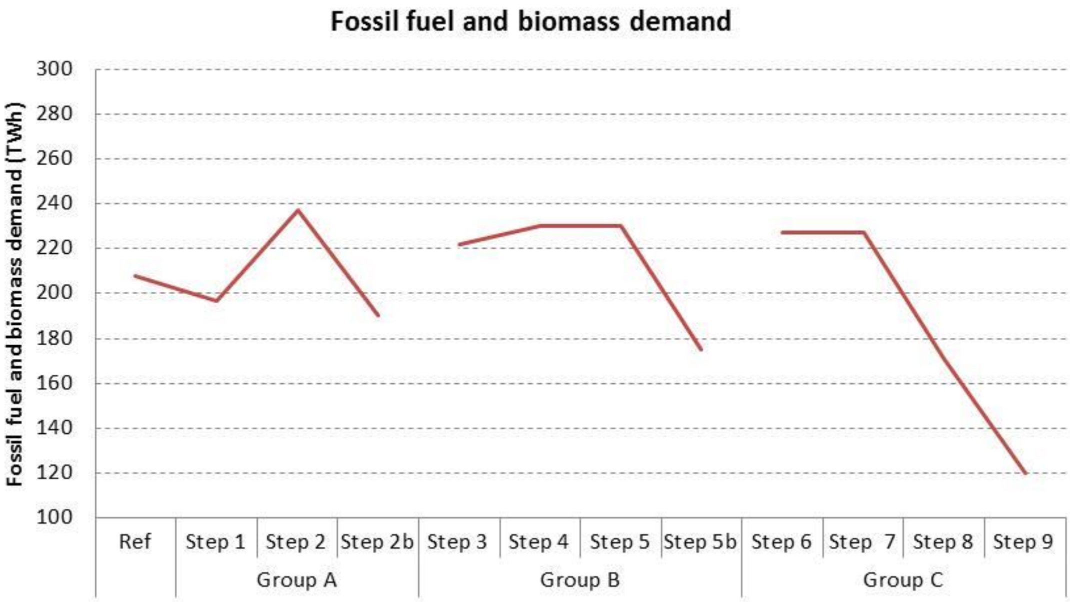

Figure 9: Fossil fuel and biomass demand in Denmark for energy system types and steps

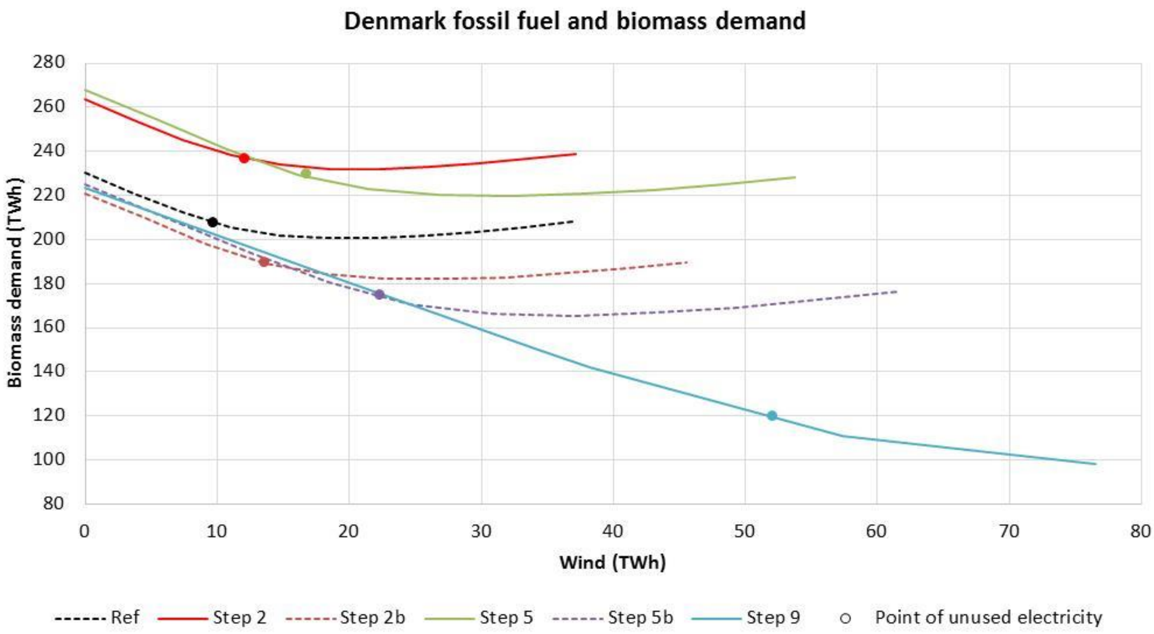

Figure 10: Fossil fuel and biomass demand for Denmark for selected steps with integration of wind from 0-100% of electricity demand

- The fuel demand reduces for step 1 due to the removal of natural gas flaring while in step 2 the fuel demand increases to a level higher than the reference system when implementing biofuels in the transport sector. This is because biofuels require a higher energy input per fuel output than fossil fuels.

- When implementing electric vehicles in steps 2b, 5b and step 8 the fuel demand is improved to a level below the reference system. The implementation of electric vehicles for all energy system types reduces the fuel demand.

- The integration of electric vehicles and synfuels in step 8, and the gasification of biomass in step 9 reduces the fuel demand significantly to a level of 120 TWh compared to 208 TWh in the reference system, which equals a reduction of 42%.

- For energy system types A and B fuel reductions only occur compared to the reference system when electric vehicles are implemented, otherwise the fuel demand is increasing.

- For energy system type C the fuel demand when conducting all the steps in this energy system type is lower than in the reference system, and causes a reduction of up to 42% at the point of unused electricity, compared to the reference system.

- The biomass demand in Denmark is higher than the available domestic potential and more measures (e.g. conservation) are required to meet the biomass demand

1.2.4 Socio-economic costs

The socio-economic costs for Denmark are presented below in Figure 11 and Figure 12.

Note: the socio-economic costs can vary in the future, which leads to higher uncertainty, and therefore these results should be investigated further over the next few years.

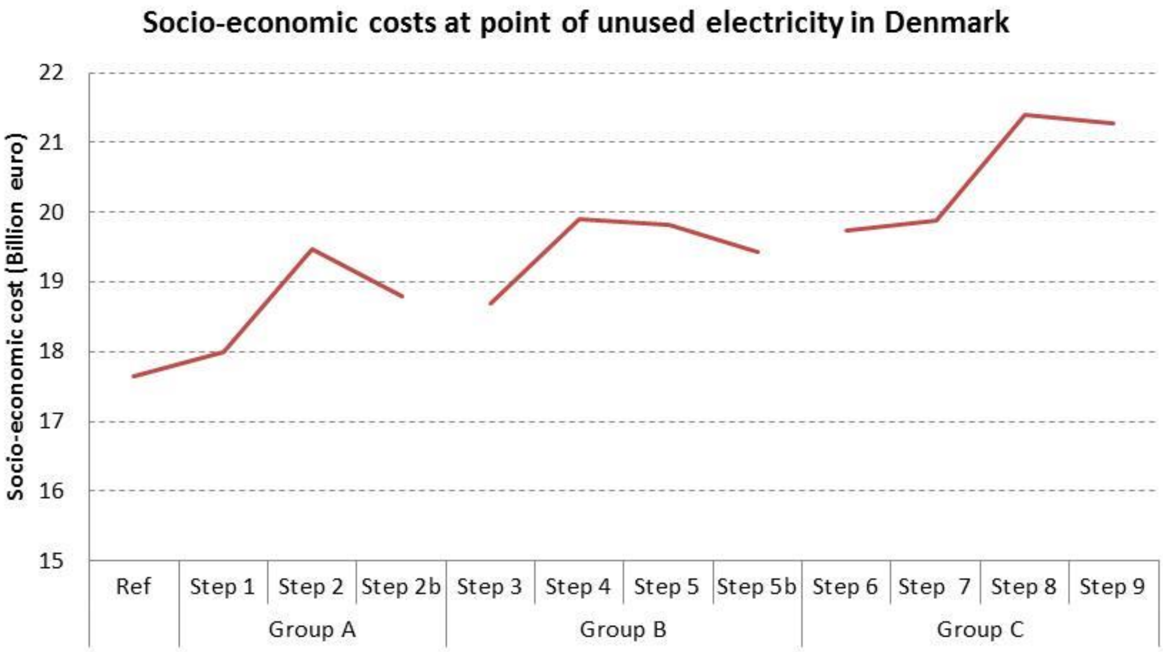

Figure 11: Socio-economic costs in Denmark for energy system types and steps

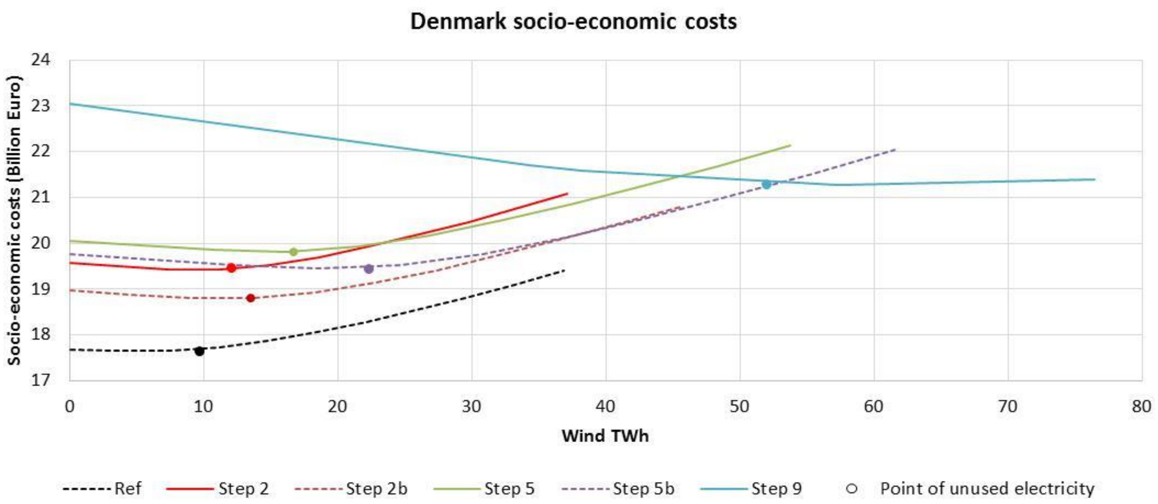

Figure 12: Socio-economic costs for Denmark for selected steps with integration of wind from 0-100% of electricity demand

- Step 2 causes higher costs due to increased investment costs for biofuel plants while the fuel costs decrease slightly due to lower prices for biomass compared to fossil fuels.

- For technologies in steps 3-5b the costs increase slightly. When implementing district heating and large heat pumps in steps 6 and 7 the costs remain almost constant to the previous steps.

- The implementation of synfuel technologies in step 8 have around the same costs as for biofuel production, but the integration of EVs increases costs to a level higher than step 7. This is due to the high operation and maintenance costs for EVs.

- All the energy system types range between 18-21 billion euro while the reference costs are 17.6 billion euro. All the technological solutions result in increased costs compared to the existing energy system. One of the reasons for this might be the replacement of coal with biomass that has higher costs and that the replacement of fuels with wind does not outweigh the increased investment costs for example for wind or for EVs.

- Overall, the costs in energy system types A, B and C increase by 7%, 10% and 21%, respectively for the last step of each energy system type compared to the reference system costs.

1.2.5 CO_2 emissions

- The CO_2 emissions are reduced to 0 Mt from step 2 and onwards as the systems are supplied solely by renewable sources such as biomass and wind.

2 Introduction

It is predicted by the Intergovernmental Panel on Climate Change (IPCC) that global warming by over 2°C over preindustrial times is dangerous for humanity (Solomon et al. 2007). In the latest IPCC report the temperature increase is 0.85°C in the period 1880-2012 (Stocker et al. 2013). As of 2013 it is 95% certain that human induced greenhouse gas emissions are a dominant contribution to this rising temperature (Stocker et al. 2013).

As shown in climate research as the concentration of CO_2 increases in the atmosphere the atmospheric temperature also increases due to the greenhouse effect (Stocker et al. 2013). As stated in Hansen et al. (2008), pg.1 "*If humanity wishes to preserve a planet similar to that on which civilization developed and to which life on Earth is adapted*" the limit for atmospheric CO_2 emissions is maximum 350 ppm (parts per million), which the planet has already passed. As of May 11 2014 the atmospheric concentration of CO_2 was 401.79 ppm and the level is still increasing (NOAA 2014).

IPCC state that an increase of temperature of 2-3°C would increase the possibility of extreme weather events, such as increased intensity of storms, flooding, biodiversity loss, droughts and so on, all affecting human life (Field et al. 2014).

2.1 Renewable energy transition

Since the majority of energy is sourced from fossil fuels in modern societies today (87% globally in 2011 (IEA 2013a)), the focus for solving the climate issue is being placed on transitioning away from fossil fuels to energy sources that are less carbon intensive and renewable.

Numerous countries and regions are now trying to shift towards a renewable energy future, such as Denmark, and a number of academic studies have been carried out researching ways to achieve this (Renewables 100 Policy Institute 2014). Research has been carried out looking purely at the country or region becoming 100% renewable including countries in Europe, such as in Denmark (Lund and Mathiesen 2009), Ireland (Connolly et al. 2011), Macedonia (Ćosić, Krajačić, and Duić 2012), including some Islands in Europe (Duić and da Graça Carvalho 2004), but also in New Zealand (Mason, Page, and Williamson 2010) and Australia (Elliston, Diesendorf, and MacGill 2012).

Some studies focus on elements of the energy system that would contribute to a 100% renewable energy system, such as the transmission and distribution grid, for example the supergrid (Macilwain 2010; Xydis 2013; Purvins et al. 2011; Torriti 2012; Rodríguez et al. 2014), smart grids (Kempton and Tomić 2005; Moslehi, Kumar, and Member 2010; Crossley and Beviz 2009; Orecchini and Santiangeli 2011; H. Lund et al. 2012), and smart energy systems (Lund et al. 2012; Lund et al. 2010; Lund and Mathiesen 2009). Research has begun to compare these different energy system types (Blarke and Jenkins 2013; Steinke, Wolfrum, and Hoffmann 2013) and to investigate the combination of these energy system types creating supersmart grids for example (Battaglini et al. 2009).

Some studies investigate the technologies that should be integrated in order to integrate more renewable energy (Lund and Mathiesen 2008; Kiviluoma and Meibom 2010; Kempton and Tomić 2005).

Other studies have focused on other aspects of 100% renewable energy systems such as economic outcomes (Karlsson and Meibom 2008), and biomass potentials for creating 100% renewable systems for specific countries (Scarlat et al. 2011).

As evidenced in the diversity of research covering the topic, the transition to a renewable energy system is a complex and drawn out process extending over numerous decades, and the pathway to a renewable energy system is not fully understood. The pathway is continuously evolving through continuous research and analysis.

However in saying this, it has become evident that three main energy system types have been identified for integrating large-scale renewable energy, namely supergrid, smart grid, and smart energy systems, or a combination of these.

2.2 Future energy system types

The energy system types that have been identified in the literature review and that will be analysed in this report are described below. The descriptions of these types of energy systems described derives from the literature review conducted in this report and does not reflect any external partners' perspectives.

2.2.1 Supergrid energy system

Supergrid is defined in broad terms as a way of connecting production zones of high renewable energy potential with high demand zones. The North Sea region is an example of exporting wind electricity to the high electricity demanding central European countries. A key difference from a traditional grid is the reliance on direct current (DC) cables (Macilwain 2010b).

A definition for a supergrid provided by (Blarke and Jenkins 2013) is:
"*The SuperGrid relies on the mechanism of cross-system electricity exchange (export and import) across systems with different intermittency sources, balancing technologies, and demand patterns. This mechanism makes it theoretically possible to handle large-scale penetration of intermittent resources without any short to medium-term need for storage or demand flexibility*" (Blarke and Jenkins 2013, P. 382).

Or alternatively in Europe's case:
"*A pan-European transmission network facilitating the integration of large-scale renewable energy and the balancing and transportation of electricity, with the aim of improving the European market*" (Friends of the supergrid 2014).

Some of the characteristics for a supergrid system are (European Commission 2011a; Battaglini et al. 2009; Blarke and Jenkins 2013):

- The construction of electricity corridors or electricity highways for prioritised corridors.
- Connection of different production and consumption centres to integrate more renewable energy, for example across Europe and Northern Africa.
- The supergrid might allow a country to produce more electricity than it needs since it can sell this elsewhere.
- Individual countries can be influenced by the supergrid since it allows more electricity to be imported and exported over great distances and thus replace the need for local production.

The key characteristic of the supergrid is the greater interconnections between the countries in order to optimise the balancing power and integration of renewable sources. Hence, the key principle is to use the benefits of the energy systems between different countries. Therefore no new technologies are required as such, as in theory it could continue from the existing system, using 100% renewable sources.

This also applies for Denmark that is already connected to the neighbouring countries, but with a supergrid system the potential benefits could be increased even more.

The development of interconnections that are required in a supergrid includes high investment costs and hence the cables must be used in order to pay back the initial costs.

2.2.2 Smart grid energy system

The smart grid is defined as (European Commission 2011a):

"*Electricity networks that can cost efficiently integrate the behaviour and actions of all users connected to it – generators, consumers and those that are both – in order to ensure economically efficient, sustainable power* *systems with low losses and high levels of quality and security of supply and safety*" (European Commission 2011, P. 36).

Or alternatively defined as (Danish Ministry of Climate, Energy and Buildings 2013):
"*An energy system with a smart grid design requires greater exploitation of the energy from wind as soon as it is produced, for example by heats pump and electric cars. This will allow for greater exploitation of cheap wind turbine electricity, and it will mean less need to expand the electricity infrastructure to meet new electricity consumption.*" (Danish Ministry of Climate, Energy and Buildings 2013, P. 7).

Some of the characteristics for a smart grid system are (Lund et al. 2012; Giordano et al. 2011; Danish Ministry of Climate 2013):

- The smart grid consists of a bi-directional power-flow meaning that the consumers could potentially produce electricity for the grid;
- "Approaches regarding smart grids all seem to have a sole or predominant focus on the electricity sector." (Henrik Lund et al. 2012, P. 97);
- It is expected that all consumers by 2020 will have remotely-read hourly meters in order to enhance the flexibility of the energy system, for example through flexible demand; and
- Key capabilities include the integration of:
    - Distributed energy resources
    - Demand-response
    - Large-scale renewable energy sources

As opposed to the supergrid, the smart grid operates within country rather than between countries. It focuses on managing electricity in the country with end-users and with producers. In saying this, a smart grid and supergrid can operate in conjunction with each other to some extent, but not always in the most optimum level (Blarke and Jenkins 2013).

The key principle about smart grids is that it can align the demand and production of electricity by improving the flexibility of the system by for example integrating improved communication facilities and technologies.

2.2.3 Smart energy system

A definition of a smart energy system is (Blarke and Jenkins 2013):
"*Relies on the mechanism of storage and relocation (coupling of energy carriers, e.g. integrating heat and transport and cooling) under constraint of strict system boundaries. Storage and relocation makes it theoretically possible to handle large-scale penetration of intermittent resources without any excess electricity transmission and distribution capacity*" (Blarke and Jenkins 2013, P. 383).

Some of the characteristics for a smart energy system are (Lund et al. 2012):

- It can be an option to help electricity balancing by converting electricity into various energy carrying gases and liquids;
- The integration of renewable energy into the electricity sector must be coordinated with other sectors; and
- Seeing the electricity sector as part of a complete sustainable energy system paves the way for better and more cost-effective solutions to smart grid applications compared to looking at the electricity sector as a separate part of the energy system

Unlike the supergrid and smart grid, the smart energy system incorporates all components of the energy sector, including transport and the heating sector, so that they function in conjunction with each other. In general the smart energy system might include a smart grid, but not a supergrid since the smart energy system relies on decentralised distributed solutions rather than inter-country exchange of electricity for balancing and optimisations of the energy system.

The Danish national smart grid strategy describes the integration of a smart electricity grid with other sectors (Danish Ministry of Climate, Energy and Buildings 2013):
"*However, development of the energy system will not stop with the electricity grid. The next step is to utilise and store wind energy in other energy sectors and thus render the entire energy system smart. Primarily with regard to wind energy and, in future, solar energy, fluctuating electricity production in the district heating system may be exploited via heat pumps and electric cartridges (electricity cartridges). In the gas system, wind energy can be stored seasonally in connection with production of hydrogen, which can be used either directly in the gas grid or to upgrade biogas to natural gas quality*." (Danish Ministry of Climate, Energy and Buildings 2013, P. 7).

The core of a smart energy system is the integration of energy sectors in order to utilise the benefits and dynamics that these sectors offer in combination. The system relies more on distributed systems than on exchange of energy between countries.

2.3 Purpose of this report - The Danish case

Denmark has set an ambitious goal to become 100% renewable by 2050, and this study aims to investigate alternatives for how Denmark could achieve this goal (Danish Government 2011). This study aims to progress the research field further by investigating an area that has not been focused on before.

This study aims to compare the three energy system types in the context of Denmark and Scandinavia, in order to understand the implications of each system being implemented.

In order to carry out the study, it is recognised that the development and success of these energy system types is largely dependent on the local context in which they occur, for example based on the energy systems that are currently in place, and the local economy, institutions and society (Purvins et al. 2011).

In order to narrow down the research question for this study, the Danish context is investigated further.

2.4 Diamond-E analysis

In order to narrow down the research question a tool called diamond-E analysis was applied. The diamond-E analysis was developed to help define feasibility studies for the energy sector (Hvelplund and Lund 1998). The diamond-e analysis allows the user to determine important priorities to focus on for long-term scenarios in the feasibility studies. Although the diamond-e analysis tool is ultimately used for designing a strategy, this study does not design a strategy, but rather makes recommendations that could be used for a strategy.

The areas investigated in the analysis include the organisational goals, organisational resources, and financial resources of the organisation. Figure 13 shows the different areas investigated in a diamond-e analysis. Diamond-E analysis is carried out in the context of the natural and socioeconomic environment in which the organisation is placed which allows the appropriate priorities to be determined.

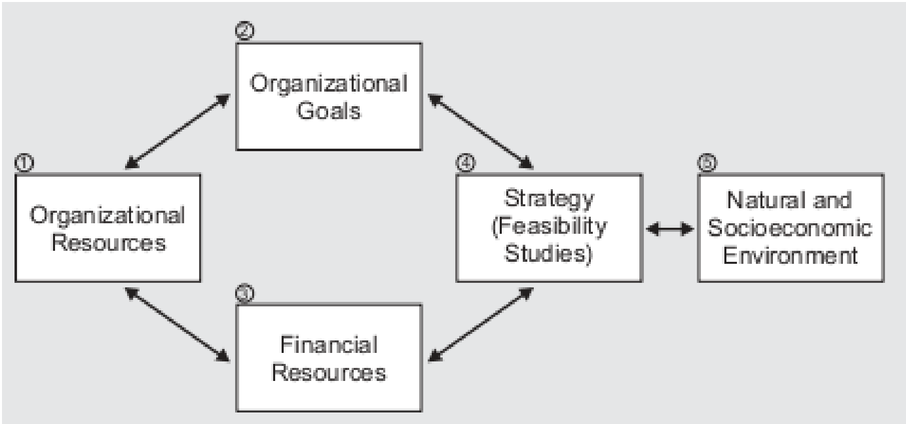

Figure 13: The content of a diamond-E analysis

This study focuses on the Danish society as the organisation and the feasibility studies for the energy system are carried out in this context.

The key factors that are found to be most critical using the diamond-E analysis in this study are presented below including the reasons for why they are included. The full diamond-e analysis is presented in Appendix A – Diamond-E.

2.4.1 Denmark in the Scandinavian region

Denmark lies next to other countries such as Norway, Sweden and Germany and therefore it has been possible to install electricity interconnectors in order to trade electricity between the countries. The existing network of transmission connections in the Northern European area can be seen in Figure 14.

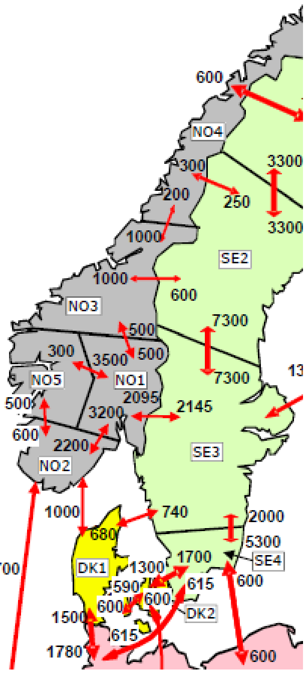

Figure 14: Transmission capacity between Denmark, Sweden and Norway (Nord Pool 2014)

The transmission lines and capacities that exist today between Denmark and the surrounding countries are presented in Table 1 below.

Table 1: Transmission capacity between Denmark, Sweden and Norway (Energinet.dk 2014)

Transmission capacities (MW)	**DK→ SE**	**DK→ NO**	**DK total**	**SE→ DK**	**SE→ NO**	**SE total**	**NO→ DK**	**NO→ SE**	**NO total**
	2440	1000	3440	1980	3995	5975	950	3695	4645

The existence of these interconnectors between the countries allows more electricity to be traded and increases the possibility to exchange electricity that cannot be used in Denmark.

The amount of electricity traded between Denmark, Sweden, and Norway is shown in Table 2, which shows the net exchanged electricity between the countries per year. The data is only for the countries Denmark is connected to, while Sweden for example is connected to Finland this is not included.

Table 2: The amount of electricity traded between Denmark, Sweden, and Norway

Import/export (TWh)	**Denmark**	**Sweden**	**Norway**
Denmark from	N/A	5 (2011)	3.9 (2009)
Sweden from	2.5 (2011)	N/A	6 (2011)
Norway from	1.4 (2009)	6 (2011)	N/A

These interconnectors are part of the Scandinavia electricity market that allows for electricity exchange and is carried out via the Nord Pool spot market, which is the largest market for electrical energy worldwide.

The IEA explains that "*in reality, Denmark is neither an importing nor an exporting country, but functions as a transit country between the Scandinavia and central western European systems.*" (IEA 2011, P. 94).

Due to these interconnectors with other countries, it can be argued that the Danish electricity sector is now part of a larger international electricity grid. Since this is the case, any future predictions of having a 100% renewable energy society in Denmark also depends on what happens with the electricity sector in the other countries and the interconnectors that are built in the future.

This is a key factor when designing the methodology for this study. In this study only Norway and Sweden are investigated in connection with Denmark. These countries also form the Scandinavian region which to some degree operates in an independent block fashion, for example through the Nord Pool electricity market, whereas Germany is part of continental Europe which is largely separate from the Scandinavia energy system.

2.4.2 Political CO_2 and renewable energy targets

The overarching policy targets in Denmark, Norway and Sweden stems from the European Commission who has set a policy that by 2020, the EU members should achieve a 20% greenhouse gas reduction, 20% greater energy efficiency, and have a total of 20% renewable energy. The overall goal for the EU is to reduce total CO_2 emissions by 80-95% in 2050 (European Commission 2011a).

The response by the individual countries has been to develop their own policies for the energy systems in the future. As explained above, Denmark has set a target to be 100% renewable by 2050. In the shorter term Denmark aims to have its electricity and heat covered by renewable energy in 2035 and by 2020 wind should cover 50% of the electricity demand. Furthermore, the target is to phase out all coal consumption in the energy system by 2030 (Danish Government 2011).

Much like Denmark, Norway and Sweden have also set ambitious targets for 2050. Both Norway and Sweden have set targets to have zero net greenhouse gas emissions by 2050. Sweden also has an ambitious target of having a fossil fuel independent vehicle fleet by 2030 (IEA 2011b; IEA 2013b).

The targets will obviously require changes in the energy system in each of these countries which would likely impact on Denmark due to the interconnections.

This is a key factor when designing the methodology.

2.4.3 Flexibility and integration of more renewable energy

As explained above, by 2020 in Denmark 50% of the electricity demand should be delivered by wind power. As of 2010 Denmark relied on around 24% of electricity demand from wind (Danish Energy Agency 2010). In order to increase wind further and to avoid production of unused electricity the energy system should be able to integrate fluctuating electricity further, or the unused electricity should be able to be exported.

As explained above, in the shorter term Denmark aims to have its electricity and heat covered by renewable energy in 2035 which would likely lead to more renewable electricity integration into this sector (Danish Government 2011).

The flexibility of the system to integrate more renewable energy is therefore a key factor for the methodology.

2.4.4 Energy efficiency - fuel and energy consumption

Over the last few decades as Denmark's economy has grown, the energy demand of the country has remained largely the same. However energy efficiency is still an area that is being focused on in the country.

Since it is expected that biomass will replace some of the fossil fuels in the energy system, the focus on energy efficiency is important since Denmark has limited biomass potentials of around 40-67 TWh (Danish Energy Agency 2014a; Danish Commission on climate change policy 2010; Scarlat et al. 2011; Lund et al. 2011).

The total energy demand from fossil fuels in Denmark in 2013 was around 672 TWh (Danish Energy Agency 2010). Therefore energy efficiency is a key factor for the methodology of this feasibility study.

2.4.5 Socio-economic costs

In recent years Denmark has had a positive balance of payment and one of the reasons for this was the production of oil and gas (Ministry for Economic Affairs and the Interior 2013). However in recent years the supply of oil and gas has grown smaller and for the first time since 1996 Denmark is now importing more energy than it is exporting (Danish Energy Agency 2014b).

With oil and gas resources depleting in Denmark the socio-economic costs may rise in the future due to net import of oil products with higher prices. Therefore the socio-economic costs are considered a key factor for the feasibility study.

2.4.6 Climate change impacts - CO_2 emissions

The Danish energy system has high greenhouse gas emissions that arise from burning fossil fuels in the energy system, which contributes to climate change. This has led to Denmark having one of the highest carbon footprints per capita in the world (no. 35) with a CO_2 emission of 8.27 tons/capita in 2009 (Indexmundi 2014). According to national policies the Danish CO_2 emissions should be reduced by 40% in 2020 compared with 1990 (Danish Government 2011).

Therefore CO_2 emissions are a key factor for the feasibility study.

2.4.7 Other priorities

Other priorities that could have been selected and which are included in the table in Appendix A – Diamond-E were for example, job creation, investment opportunities, national energy security, government support and so on. These other aspects are also important and should be investigated in further studies.

2.5 Specific research question

Based on the literature review, identification of energy system types, and the diamond-e analysis, a specific research aim was identified for the study.

As explained above, the actual design of a 100% renewable energy system is uncertain at present and will probably be uncertain for the next few years. But three main energy system types are apparent; being super grid, smart grid and smart energy system. Each of the these energy system types try to enable more renewable energy into the energy system, but using different technological solutions, involving different development pathways. The answer to the question about which is better - a Disconnected or Connected Scandinavian energy system, is most likely different for each of these energy system types and technological solutions. For instance one technological solution may be better when in a connected system and one may be better in a disconnected system. Therefore, in this study the comparison between these two extremes will be made by analysing a range of technological solutions that have been chosen to represent each energy system type, within the context of a Connected and Disconnected Scandinavia. The specific technologies under each energy system type are described in more detail in chapter 4 Methodology along with further description of the methodology.

The research question investigated in this feasibility study is:

- **How is a 2050 100% renewable Danish energy system in the context of an interconnected and disconnected Scandinavian energy system affected when applying super grid, smart grid and smart energy system technologies, in terms of energy system flexibility, energy efficiency, socio-economic costs and CO_2 emissions?**

To provide clarity around some of the key terms used in the research question and the study, each of the key terms are described below.

2.5.1 Disconnected Scandinavia

At present the Scandinavian countries are connected for electricity exchange as described in the introduction above. However in this study the Disconnected Scandinavia means that the three countries operate individually and have no exchange of electricity between them. This situation is hypothetical but is necessary for the analysis.

2.5.2 Connected Scandinavia

The Connected Scandinavia energy system is not simply about installing more cables to provide greater electricity exchange between the countries. It is about having one energy system for the three countries meaning that the demand profile for electricity for example for the three countries is combined into one profile and the electricity produced to meet this demand can draw from all the available power production options in any of the countries at any time. This is an extreme interconnected situation and is also hypothetical and necessary for the analysis.

2.5.3 Future energy system type

Future energy system types refer to an energy system either based on super grid, smart grid or smart energy system.

2.5.4 Technological solution

Technological solutions refer to the technologies that are part of each energy system type. Some technologies may belong under more than one energy system type, for example wind power could belong under all three. However for this study the energy system types are defined in a way that limits them to particular technological solutions.

2.5.5 Key factor

The key factors that are referred to in this study include carbon dioxide emissions, fossil fuel and biomass demand, energy system flexibility, and socio-economic costs.

2.6 Report outline

The report is structured into five main sections.

The first section in chapter 3 Theoretical framework describes the theoretical approach that underpins this study, in which the main theory is Choice Awareness Theory which theorises that not all choices are made apparent and greater awareness of all the choices should be made. The theory provides the basis for the methodology.

The second part of the report is the methodology section in chapter 4 Methodology that provides insight into how the results were developed.

The third part of the report is results in chapter 5 Results where the results are split into three main parts, the first part describes the main results for the reference energy systems for Denmark, Sweden, Norway and the two Scandinavian energy systems analysing how much renewable electricity could be integrated today. The second part describes the findings for the steps analysed in the study for the year 2050, while the third section describes the sensitivity analysis carried out to test the sensitivity of the results.

In the fourth part in chapter 6 Discussion the main findings and methodological approach are discussed in terms of the main outcomes and learnings from the study.

In the fifth part in chapter 7 Conclusion the main conclusions from the study are presented along with key recommendations in chapter 8 Recommendations and short-term outlook for Denmark for developing the future energy system.

Supplementary methodology and results are provided in the appendix that could not be included in the main part of the report. The result figures in the appendix may be useful for carrying out further analysis.

3 Theoretical framework

This study aims to analyse the Danish energy system in the context of the Scandinavian energy systems (including Denmark, Norway, Sweden) to understand the implications for Denmark when transitioning to a renewable energy society in this context.

This form of sustainable development, involves a shift away from technologies relying on fossil fuels and towards a more environmentally friendly and sustainable alternative; whilst not diminishing the prosperity of the current society. As defined in the UN's Agenda 21 (UN Sustainable Development 1992) there are three main actor groups in sustainable development, being government, civil society, and business, as shown in Figure 15. All three actor groups interplay to some degree to create sustainable development.

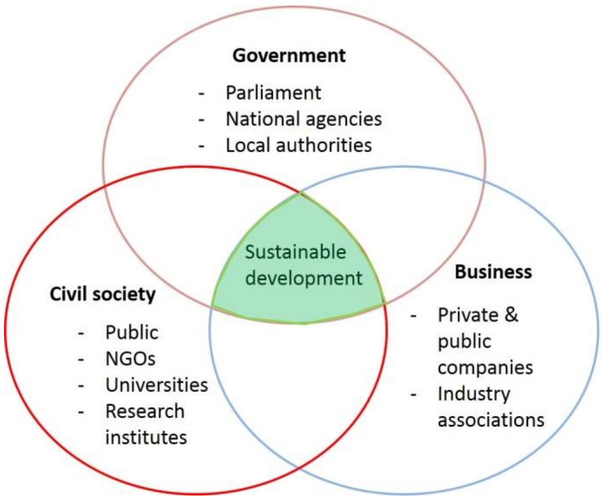

Figure 15: Three main actor groups in sustainable development (UN Sustainable Development 1992)

This study takes point of departure from a policy development perspective. This is assumed to take place at the Government level. Additional studies should take point of departure with the focus on civil society and business.

3.1 Choice Awareness Theory

The methodology of this study is underpinned by Choice Awareness Theory which has the theses that the organisations and institutional framework surrounding the current regime will influence the awareness of choice, and thus awareness of choice needs to be made apparent. Choice Awareness Theory evolved by analysing different energy systems, mainly in Denmark, over the past 25 years, and through this research the theory became more validated (Lund 2010).

The current energy system in Denmark is based on a number of characteristics that define the system. Some of the characteristics include (Hvelplund and Lund 1998):

- Single purpose companies in the form that companies have one purpose in the energy system such as electricity production, etc.
- Sectorized in energy systems, e.g. heating system, electricity system, etc.
- The investments and technologies often have long lifetimes, e.g. up to 40 years.
- The investments are capital intensive and asset specific, i.e. the technologies can only be used for their present purpose

In summary the system of today is dominated by a few large single-purpose companies that supply the goods and services demanded. This type of energy system arrangement is common among most modern societies.

Due to the nature of energy systems of today, transitions towards renewable energy systems are different and relatively more difficult compared with other technology transitions (Verbong and Geels 2010). This is due to the stability and lock-in of current regimes. The existing socio-technical regimes within the energy system are often characterised by path dependence and lock-in, and this results from particular stabilising mechanisms, for example, hidden interests, 'organizational capital', sunk investments and institutionalised beliefs (Verbong and Geels 2010).

The dynamics of technological change require the awareness of choice in energy system transitions, especially at the option selection, scenario analysis and recommendation stages of strategy development (Verbong and Geels 2010). Therefore the choice awareness theory is used in this study to open up new choices that can be investigated further.

A central component of the Choice Awareness Theory concerns the definition of technology and its role in this change, since technology is what is actually being changed in the system. It is not only the physical part of technology that is changed however. Technology actually consists of four elements; product, knowledge, technique and organisation (Muller, Remmen, and Christensen 1985).

Usually when one element changes then the others adapt to this change. This happens often in modern societies, for example, when incandescent light bulbs transitioned to compact fluorescent lightbulbs (CFL) the product changed, but the technique, knowledge and organisation around this technology largely remained the same. Verbong and Geels (2010) poses the theory that this type of change is primarily carried out by the current regime actors, and they redirect their existing development trajectories towards the new one. And this is not a radical technological change. Choice Awareness Theory focuses on the radical technological change which is when two or more of the elements of technology change.

The theory poses two theses (Lund 2010).

3.1.1 Thesis 1

When society aims to change its objectives, such as having a 100% renewable energy system, which implies that a radical technological change may occur – for example shifting away from fossil fuels – the existing organisations will try to make it seem that there is no option to choose a radical change and the only option is to choose an option presented by the current organisations or nothing at all; thus cementing the current regime's position.

3.1.2 Thesis 2

The second thesis is that it is possible to create awareness that these alternative choices do exist and that society can make a choice.

The theory is primarily used in this report for designing the methodology and investigating different alternatives.

Four key strategies are proposed by the theory to raise awareness and implement new energy systems (and for other technology transitions too), see Figure 16 (Lund 2010).

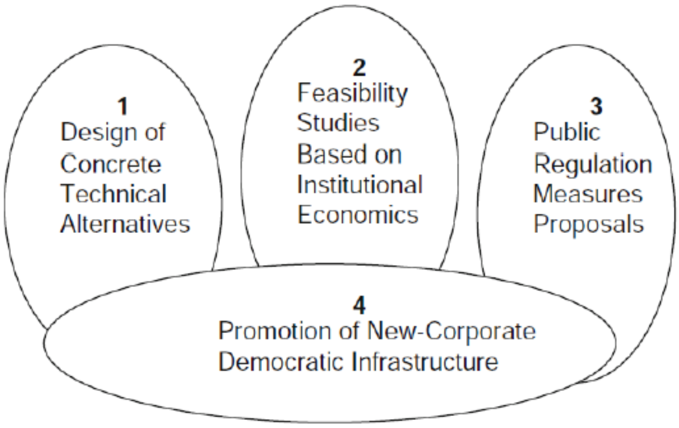

Figure 16: Choice awareness strategies (Lund 2010)

The first strategy is concerned with the technical validity of alternative choices. It is not appropriate to simply suggest an alternative if it has not been technically assessed to see if it is possible in the local context. The technical assessment involves a thorough analysis of the system being proposed so that it is robust and can withstand critique.

The second strategy takes the technical alternative a step further and determines the feasibility of the alternative in terms of economic viability. This is based on institutional economics or the real economic system that the energy system exists in. Institutional economics is concerned with how humans have created institutions that shape how the economy works (Bremmer 2010). This study is however not focusing on institutional economics, but analyses the socio-economic cost feasibility of different alternatives.

The third strategy is concerned with the public regulation measures that should be implemented in order to shift towards the alternative choices. New regulations are necessary to supplant the old system with the new system.

However the main barrier to the third strategy is that the policy of government is often also controlled by the current system, because of the institutionalised economics (Bremmer 2010). Therefore, coupled with the third strategy, the last strategy is added which stretches across all the other strategies and it involves the promotion of a new-corporate democratic infrastructure. This means that there needs to be a change in how democratic decisions are made, in order to avoid corporate democracy.

In this study, strategy one is carried out along with a socio-economic cost analysis of different alternatives, inspired and adapted to the approach in strategy two.

3.2 Further refinement of scenario development

It is stressed that in feasibility studies and strategy development for energy systems, it is necessary to discuss solutions going beyond the short term "end of pipe" thinking (Hvelplund and Lund 1998).

There are three main groups of technologies to be considered when developing long-term scenarios (Hvelplund and Lund 1998, P. 11):

(A) Energy conservation technologies within heat as well as electricity at the consumer level.

(B) Renewable energy systems, e.g. wind generators, biomass energy, wave generators, direct solar energy, etc.

(C) Improved efficiency of supply systems, which are based on fossil fuels (including uranium).

In this study the long term technical scenarios are investigated based on main energy system types B and C described above. Energy system type A is not included in this report since the focus lies on comparing different technologies and their system impacts. If this was included it would skew the comparisons between future energy system types based on Energy system type B and C and hence make it more unclear how the technologies impact the systems.

More about the methodology that was developed for this study is described in the next section.

4 Methodology

The methodology of the report is presented in this chapter. The chapter includes a description of the methodology procedure; detailed methodology; delimitations and assumptions of the analysis; analytical key factors; energy system analysis tool (EnergyPLAN); and data collection.

4.1 Methodology procedure: From research question to recommendations

In this section all the phases in the report from defining the research question to forming recommendations are described. The purpose of this section is to make it transparent how the results were created and interpreted in order to make recommendations. An overview of all the phases can be seen in Figure 17 and further description of this is provided in Appendix B – Methodology.

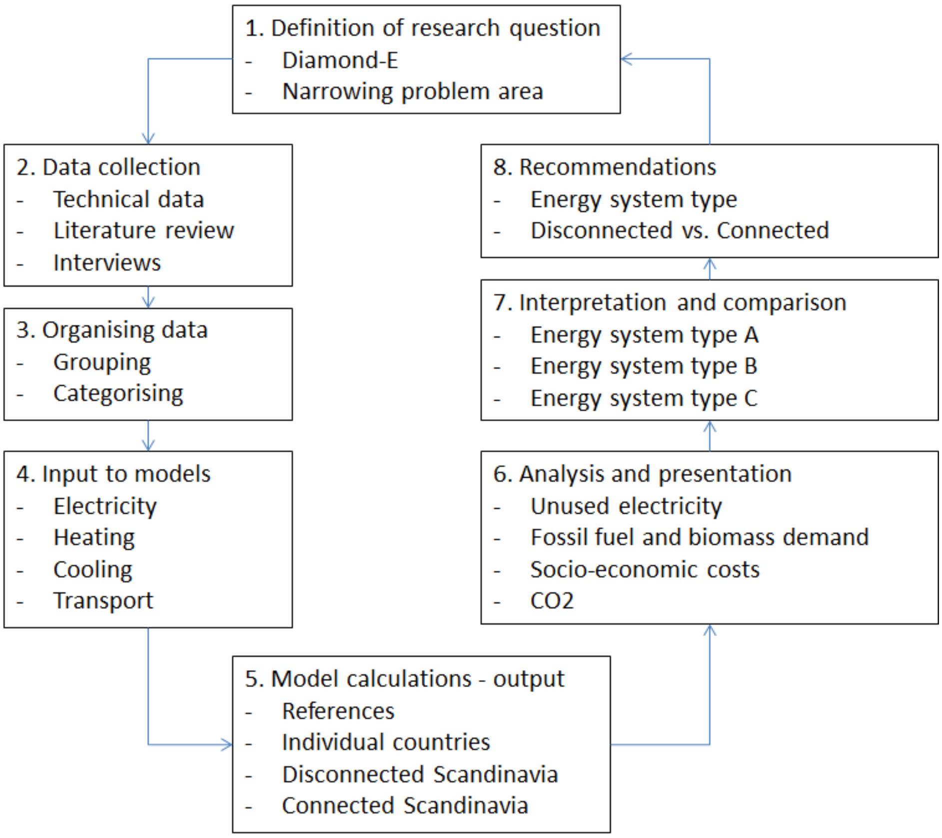

Figure 17: The phases in the report

4.2 Detailed Methodology

This chapter describes the methodology applied in this report to investigate the Danish and Scandinavian energy systems, and contains five different sections:

- Description of the countries and region analysed in the study.
- The energy system types methodology is presented.
- The delimitation of the study, including key factors of analysis.
- A description of the energy system tool that is applied to carry out the analysis
- The data collection methods are described.

The countries and region analysed in the study are defined below. All future energy systems have been defined with an end target for 2050 due to policy targets.

4.2.1 Denmark, Sweden, Norway

The geographical delimitation in this report is defined as the energy systems of Denmark, Sweden and Norway and is talked about as the Scandinavian region in the report.

The selection of exactly these three countries is based on different arguments.

Firstly, the Danish energy system is characterised by wind and thermal production combined with district heating, the Swedish energy system is characterised by nuclear power, hydropower, thermal production and district heating while the Norwegian system is characterised primarily by large hydropower production and electric heating with some minor thermal and district heating. This means that the countries have rather distinct and different energy system compositions, which means that it can be investigated what the implementation of various technological solutions implies in different types of energy systems. Furthermore, it is investigated how the system dynamics changes in such different energy system types when integrated further into a Scandinavian energy system.

Secondly, the frame of this project did not allow for more energy system analysis and since the inclusion of more countries (such as e.g. Finland, Germany or Iceland) would increase the number of analysis significantly the boundary was set to these three countries and energy systems. These three countries are connected already in a network for electricity trade (Nord Pool) so it is not unreasonable to select them as a group together.

4.2.2 Disconnected and Connected Scandinavian energy systems

One of the report objectives is to analyse the influence of interconnections in the future Scandinavian energy system within different energy system types and technological solutions as this inevitably will influence the Danish energy system. Hence, a methodology has been developed to answer this question, which is described below.

Based on the energy systems of the individual countries of Denmark, Sweden and Norway two types of Scandinavian energy systems are created entitled the Disconnected Scandinavian energy system and the Connected Scandinavian energy system. The two systems are extreme situations in terms of their transmission interconnections where the Disconnected system does not have any interconnections and leaves the three countries without the opportunity of import and export. The results from the three individual countries are aggregated to represent the situation with no transmission in the Disconnected Scandinavian system while the Connected Scandinavian system on the other hand is the extreme situation where there is unlimited transmission as the system is modelled as if it was one combined energy system. The two situations are illustrated in Figure 18 and Figure 19.

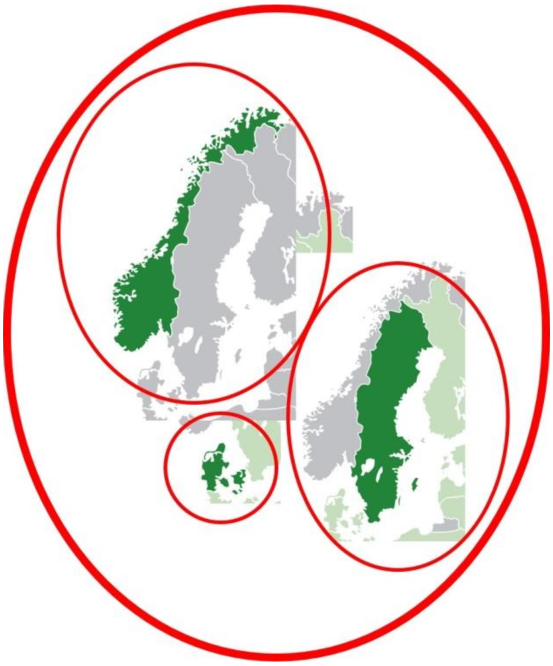

Figure 18: Disconnected Scandinavia system with countries independent from each other and producing their own electricity with zero import/export.

Figure 19: Connected Scandinavia where all countries are combined into one system with unlimited transmission within this region.

The Disconnected Scandinavia energy system involves individual analysis of each country and then after the analysis of the demand and production profiles for each country, the results are aggregated to get the total demand and production values for the aggregated energy system.

The Connected Scandinavia energy system involves aggregating the demand profiles and production technologies of each country before the analysis, and one set of results are produced for the combined Scandinavia which present the demand and production profiles for one Connected Scandinavia. There are no individual country results in this completely interconnected system.

The different energy system types and technological solutions are integrated in both extreme situations to investigate if some energy system types benefit from transmissions while others do not. The results between the two situations are compared to make recommendations regarding the findings are made.

4.3 Energy system types and technological solutions

In this section the modelling of the energy system types and technological solutions are described.

In Table 3 below the steps in each energy system type are illustrated along with two additional steps 2b and 5b.

Table 3: The three different energy system types

Energy system type A (supergrid) - Biomass conversion	Energy system type B (smart grid) - Electrification	Energy system type C (smart energy system) - Integration of sectors
Step 1 - Biomass conversion	Step 3 - Increase in individual heat pumps	Step 6 - District heating expansion
Step 2 - Biofuel implementation	Step 4 - Electrification of industry	Step 7 - Integration of large heat pumps
Step 2b - Integration of electric vehicles	Step 5 - Flexible electricity demand	Step 8 - Integration of electric vehicles and synthetic fuels in transport
	Step 5b - Integration of electric vehicles	Step 9 - Gasification of biomass for thermal production

The energy system types B and in particular C are much more complex systems than energy system type A, as energy system type A more or less is a continuation of the existing reference energy system, but with other fuels, while the other energy system types require more radical technological changes. However, some of the technologies integrated in energy system types A and B were also required in energy system type C, which is an argument for building on top of these technologies.

4.3.1 Energy system types methodology

The steps have been developed so they sequentially build on top of each other. This means that the first steps in energy system type A are also part of the modelling in energy system type B and C while the steps in energy system type B are also part of energy system type C, see Figure 20.

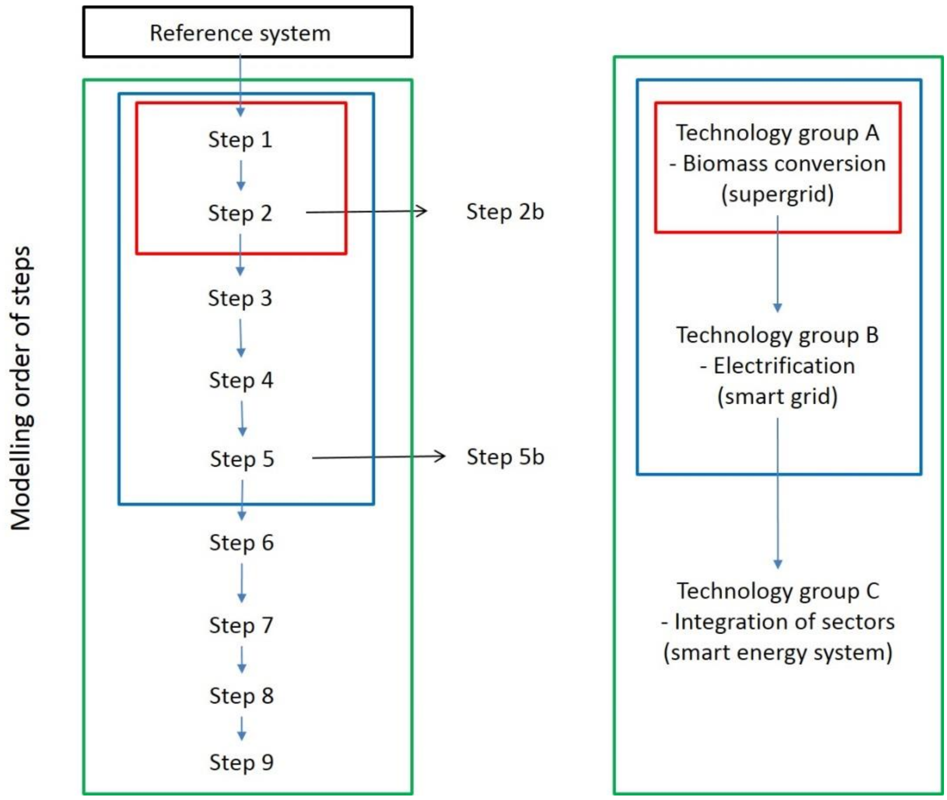

Figure 20: The sequence of energy system types and steps

As shown in the figure more than one step has been integrated in the system from step 2 and onwards. In some steps certain technologies replace other technologies, for example step 6 is about district heating expansion replacing some of the changes that were conducted in step 3 where more individual heat pumps were installed.

The steps 2b and 5b in energy system type A and B integrating electric vehicles were included as additional steps for these energy system types, but were not carried on into the next energy system type meaning that for example step 3 and 6 does not include electric vehicles in the energy system, but is based on biofuels in the transport sector to become 100% renewable. The purpose of conducting these additional steps 2b and 5b in energy system types A and B was to make the energy system types more comparable. Energy system types A and B do not include electric vehicles in the definition of their characteristics. Comparisons can however be drawn between the energy system types both with and without this additional electric vehicle step for energy system type A and B.

It can be argued that energy system type A is a continuation of the existing planning that adds more cables whereas the other energy system types are a change compared to the present (Franck and Sørensen 2014).

The purpose of developing the energy system analyses is to investigate the differences between the steps in terms of the key factors and how certain technologies influence the systems rather than designing an optimal technology mix in the energy system. Therefore the order of the steps is less important than if the purpose was to create an optimal future scenario with as low fuel consumption or costs as possible. The order of the steps however do have some influence on the results from implementing one technological solution before another, but will regardless of the order still provide indications of whether a certain technology is improving the system compared to if it is not implemented. An example is the order of when individual heat pumps are installed in line with the district heating expansion as the district heating expansion step is affecting the amount of individual heat pumps that are required in the system. An argument may also be that in the final steps the same technologies are installed regardless of the order of their implementation and that they accordingly will be scaled to fit in the same energy system.

4.3.2 Technological solution methodology

The various steps in the energy system types are described below in broad terms to get an idea about the intention of the step, how it relates to the energy system type and how it was converted into actual modelling in the modelling tool. The exact technical data for the different steps can be found under the step description in Appendix D – Technical background information.

The different steps are described below for the reference system and the energy system types A-C.

4.3.2.1 Reference energy system

The intention of creating a reference system for the various countries is to get an insight into how the existing energy systems are composed and to be able to build on top of these for the future energy scenario steps. The reference for the individual countries is constructed with data from energy statistics, - balances and other data based on the year of 2009. The reference is used as the baseline for developing the future steps and only the technologies that are involved in the specific step is alternated from the reference. In the reference system no decisions or bias towards any possible energy system types are prioritised and all types of technologies can in theory be implemented. From the reference energy system results key learnings about the composition of the energy systems can be drawn to inform the later steps about key components, fuels and other information.

The reference system was operationalised by investigating energy statistics from the different countries, first and foremost based on the International Energy Agency's energy database for OECD countries from 2009 that was used to extract energy demands for all sectors, heat and electricity production from different technologies and how the fuel mixes are composed (IEA 2010).

4.3.2.2 Energy system type A - Biomass conversion

The steps in energy system type A include steps 1-2b and these are described below.

4.3.2.3 Step 1 - Biomass conversion

In step 1 all fuels used in the energy system, except from in the transport sector, is converted into solid biomass consumption. This includes all technologies in the heat and electricity sector, individual households and industries while the waste incineration is converted to only organic waste for district heat and electricity production. This step is part of energy system type A as it might be part of a supergrid system that is rather similar to the existing energy system, but relying on biomass resources instead of fossil fuels.

Furthermore, two additional changes are conducted in this step that affects the energy system and the results. Firstly, the flaring of natural gas from natural gas extraction is removed since natural gas is no longer required in the future when the aim is a 100% renewable energy system. Secondly, the nuclear power in the Swedish energy system is removed and replaced by other technologies since nuclear power in this report is not defined as renewable energy.

4.3.2.4 Step 2 - Biofuel implementation

In step 2 the transport sector is converted to biofuels for all transport modes in the forms of biodiesel, biopetrol and biojetfuel. This conversion makes the energy system 100% renewable and is part of energy system type A that is based on a supergrid system. The transport modes that in the reference system consumed petrol are converted to biopetrol, diesel consuming modes are converted to biodiesel while air transport is converted to biojetfuel. The reason for separating the conversions in step 1 and 2 is that the fuels that are integrated in the system are different. In step 1 the fuel is solid biomass while step 2 is converting into liquid biofuel that is more complex to produce, but still produced from solid biomass.

4.3.2.5 Step 2b - Integration of electric vehicles

Step 2b is integrating electric vehicles in the energy system by replacing all cars and vans with models that are run by electricity while all other transport modes remain on biofuel. The intention of step 2b is to make energy system type A comparable with the other energy system types after integration of electric vehicles. In the energy modelling tool the integration of electric vehicles is carried out by increasing the amount of electricity for the transport sector while the charging is conducted in a dump manner meaning that the electricity is charged when the cars are plugged into the grid rather than when e.g. fluctuating electricity is produced. This charging method was selected for energy system type A because this energy system type not yet is integrated with the other sectors in a smart way with the purpose of utilising any potential unused electricity.

4.3.2.6 Energy system type B - Electrification

The steps and technologies in energy system type B include the steps 3-5b and are described below.

4.3.2.7 Step 3 - Increase in individual heat pumps

Step 3 is the first step in energy system type B that is based on a smart grid system, which implies a large focus on the electricity sector in terms of electrification. Note that the integration of electric vehicles that were conducted in step 2b is not included in this step and that all transport is fuelled by biofuels.

In this step the heating from individual boilers and electric heating is converted into individual heat pumps as part of electrifying the heating system. The district heating demand is constant in this step and is not affected by the changes. The electric heating is already based on electricity, but the conversion to individual heat pumps improves the energy efficiencies due to the increased efficiency of heat pumps, which is assumed to be 3.2, while it for electric heating is only 1. This means that every time 1 kWh of electricity is put into the heat pump 3.2 kWh of heat is produced from the heat pump while the electric heating is consuming 1 kWh of electricity to produce 1 kWh of heat. The conversion from boilers to heat pumps increases the electricity demand while the conversion from electric heating to heat pumps on the other hand, induces electricity savings.

4.3.2.8 Step 4 - Electrification of industry

Electrification of industries is part of energy system type B with emphasis on the electricity sector. The industrial sector is one of the main consumers of solid biomass and is therefore converted into higher reliance on electricity.

In step 4 40% of the industrial fuel demand is converted from biomass to electricity. The direct biomass demand in industries is hence reduced and replaced by electricity from preferably fluctuating renewable sources or other sources.

4.3.2.9 Step 5 - Flexible electricity demand

One of the main ideas behind developing a smart grid system is to make it more flexible and enable the consumption to align more with the production and hence flatten the peak demands. This can be created by implementing smart meters in houses or installing smart appliances such as washing machines that are using electricity when it is cheap because of fluctuating power production. This is investigated in step 5 where 20% of the total electricity demand is converted into flexible demand within 24 hours, as longer periods is not realistic with the current technology available (Lund 2013).

4.3.2.10 Step 5b - Integration of electric vehicles

Step 5b is not as such a part of energy system type B, but is similarly to step 2b an additional step where electric vehicles are integrated in the transport sector. The difference from step 2b is that the charging in this step is performed in a smart way, i.e. the electricity charging has the aim of decreasing unused electricity production and the condensing power production in the energy system (Lund 2013).

4.3.2.11 Energy system type C - Integration of sectors

The steps and technologies in energy system type C include the steps 6-9 and these are described below.

4.3.2.12 Step 6 - District heating expansion

Energy system type C is about integrating the different sectors in the energy system and step 6 is part of this. In step 6 the district heating network is expanded according to the feasible district heat expansion for each country. The district heating expansion is replacing some individual heat pumps and hence saves electricity in the individual households and produces the heat in the technologies connected to the district heating network such as CHP plants, boilers or large heat pumps.

4.3.2.13 Step 7 - Integration of large heat pumps

In step 7 the large heat pumps connected to the district heating network is expanded to connect and integrate the different energy sectors even more. This is occurring as the unused electricity from fluctuating renewable electricity production can be converted to heat by the large heat pumps that acts as a relocation technology between the two sectors. The large heat pumps already exist in Sweden, but are almost non-existing in Denmark and Norway. The capacity in all countries are increased and the large heat pumps does not affect the electricity demand as they are intended to utilise excess production that otherwise would have been unused.

4.3.2.14 Step 8 - Integration of electric vehicles and synthetic fuels

In step 8 the electricity and transport systems are integrated when electric vehicles are introduced into the energy system to replace biofuels for all cars and vans. Furthermore, to reduce the biomass demand for other modes of transport synthetic fuels are created that reduce the biomass demand and instead increase electricity demand. The synthetic fuels are created from a gasification process that produces carbon containing molecules, e.g. CO or CO_2, which is then hydrogenated by adding hydrogen that is created from an electrolysis process and the end product is biomethanol that can be used by heavy transport modes. A detailed description of creating the synfuels can be found in Appendix C – Technology catalogue.

4.3.2.15 Step 9 - Gasification of biomass for thermal production

The final step in energy system type C is the gasification of biomass for thermal production, i.e. the large CHP plants and condensing power plants. The purpose of this step is to connect the heating and electricity system with the gas grid in order to store the gas for when it is required and because the traditional power plants and CHP plants hence can be replaced by technologies using gas that are more efficient than the traditional ones. The gasification process also increases the electricity demand slightly for the system. A more detailed description of the gasification process is in Appendix C – Technology catalogue.

4.4 Delimitations and assumptions of the analysis

The delimitation highlights the boundaries for the report and explains what is excluded from the report and why it is found feasible to draw these boundaries. Furthermore, it explains the key factors of the report and how these are applied.

The delimitations in the report are described and explained in this section.

4.4.1 Technical energy system delimitations

In this report no measures are included to reduce demands for electricity, heat or transport. The reason for this is to make the comparisons between technological solutions and energy system types more transparent without being affected by reduced demands. Demands only change in the analysis when the technological solutions are forcing the electricity to change, for example when integrating more heat pumps.

Furthermore, it is assumed that the demand over time in this study based on the 2009 reference system remain constant until 2050. This is assuming improvements for technologies and energy consuming devices such as household appliances on one hand while the reduced demand will be replaced by additional consumption from the consumers (the rebound effect). Hence, the demand will remain constant. In addition this allows making more clear comparisons between the technologies and energy system types as they are not influenced by changing demands.

For the Danish energy system it is assumed that power plants have to operate for grid stabilisation in order to provide the required inertia in the system and because these plants may have difficulties in going below a certain technical minimum. The power plants are set to operate at a minimum 30% production share as this share is recommended for grid-stabilising units (Lund 2013). It is assumed that hydropower plants and nuclear power can provide grid stabilisation and hence no power plant grid stabilisation is required for Sweden or Norway. This ability is further investigated throughout the analysis of the Danish energy system.

When integrating more wind in the energy systems no analysis of electricity grid upgrades have been carried out even though this might be the case in some situations. Neither are the associated costs for such upgrades included in this study.

The wind power technology that is implemented in the analyses is based on onshore wind power. This is both due to the national energy policies of Sweden and Norway that plans to implement primarily onshore wind and since the wind distributions in the energy system analysis are similar for onshore and offshore wind power due to data availability (IEA 2011b; IEA 2013b). The costs however might be influenced by this choice, but due to the Swedish and Norwegian energy policies onshore wind was chosen. The wind technology that is integrated is furthermore assumed to have same efficiency for both 2009 and 2050 in order to get a clearer picture of the impacts of the different energy system types and technological solutions.

For the energy system analysis the electricity demand changes between the different steps and this resulted in different power plant capacities so that the individual countries were able to meet the domestic peak electricity demand without any import. This means that the steps and countries with the highest electricity demands will have the highest power plant capacities and that they are adjusted between the different steps. The peak capacity is designed so it can meet the peak electricity demand when there is no wind.

When analysing the wind integration in the different energy systems 5% curtailment has been included. After analysing recent literature on wind curtailment a reasonable value of 5% of the total wind production can be assumed to be curtailed (Lew et al. 2013). This curtailed wind shifts the point where unused electricity is produced so that more wind can be integrated. Throughout the report it is investigated when the point of unused electricity begins for the different energy system types and this point is including the 5% wind curtailment.

4.4.2 Transport sector

Delimitations and boundaries have been created for the transport systems of the different energy systems in order to outline what is included and excluded in the transport systems. The transport sector is a complex sector that is composed of numerous demands, transport modes and functionalities. Hence, it is comprehensive to encompass the entire transport system for all the countries analysed in the report, which made it necessary to draw some delimitations about what is included in the study.

As no measures related to energy conservation are part of this report transport measures such as modal shifts and reduction of demands are not analysed. Within the transport sector the measures included are related to either fuel conversions or integration of new technologies such as electric vehicles.

Energy demands for the transport sector for the different countries have been defined as in the IEA OECD energy database as of 2009 supplemented with data from the national energy agencies and includes passenger and freight transport as well as all types of fuels and transport modes (IEA 2010).

The transport costs in the report include the fuel costs as well as the investments and operation and maintenance costs for the entire vehicle fleet in the respective countries. It is assumed that cars have a lifetime of 16 years and costs are based on data from the Danish Energy Agency (Danish Energy Agency and COWI 2013a). When converting to electric vehicles costs also include charging infrastructure and a 10% loss in electricity production.

4.4.3 Socio-economic analysis

The socio-economic analyses in the report include different types of costs such as investments based on the capacity installed and the lifetimes of the various technologies. The costs furthermore include operation and maintenance as a percentage of the investments as both a fixed cost according to installed capacity and a variable cost depending on production. Finally, the costs are also based on the fuel costs, which vary between the different fuels, see Appendix D – Technical background information for a detailed description of costs applied in the analyses. Fuel handling costs are also included for fuels along with a fixed CO_2 price per unit emitted. There are no taxes included for fuels or electricity because the analysis has a socio-economic perspective rather than business-economic. The fuel costs remain constant across all the cost analysis in both the reference system and the future energy systems and the investment costs for technologies that are not changing in a certain step also remain constant

The interest rate in the socio-economic analysis is assumed to be 3% for all energy systems in this report. The interest rate is a measure of the importance of investments according to the time perspective, i.e. the higher the interest rate the more importance is asserted to short-term or present investments as the future benefits are decreased and this might affect for example the integration of renewable technologies. The 3% in this report is hence trying to reflect the balance between the importance of short-term and long-term investments.

As of 2013 the Ministry of Finance in Denmark lowered the interest rate in long-term investments to 4% in the first 35 years of a project lifetime, 3% for the years between the years 35 and 70 and 2% for the years after year 70 (Danish Ministry of Finance 2013). The interest rate in this report is hence more or less in line with the recommendations from the official guidelines from the Ministry of Finance. The importance of the interest rate is furthermore investigated in the sensitivity analysis, see chapter 5.4 Sensitivity analysis of results, methodology and delimitations.

It should be noted that for all socio-economic cost calculations there are significant uncertainties as future fuel prices, electricity prices and technology costs are very uncertain.

4.4.4 Life-cycle phases included in the energy system analysis

In the energy system analysis in this report only the fuels, emissions and costs with more that are used directly in the energy system is included. This means that other phases such as the extraction and transport of fuels and technologies do not lead to any CO_2 emissions or costs and that CO_2 and energy required for constructing new infrastructure and emitted in relation to the end-of-life phase is not included when assessing the key factors. Only the demand and consumption within the energy system are included as inclusion of the other phases would have enlarged the analysis significantly and is at the same time not part of the scope of this report.

4.4.5 Biomass assumed to be CO_2-neutral

In this report biomass consumption is assumed to be CO_2-neutral, even though this is heavily debated in scientific circles in present days. This assumption is important to have in mind, e.g. during the first two modelling steps concerning biomass conversion, where it is assumed that a conversion towards biomass consumption is creating a CO_2-neutral energy system. This assumption and importance is further discussed in the discussion chapter of the report, see chapter 6 Discussion.

4.4.6 Definition of renewable energy sources

Renewable energy sources can be defined in many ways and has therefore been defined for the purpose of this report. The definition in this report is based on the definition from IEA since this is the source for the largest part of the reference energy system data for the Connected Scandinavia countries.

IEA defines renewable energy as:
"E*nergy that is derived from natural processes (e.g. sunlight and wind) that are replenished at a higher rate than they are consumed. Solar, wind, geothermal, hydro, and biomass are common sources of renewable energy.*" (IEA 2014).

This definition means that e.g. nuclear power is not included as renewable energy as it is not replenishing at a higher rate than it is consumed.

4.5 Analytical key factors

The objectives described above are all analysed in terms of their impacts on a number of key factors. These key factors are described below.

The problem analysis in the introduction, see chapter 2 Introduction, is used as the backbone of identifying relevant challenges within this report's study field and based on this a number of key factors are defined and used in the analysis. In the Diamond-E analysis the challenges within the areas of organisational goals, natural and socio-economic environment, organisational resources and financial resources were discussed. The key factors are selected based on priorities in the Danish society and are reported in this study according to the depth of analysis that was carried out for them. The first two factors were analysed more in detail in order to increase the level of certainty whereas the second two were analysed with less depth due to their inherent uncertainty.

The first key factor is flexibility and integration of renewable energy in the national energy system. This is a priority in several organisational goals in the national energy plans and can contribute to meeting other priorities such as climate change mitigation and improving national energy security as the self-sufficiency rate is declining in Denmark (Danish Energy Agency 2014b). The renewable electricity integration potential refers to the amount of wind electricity that can be integrated in the energy system when a particular technological solution is integrated. Other forms of renewable electricity are not considered in the study, for example solar power.

The second key factor is energy efficiency of the system in terms of fuel consumption as the self-sufficiency is declining and the domestic biomass potentials are limited if impacts on land-use and food production are to be avoided. Therefore biomass consumption is of particular interest. The fuel demand only investigates fossil fuel and biomass demand and does not consider the demand from for example the fuels required to harvest biomass.

The third key factor in the report is selected to be climate change impacts in the form of CO_2-emissions as this was both part of the organisational goals in the national energy policies and affects the natural and socio-economic environment. The assessment of carbon dioxide emissions refer only to these emissions and do not account for other greenhouse gas emissions such as methane.

The fourth and last key factor is the socio-economic costs as future energy systems should not contribute to increasing debt and preferably contribute to job creation. The total energy system costs are hence investigated including fuels, investments and variable costs such as operation and maintenance and electricity exchange. The cost for carbon dioxide are also considered. The costs from Government taxes, or business costs are not considered.

These four factors; climate change impacts, flexibility and integration of renewable energy, energy efficiency and socio-economic costs, are used as the parameters that are investigated for each step in the energy system analysis.

4.6 Energy system analysis tool - EnergyPLAN

In the report a computer based energy system analysis tool called EnergyPLAN was used. Background information about this tool is provided in Appendix 10.2.2 EnergyPLAN. The description and objective of the tool is based on the book *Renewable Energy Systems - The choice and modelling of 100% Renewable solutions* from 2010 by Henrik Lund who was one of the creators of the tool (Lund 2010).

4.6.1 How the EnergyPLAN tool is applied

The EnergyPLAN tool is found suitable for the analysis in this report because it is designed for comparing alternative energy systems in a transparent and consistent manner, which is feasible in terms of the research question of the report. When modelling a future system with increasing renewable energy an hour-by-hour model is necessary in order to analyse the fluctuations that arises from these technologies (Lund 2010).

The EnergyPLAN tool can be operated in a number of ways according to its purpose, but is operated as described below in this report.

The EnergyPLAN tool is operated in technical optimisation, which seeks to minimize import/export and identify the least fuel consuming solution. This is opposed to the other optimisation strategy called market-economic optimisation that optimises the operation of each station within the electricity market in order to optimize business-economic profit. The reason for this is that the purpose of the report is to investigate the energy efficiency of the system and for this purpose a technical optimisation is preferable. Besides, the purpose of the report analysis is to investigate the energy system costs from a socio-economic perspective without taking into consideration whether the individual plants are operated optimal according to a business-economic point of view.

The tool was furthermore used to create scenarios across time periods with a number of different technologies that both exist in the present energy systems and might become part of a future renewable system.

Additionally, the tool allows for analysing different transmission capacities and strategies for managing unused electricity production, which is one of the purposes in the report.

4.7 Data collection

The data collection methods that are used in the report are described in this section.

4.7.1 Priority of references

The references that are used in the report are prioritised according to the following order. This was used to ensure that the data and information are from the most trustworthy source whenever possible.

- Research journals
- IEA
- National agencies and TSOs
- Other organisations and research institutes
- Interviews
- Media

The reference source with the highest priority is research journals as these have been peer-reviewed by research colleagues and are generally often known as having high quality. This type of reference was used mostly for discussions and reviewing previous studies on energy systems. Next, IEA data was prioritised as the organisation is one of the central organisations for energy data and provided cross-country data, which was feasible in this report. The IEA data was primarily used in the collection of technical data for the modelling of energy systems. The national agencies and TSOs were used for collecting technical data related to e.g. distributions of demands and productions as well as statistical energy balances for the 2009 reference. If data was not available from these sources it was supplemented by data from other organisations and research institutes. The interviews were used to collect viewpoints from actors in the energy system about possible future developments and to feed into the discussion of the results. Media sources were rarely used, but might contribute to inform about recent trends among e.g. politicians or researchers.

4.7.2 Technical data

The technical data was the largest group of data that was collected for the report. Many types of technical data was collected in order to create first of all a reference system for the different countries in 2009, but also to learn about potential technologies for a future renewable energy system. The technical data was collected from the IEA energy database for OECD countries for 2009 and supplemented by data from the various national energy agencies and TSOs when feasible (IEA 2010). Not all data was available from these sources and hence it was supplemented by data from previous research projects such as the CEESA research project about renewable energy scenarios in the Danish energy system (Lund et al. 2011).

The data collection focused on generic data for the different countries and as an example, data was not collected in the transport sector for each country with its many modes and both passenger and freight transport. Furthermore, not all data was available and hence data from other countries had to be used, e.g. for the wind power distribution in Norway that is based on the Swedish wind distribution.

4.7.3 Literature review

Literature review also formed an important part of the data collection and was used e.g. in the phases of defining the problems in the energy system and formulating the research question. Furthermore, it was part of describing the different types of future energy systems and technologies. The purpose of the literature review is to convey the knowledge that have been established within a certain topic. The literature reviewed followed the priority of references described above.

4.7.4 Interview

During the project interviews were conducted with two external actors in the Danish energy system in order to learn more about the trends in the existing energy debates and developments and to learn about these actor's standpoints in terms of future development. The two external actors are Energinet.dk and Dansk Energi (Franck and Sørensen 2014; Søndergren 2014).

The interviews in the report were conducted as semi-structured interviews within the same framework with the purpose of learning about their role in the Danish energy system, how they cooperate with other actors in the system and how they envision the development in the Danish and Connected Scandinavia energy systems.

The interviews were analysed for relevant statements and information in regards to the future energy systems and were incorporated in the report when feasible.

5 Results

This section describes the results of the study in three main parts. The first part describes the results for the reference energy system of each country plus the Disconnected and Connected Scandinavia systems from 2009, when wind power is integrated from 0-100% of the electricity demand. The results are presented for the wind integration capacity, fuel demand, CO_2 emissions and socio-economic cost. See more about input data for the reference systems in Appendix E – Supplementary results.

The second part of the section shows the same set of results for the energy system types and technological solution steps from step 1 to 9. See more about input data for the energy systems in Appendix E – Supplementary results.

The third part of the results is the sensitivity analysis, where a selected number of key variables are modified to understand the sensitivity of some of the main results.

There is a certain type of graph used to represent the results in this section, which is used repeatedly. Therefore before the results are presented, a sample of this graph is presented and described in order to facilitate better understanding of the results.

5.1 Results interpretation - Wind integration analysis

The key way that the results in this study were generated was by carrying out a wind integration analysis. This involves integrating wind production from 0-100% of the electricity demand and analysing how this affects the key analytical factors; integration of wind; production of unused electricity; fossil fuel/biomass demand; socio-economic costs and CO_2 emissions.

For every key factor 11 different measurement points in terms of wind amounts of the total energy system electricity demand are analysed, i.e. 0% wind share, 10% wind share, 20% wind share, continuing to 100% wind share.

The EnergyPLAN tool was created with the purpose of aiding the design of 100% renewable energy systems and be applying this feature testing renewable energy technology integration (e.g. wind, solar power, wave power) this helps in this endeavour since multiple renewable electricity types and amounts can be tested.

This type of wind integration analysis is used as a consistent method for comparing all the steps across energy system types and technological solutions. It will allow final recommendations to be made, since all technologies were analysed in a similar fashion. The method has previously been used in various journal articles (Connolly et al. 2011; Lund and Mathiesen 2008).

The example figure below shows the curve graph integrating wind from 0-100% for the Danish reference system and steps 1,2 and 2b, showing the amount of unused electricity as wind share increases.

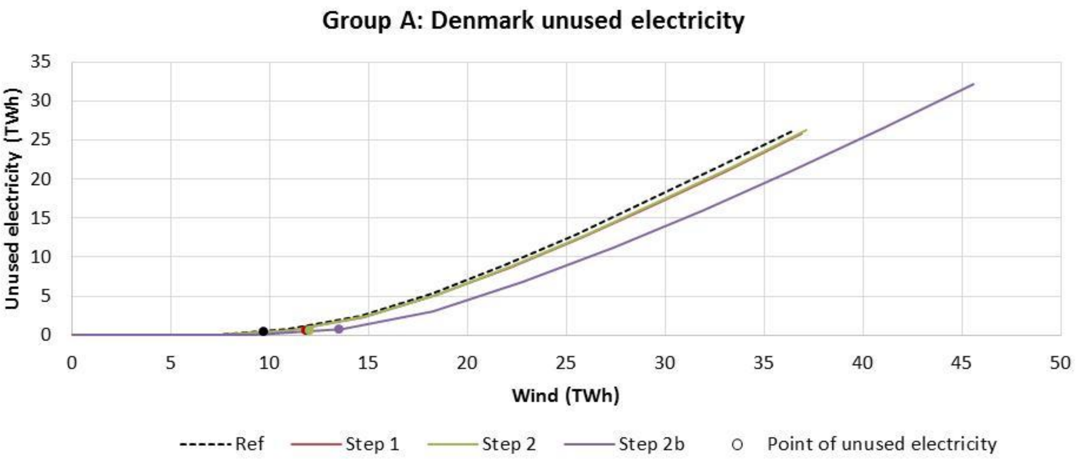

Figure 21: Unused electricity when integrating wind in the Danish energy system type A

In this figure the unused electricity is plotted as lines for numerous steps. Wind production is shown in the horizontal axis from 0-100% wind integration. The length of each line in the figure indicates the electricity demand in each step as some steps cause an increase or a reduction in electricity demand. In this figure the steps have different electricity demands therefore wind integration ranges from 0 TWh to 36 TWh in the reference system up to 0 TWh to 46 TWh for the total electricity demand in step 2b (electric vehicle integration).

As shown, after a certain point the unused electricity increases as wind integration increases since the Danish electricity grid cannot integrate more wind. In this study a 5% wind curtailment has been allowed; meaning that 5% of the electricity from wind can be unused. This is shown as the dots on the plotted lines. This curtailed wind shifts the point further to the right as 5% wind curtailment is allowed.

The further out on the wind axis the dot is placed the better the system is at integrating wind.

This type of figure is also be used to show changes in socio-economic costs and fuel demands when wind is increased. The points where unused electricity rises above the 5% threshold is also plotted on these figures since the point represents an amount of wind which can be located on the horizontal axis and the vertical intercept on the curve is the socio-economic cost or fuel demand for that amount of wind.

The point where unused electricity increases above 5% is the optimal wind integration point in this report.

5.2 Results for reference systems

The results for the reference system for each country is described in this chapter in regards to the results in terms of wind integration, fuel demand, socio-economic costs and CO_2 emissions. The input data used for each country is in the Appendix in section 10.5

5.2.1 Output results

As described in the methodology, each of the countries are modelled individually removing the interconnection cables, and the wind integration is modelled from 0% to 100%. This is to test the flexibility of each country's fluctuating electricity production. The two Scandinavian systems are also modelled in this way to understand the flexibility of them.

In this section the key analytical factors are described and presented for the various reference energy systems when integrating wind. The results are presented for flexbility and integration of renewable energy, fuel demand, socio-economic costs and CO_2 emissions. After the results are presented for each key factor the numbers are interpreted to understand the dynamics of the energy systems and to provide insight into the dynamics of the Connected and Disconnected Scandinavian energy systems.

5.2.1.1 Flexibility and integration of renewable energy

In this section the results for each country and the Connected and Disconnected Scandinavia systems are presented when wind is increased from 0-100%.

Denmark, Norway, Sweden

The unused electricity and fuel demand when wind is increased from 0-100% of the electricity demand is shown for the three countries in Figure 22, Figure 23 and Figure 24 below. The point where unused electricity increases above the 5% curtailment is plotted on the figures as well.

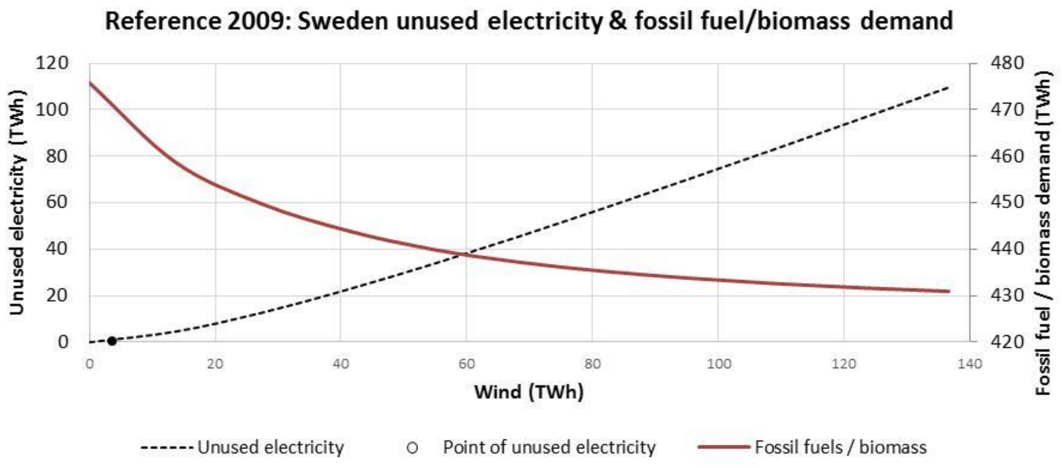

Figure 22: The unused electricity production and fossil fuel and biomass demand in the Swedish reference system

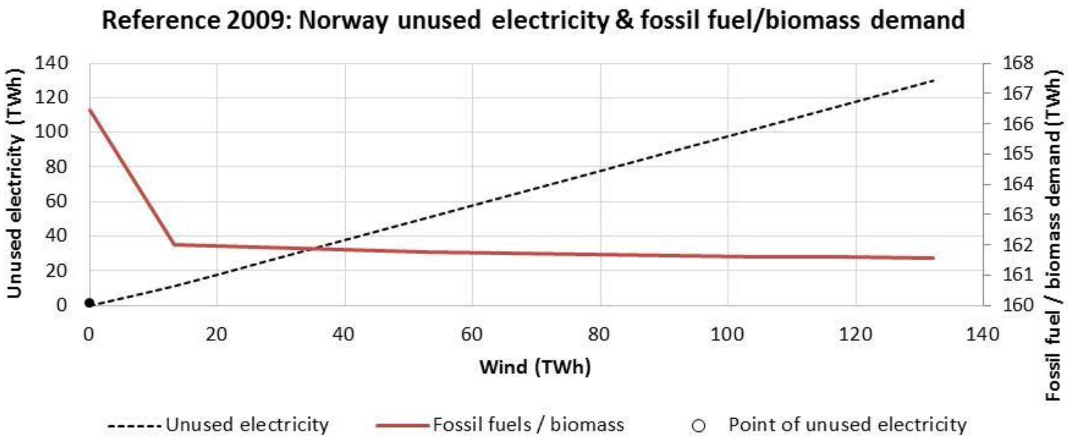

Figure 23: The unused electricity production and fossil fuel and biomass demand in the Norwegian reference system

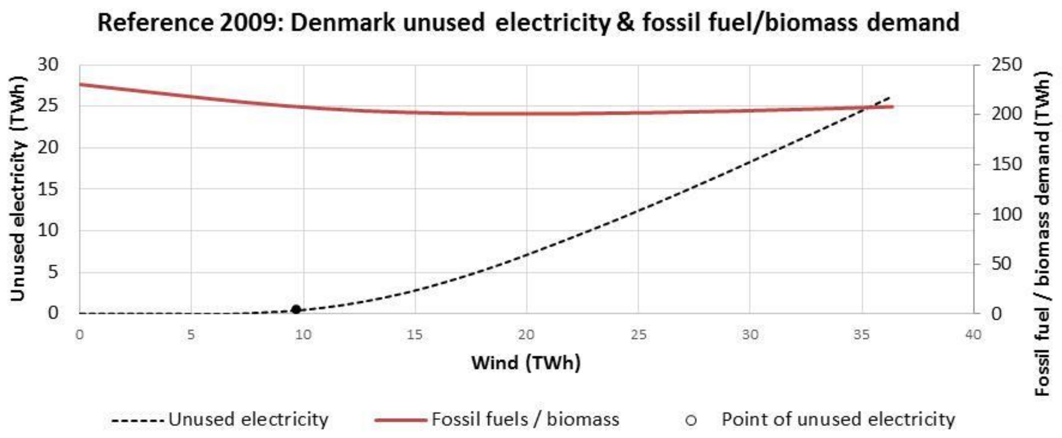

Figure 24: The unused electricity production and fossil fuel and biomass demand in the Danish reference system

This point in the reference system where wind production begins to create unused electricity above the 5% threshold for Denmark, Norway and Sweden is around 9.7 TWh, 2.5 TWh, and 3.7 TWh, respectively. After these points the higher production causes more unused electricity. The wind production share before unused electricity is produced for Denmark, Norway and Sweden is around 27%, 2% and 3% of the total electricity demand, respectively.

5.2.1.2 Fossil fuel and biomass demand

The fuel consumption for Denmark reduces according to the increased wind power until around 20 TWh of wind, and after this point the fuel demand starts increasing again. This indicates that the wind power for Denmark until around a production of 20 TWh is able to replace other fuels that are primarily fossil fuels in the Danish reference system. But fuel demand increases again after 20 TWh of wind due to increased production from thermal power plants.

In Norway and Sweden the fossil fuel/biomass demand decreases continually as the wind increases. The demand decreases less for Norway since very little thermal power production is displaced by wind.

Denmark

To help explain why unused electricity is produced when more wind is added to the system Figure 25 below has been created from a sample of the data in a Danish reference system with a wind share of 50% of the electricity demand.

The unused electricity over the total year when 50% (18.4 TWh) wind is added is 5.6 TWh which is an accumulation of the hours where wind causes the electricity supply to be higher than the demand. This is shown in Figure 25. This amount of unused electricity is 30% of the total wind electricity generation, and in this study only 5% of the wind generation is allowed as curtailment. The figure illustrates week 37 in 2009 and contains the different electricity production technologies (waste and industry, CHP, condensing power plants and wind power), and the electricity demand. The difference between these is the unused electricity.

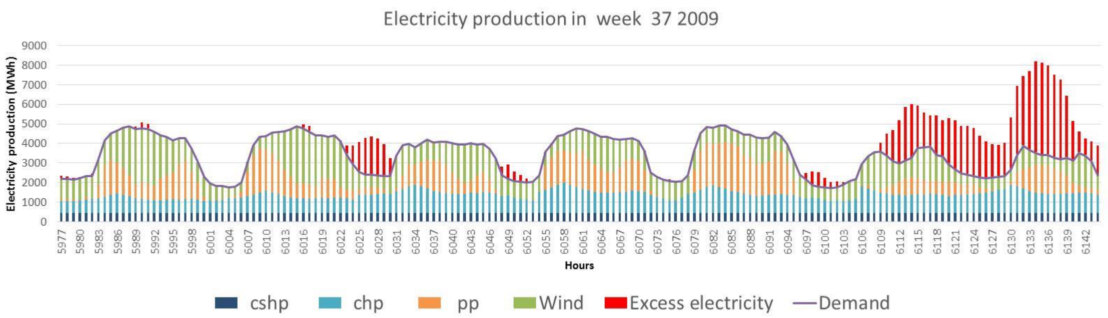

Figure 25: Electricity production distribution in a week in the Danish reference energy system

As shown in the figure the waste and industry production and CHP operates as baseload production to ensure inertia in the system and because waste and industry is producing at a constant level throughout the year. The next technology kicking in is the condensing power plants that operate according to the electricity demand and it mostly follows the demand line.

The light green is the wind power that can be integrated in the energy system and the dark green area indicates the wind power that cannot be integrated and will turn into unused production because production exceeds the demand. From the selected week 37 in 2009 it can be seen that the wind is blowing much in the last part of the week and the wind power production exceeds demand.

It is important to note that controllable condensing power plants in theory could reduce their production to integrate more wind in the periods with high wind power production, but these power plants are controlled by their regulation abilities which means that they take a certain period of time before they can operate at full load. An example is large scale coal power plants that can increase their primary load support by 5% per 30 seconds and their secondary load support by 4% per minute. In addition the minimum load is 18% of the full load capacity for these types of plants (DEA, 2012). This means that the large power plants has to operate so that the demand is always met and in order to operate at full capacity the plant has to operate in other hours as well. The power plants are therefore operating to ensure grid stability in the system.

Sweden

A similar figure is presented below for the Swedish energy system with 15% (20.3 TWh) wind share of the electricity demand. The total annual unused electricity in one year with 15% wind share is 8.2 TWh, which is 40% of the total wind generation.

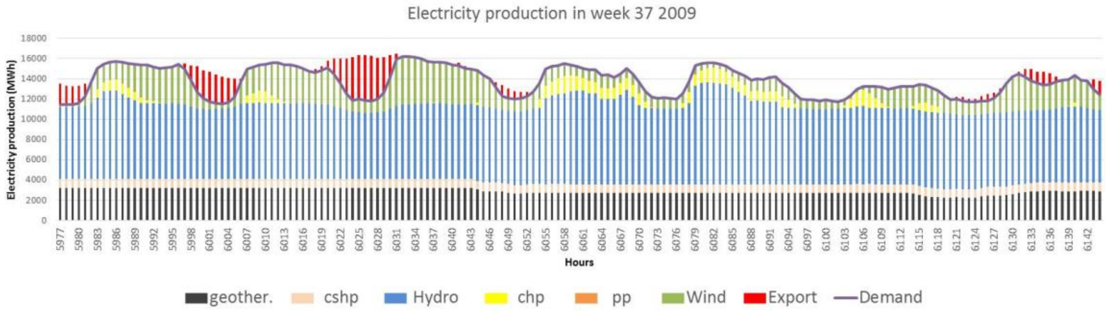

Figure 26: Electricity production distribution in a week in the Swedish reference energy system

In Sweden the production technologies are nuclear power and hydropower primarily accompanied by waste and industry, CHP and condensing power plants as well as wind. The nuclear power provides baseload throughout the year similar to the waste and industrial production, making the system less flexible and reducing the amount of wind that can be integrated in the system. Throughout the year the nuclear, waste and industry produce more than 40% of the electricity. The CHP production follows the demand peaks, but is relatively small compared to other production technologies. The largest share of the electricity production is from hydro power that can operate with relatively more flexibility than nuclear power, which can also be seen in Figure 26. In contrast to the Danish reference system there is no need for power plants to ensure inertia in the system as this role is taken care of by hydropower. Hydropower has the advantage compared to condensing power plants that they can start producing electricity with a short notice and with low costs.

As was the case for Denmark wind power is highly variable and mostly uncontrollable. From the figure it is clear that the unused electricity production from wind is mainly in the hours where the demand is lowest where there is no room for integrating more electricity production. In the example in the figure this situation occurs during night time where the demand decreases but the wind is blowing. Even when the CHP plants are turned down or off the wind causes unused electricity production.

Norway

The Norwegian reference energy system is illustrated in figure Figure 27 with a wind share of 10% (13.3 TWh) of the electricity demand equal to an annual unused electricity production of 11.3 TWh, which is 85% of the wind generation.

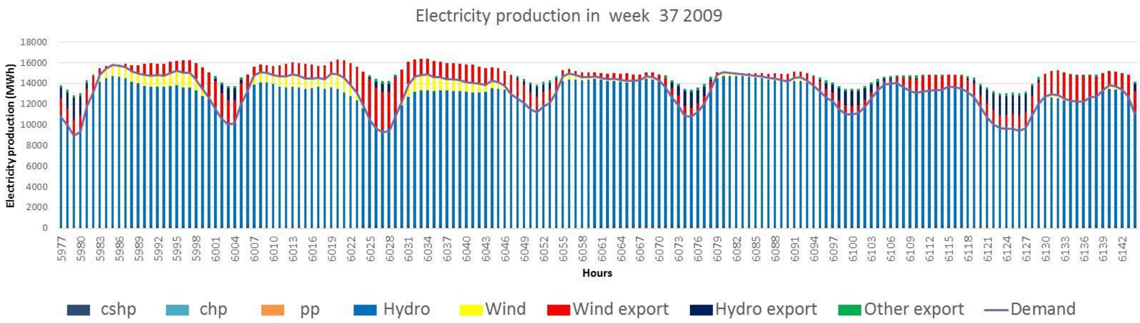

Figure 27: Electricity production distribution in a week in the Norwegian reference energy system

The Norwegian energy system is dominated by a large share of hydropower production that acts as both baseload production and to meet peak loads. The hydropower production on annual basis is equal to 97% of the total electricity demand. Other technologies in the system are waste and industry, CHP, condensing power plants and wind power. Due to the high hydropower production the majority of the wind production is unused production. Sometimes the wind that is integrated shifts some of the hydropower to a different time in the year but this causes unused production in other hours. In Figure 27 this can be seen as the wind that is integrated in the first half of the week reduces the hydropower production which means this hydropower is used in another period. The total production for hydro has to be the same in the year regardless of how much wind is produced and since there is no room in the demand to use all of it some of it has to be unused production. In a system with reduced wind such as in the reference system as of 2009 there is no unused production from hydropower and waste and industry.

It is important to note that in the example in the graph unused production is created from both wind power and hydropower at the same time, but this does not seem realistic. This is due to the fact that the input to the model is fixed and that there can be no spill in the water reservoirs. The reservoirs cannot be stored for another year as this model is created for one year. The reference system is modelled with no transmission line capacity while the hydropower in reality most likely would be exported in the hours where there is no wind in the neighbouring countries.

5.2.1.3 Wind integration

Scandinavian systems

As shown above, the three countries have different energy systems which are affected in varying ways when additional wind is added. The figures Figure 28 below shows the unused electricity for each country for the wind input. The figures also show the electricity demand of each country compared with each other. The electricity demand of each country has an important influence on the Connected and Disconnected Scandinavia results.

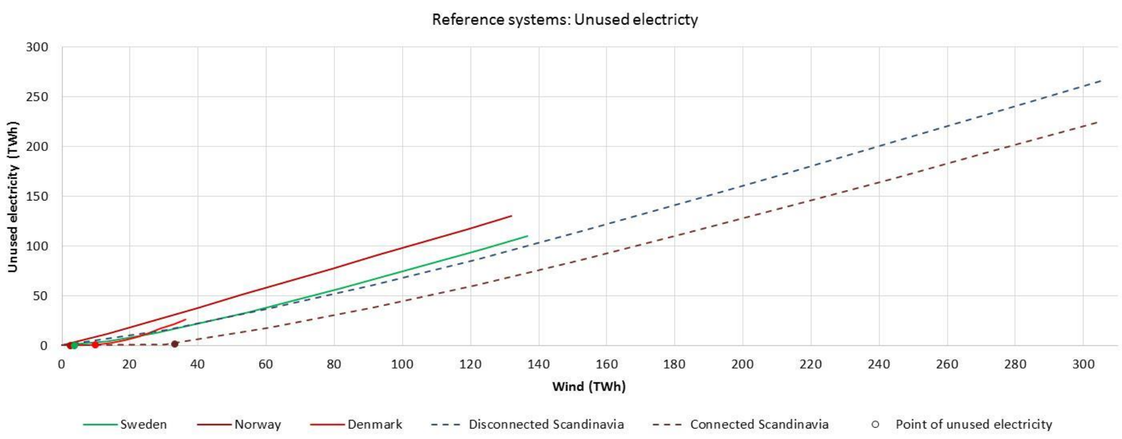

Figure 28: The unused electricity for Denmark, Sweden, Norway and Disconnected and Connected Scandinavia

As shown in figure Figure 28 the electricity demand for Denmark is much smaller than the other two countries. Denmark accounts for 12% of the total electricity demand of the three countries. Norway and Sweden account for 43% and 45%, respectively. The magnitude of the electricity demand of each country has an important influence on the Connected and Disconnected Scandinavian systems.

The point in the reference system where wind starts to cause unused electricity for the Connected and Disconnected Scandinavia system is 31 TWh and 16 TWh, respectively. The wind production share for Connected and Disconnected is around 10% and 3% of the total electricity demand, respectively.

The wind production for the Disconnected system is shown differently from the Connected system because it consists of the three countries individual unused electricity points (Denmark=9.7; Sweden=3.7; Norway=2.5) which makes it difficult to aggregate these three points into one point. The wind integration line shows the total amount of wind being integrated in the three countries combined but the point where the unused electricity is placed is more difficult to locate. For example in Norway unused electricity begins at 2.5 TWh of wind whereas in Denmark it begins at 9.7 TWh wind, therefore it is difficult to place the point. In this study one of the aims is to compare the Disconnected and Connected systems in terms of ability to integrate wind. Therefore for the Disconnected system, the point is not placed on the line for Disconnected where unused electricity begins.

Figure 29 shows the fossil fuel and biomass demand for the three countries and the Connected and Disconnected systems.

The fossil fuel and biomass demand for the Connected and Disconnected Scandinavian systems are presented in Figure 29 below.

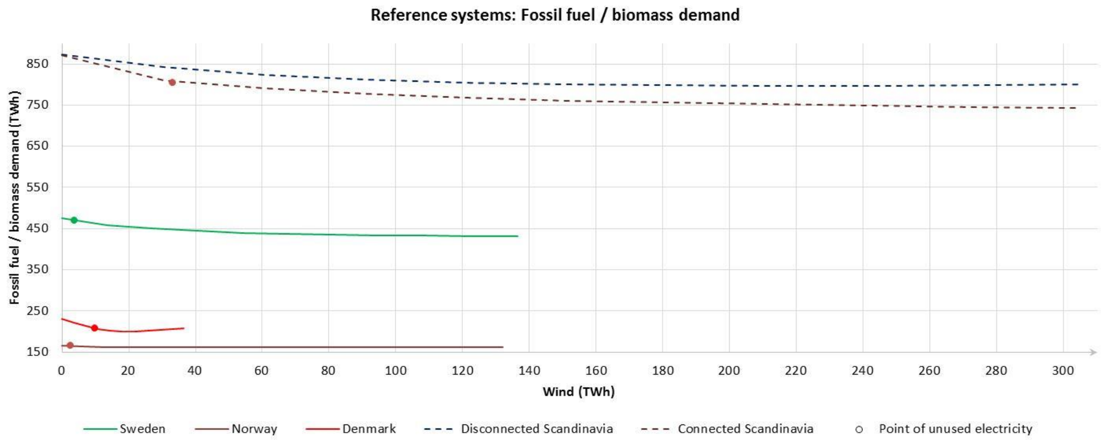

Figure 29: The fossil fuel and biomass demand for Denmark, Sweden, Norway, Disconnected and Connected Scandinavia

As the wind is integrated into the systems the fuel demand decreases however the decrease stops once the amount of unused electricity increases. The fuel demand decreases the most for the Connected system since it integrates more wind and requires less thermal power production.

The Swedish and Norwegian energy systems do not decrease much for fuel demand because the majority of the electricity does not rely on fossil fuels, therefore when wind is integrated it does not replace fossil fuels.

Scandinavian system

The Disconnected Scandinavia reference system which comprises all three countries is illustrated in Figure 30 below. The Disconnected figure is the results for all three independent countries added together, they are not actually producing this figure in reality. However the Connected figure shows the results for three countries as if they are interconnected and act as one country. The aim of the two figures is to show the difference in unused electricity when the three countries are disconnected and connected with each other. In this system a wind power production equal to 17% of the electricity demand is implemented with a total annual production of 52 TWh from wind from 22,150 MW.

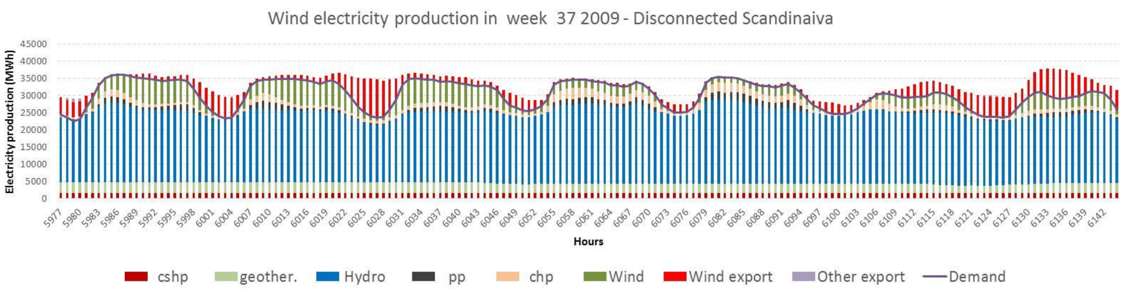

Figure 30: Electricity production distribution in a week in the Disconnected Scandinavian reference energy system

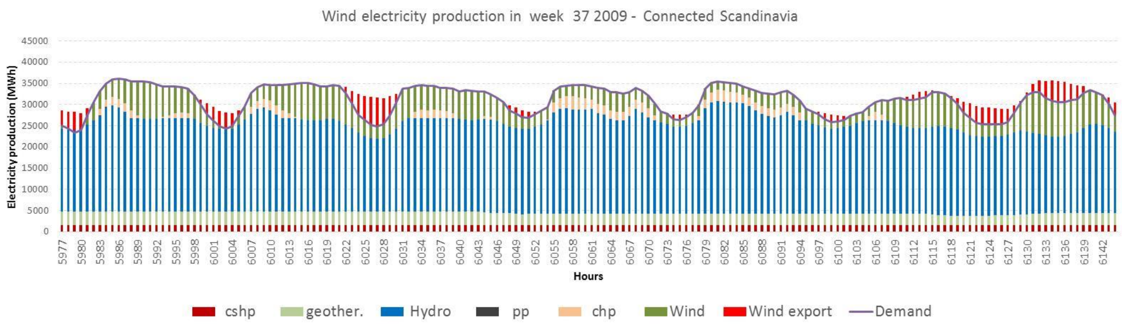

Figure 31: Electricity production distribution in a week in the Connected Scandinavian reference energy system

In the Connected Scandinavia reference system the electricity production technologies are waste and industry, nuclear power, CHP, condensing power plants, hydropower and wind. Similar to the individual country system the nuclear, waste and industry is operating as baseload production almost constant throughout the year. In the Connected Scandinavia system these technologies are around 21% of the total demand. The hydropower is the key component in the system and is also operating more or less as baseload, but is also regulating slightly according to the electricity demand. The CHP plants are only operating when there is peak demands that are not met by wind production. In the Connected Scandinavia system there is almost no condensing power plants operating as the roles of these plants (e.g. in the Danish system) are replaced by hydropower. The wind power is integrated to the extent possible and is affected by the demand and the other production technologies, i.e. the baseload is reducing the fluctuating wind production that can be integrated. All the unused electricity production is produced from wind turbines while there in contrast to the Norwegian system is no hydropower unused production in the Connected Scandinavia system. The demand is decreasing every night which then affects the unused electricity production and there is in fact unused production every night. In the last part of the week the wind power production is peaking without the demand increasing which causes the highest amount of unused production.

In conclusion, it can be summarised that the hydropower is the main production technology for the three countries to ensure that the electricity demand is met. The wind power is integrated to the extent possible, but often during the night time when the demand decreases unused electricity production is produced.

The fuel consumption decreases for both the Disconnected and Connected Scandinavia systems but the Connected Scandinavia system continually decreases whereas the Disconnected system begins to increase at around 175 TWh of wind. The Connected Scandinavia fuel consumption decreases sharply in the first 26 TWh of wind integration since all this wind is utilised and replaces thermal power production.

5.2.1.4 Socio-economic costs

The annual costs for the reference system have been calculated to get a baseline situation for the socio-economic costs of each country and the Connected and Disconnected Scandinavian systems. The socio-economic costs for the reference system for each country and the Connected and Disconnected Scandinavian system are broken down in Table 4.

Table 4: Breakdown of socio-economic costs for the reference systems in Denmark, Sweden, Norway and the Scandinavian systems

Socio-economic costs (Billion euro)		Denmark	Norway	Sweden	Disconnected Scandinavia	Connected Scandinavia
Total		17.5	19.7	35.0	72.3	72.3
Variable	**Fuel**	6.9	5.6	14.1	26.5	26.6
	Operation	0.1	0.2	0.9	1.2	1.2
	CO_2	0.7	0.6	0.8	2.1	2.1
	Other	1.4	1.9	0.4	3.7	3.8
Fixed operation		3.6	5.1	8.2	17.0	16.9
Investment		4.8	6.4	10.5	21.7	21.6

Sweden has the highest socio-economic cost out of all the countries which is expected since Sweden has a larger population leading to higher transport demands for example than the other countries. Denmark and Norway have similar costs but Norway is slightly higher due to higher fixed operation and investment costs related to the hydropower installations supplying the higher electricity demand of the country.

The socio-economic costs for the countries and the Connected and Disconnected Scandinavian systems are presented below in Figure 32.

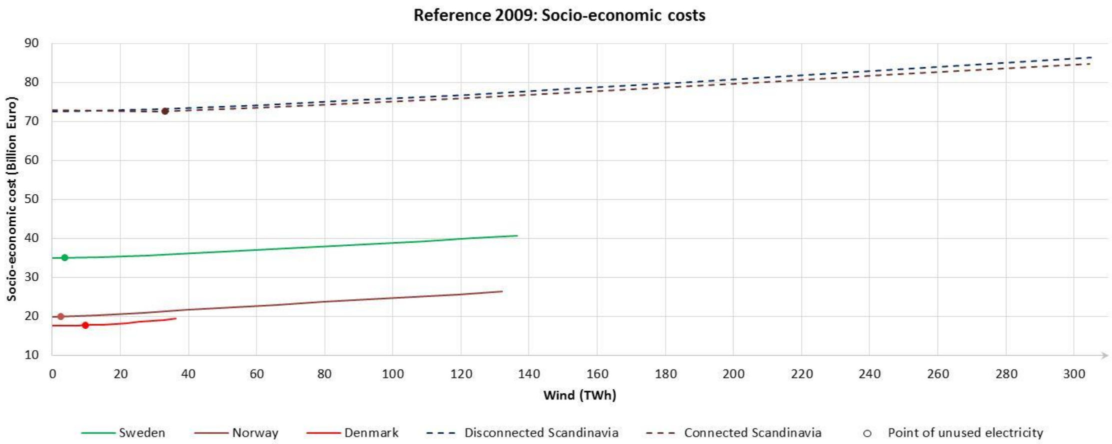

Figure 32: The socio-economic costs for Denmark, Sweden, Norway, Disconnected and Connected Scandinavia

When integrating more wind power into the reference system the socio-economic costs for the countries and the Connected and Disconnected Scandinavian systems are stable until unused electricity is produced. Even though the wind installations increase investment and operation costs, the savings on fuel level out the total cost. After that point the costs are increasing because the costs for investing in wind turbines are higher, but the wind is not able to replace any fuels and thereby create savings.

The cost for the Connected Scandinavia scenario are slightly lower than the Disconnected system as the wind increases since the Connected Scandinavia scenario can integrate more wind and thus save on fuels.

5.2.1.5 Carbon dioxide emissions

The carbon dioxide emissions for each country and the Connected and Disconnected Scandinavia systems are shown in Table 5.

Table 5: CO_2-emissions for Denmark, Sweden, Norway and Scandinavia

CO_2 (Mt)	Denmark	Norway	Sweden	Disconnected Scandinavia	Connected Scandinavia
	48	36	53	138	137

The CO_2 emissions in the Danish reference system are 48 Mt with the largest part emitted from oil consumption (in the transport sector) and coal and natural gas consumption in the CHP and power plants. Individual heating and industries are also responsible for a share of the CO_2 emissions. Even though Norway has a much higher electricity demand than Denmark it has the lowest emissions since the majority of the electricity is from hydro power. Sweden has the highest electricity demand but it only has a slightly higher emissions level than Denmark which is also because the electricity is produced from hydro power and nuclear power. The country does not depend on much fossil fuels for electricity production.

The carbon dioxide emissions for each country and the Connected and Disconnected Scandinavian systems are shown in Figure 33.

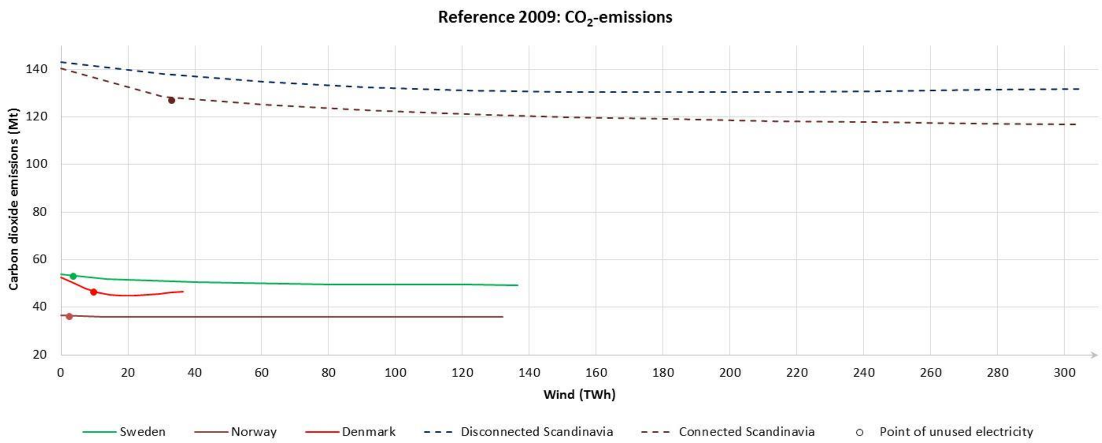

Figure 33: The CO_2-emissions for Denmark, Sweden, Norway, Disconnected and Connected Scandinavia

When conducting the wind analysis the CO_2 emissions are reduced when the wind power is able to replace fossil fuels for Denmark and the Scandinavian systems. Similar to the findings from Figure 29 the fossil fuels and thereby the emissions are decreasing in Denmark until a point around 20 TWh wind power production.

The CO_2 emissions for Sweden and Norway do not decrease since the majority of the emissions in these countries do not arise from electricity production, but transport and industry.

The CO_2 emissions from the Connected Scandinavia system fall the most compared with the Disconnected Scandinavia system which is due to the higher wind integration which decreases demand for fossil fuel power production.

5.3 Results for energy system types and technological solutions

The results for the three energy system types are presented in this section. The results are presented for the different steps in each energy system type for the Connected and Disconnected Scandinavia systems. The individual countries are not presented in this section but the figures for the countries can be found in Appendix X.

5.3.1 Results for steps in energy system type A

The results for the key factors from analysing the wind integration from 0-100% of electricity demand are explained below for the different systems in Energy system type A.

5.3.1.1 Flexibility and wind integration

The unused electricity produced when wind is increased from 0-100% for the Disconnected Scandinavia and Connected Scandinavia systems is shown in Figure 34 and Figure 35 below. The two figures are provided in order to compare the unused electricity when the same percentage of wind is integrated in the systems. For example when 20% of wind (out of the total electricity demand) is integrated in the systems. In the Disconnected system this means that 20% wind is integrated in the Denmark, Sweden and Norway systems in each step. In the Connected system 20% wind is integrated in that one system.

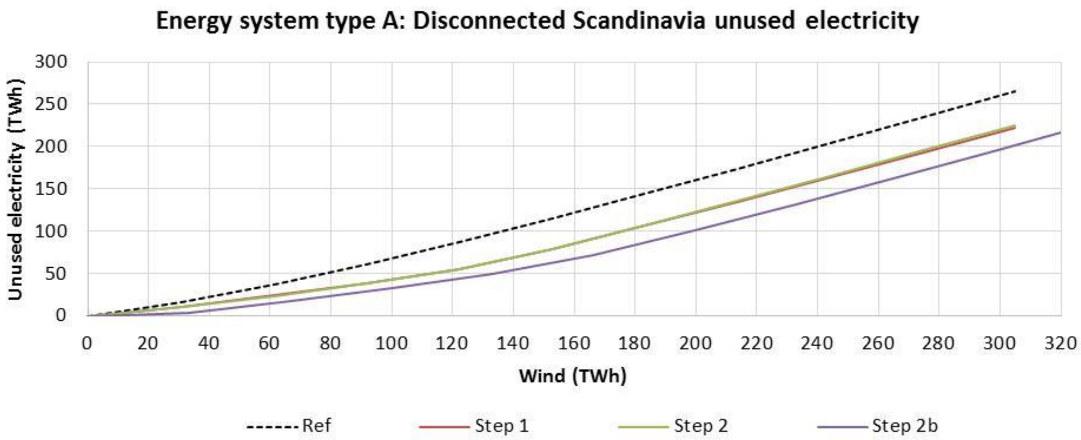

Figure 34: Wind integration for steps in energy system type A in Disconnected Scandinavian system

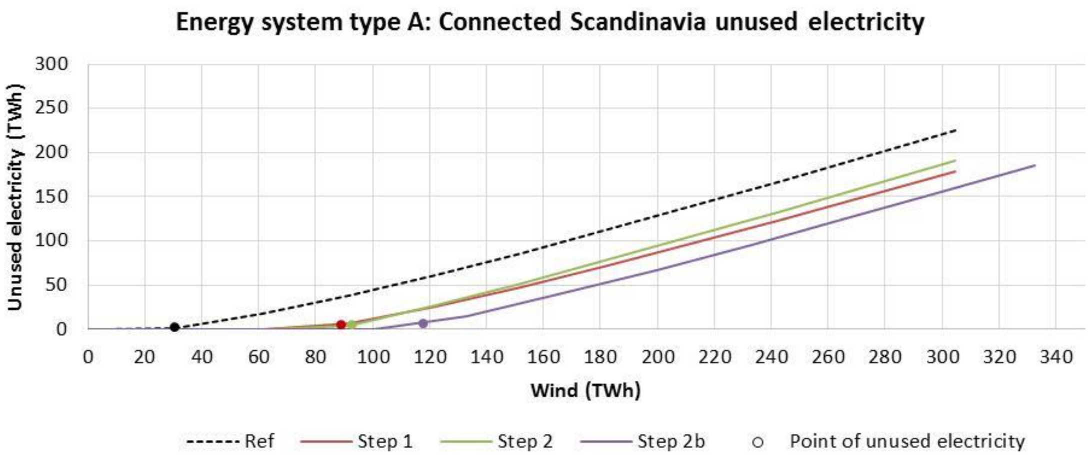

Figure 35: Wind integration for steps in energy system type A in Connected Scandinavian system

In the Disconnected system the unused electricity is higher than the Connected system because for example when 20% wind is integrated in each of the countries, there is high unused electricity. This is because some of the countries cannot integrate this much wind for example Norway. Therefore when the unused electricity for each country is aggregated the total unused electricity is high. Each country reaches the point where unused electricity is above 5% at different levels of wind integration and because of this it is not possible to plot an aggregated point of unused electricity on the curves in Figure 34, the aggregated point values are presented in Table 6 below. In the Connected system the one system is able to integrate more wind since it is one system and is more flexible, and the point of unused electricity is possible to plot since the wind integration curve represents only one system.

The wind electricity production at the point where unused electricity increases above the 5% threshold for the Connected and Disconnected Scandinavia systems is shown for each step and for the reference in Table 6. In the Disconnected Scandinavia system the point of unused electricity equals the aggregate wind production when unused electricity reaches 5% of the total electricity demand for each country. For example for the reference system the amount of wind produced in Denmark, Sweden and Norway when 5% unused electricity is produced in each country equals 9.7, 3.7 and 2.5 TWh, respectively, which equals 15.9 TWh total wind production at the point of unused electricity. In this example it shows that Norway hits the point first and Denmark is able to integrate more wind before it hits the point.

Table 6: Wind production at the point of unused electricity for Disconnected and Connected Scandinavian systems

Wind input at point of unused electricity (TWh)	Reference	Step 1	Step 2	Step 2b
Disconnected	15.9	72.3	72.3	91.9
Connected	30.6	89	93	117.8

In step 1 for the Disconnected Scandinavia system the wind integration increases from the reference system which is due to the Swedish energy system. In the Swedish energy system when the nuclear power is removed and is replaced by thermal power plants the country experiences a significant improvement in the ability to integrate wind in the system. The power plants that replace the nuclear power create enhanced flexibility in the system and this allows more wind to be integrated. In the Swedish reference system from 2009 including nuclear power around 3% of the electricity demand could be covered by wind before unused production was created. For step 1 without nuclear power this improved to around 43% of the electricity demand. The reason for this improved integration is that the base load electricity production is removed and hence, there is more room for regulating the production according to wind production, for example by using the hydropower or thermal production as baseload production which is more flexible.

When all three countries have reached the 5% threshold in the Disconnected Scandinavia system, the amount of wind that can be integrated is 24% (step 1 and 2) and 28% (step 2b) of the total aggregated electricity demand.

In the Connected system steps 1,2 and 2b are able to increase wind capacity to produce 89, 93 and 113 TWh wind electricity, respectively, before the unused electricity surpasses the 5% threshold. This is equivalent to 29%, 30% and 34% of the total electricity demand, respectively. Since all three countries are connected the balancing power can be supplied by hydro from Sweden and Norway.

The conversion to biomass in the electricity and heat sector in step 1 and the conversion to biofuels in step 2 did not affect the wind integration noticeably.

In step 2b, when integrating electric vehicles into the system, improvements are found for all systems because the electricity demand is increased and more wind can thereby be integrated. When the demand is increased a larger share of the total production is produced from technologies that can regulate according to wind power. The electric vehicles are in all scenarios therefore improving the wind integration ability where the Swedish system can integrate around 46% wind, In Denmark the share is around 30%, in Norway the share is around

8%. The overall Scandinavia Connected and Disconnected systems can integrate 34% and 28% wind, respectively.

5.3.1.2 Fossil fuel / biomass demand

The fossil fuel / biomass demand when wind is increased from 0-100% for the Disconnected Scandinavia and Connected Scandinavia systems is shown in Figure 36 and Figure 37 below. As explained above the two figures are provided in order to compare the fuel demand when the same percentage of wind is integrated in each system.

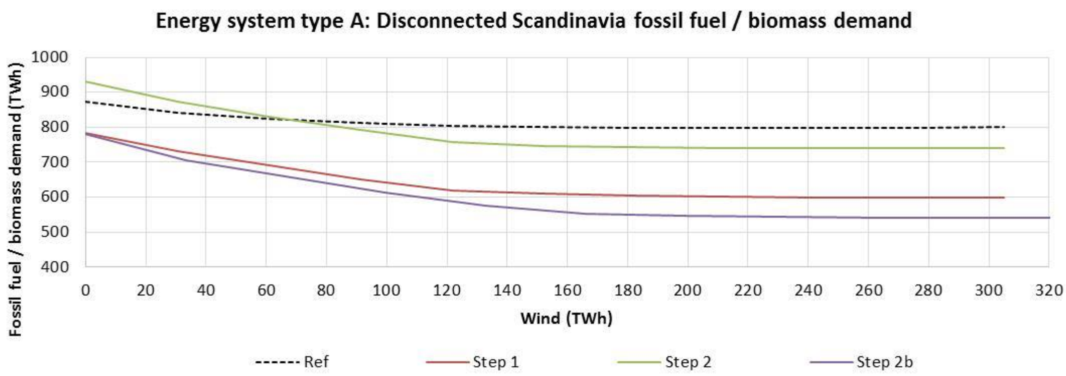

Figure 36: Fossil fuel and biomass demand for steps in energy system type A in Disconnected Scandinavian system

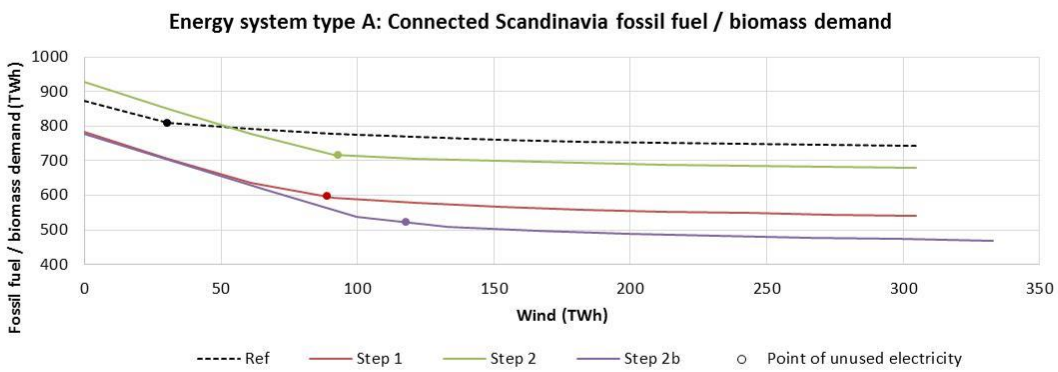

Figure 37: Fossil fuel and biomass demand for steps in energy system type A in Connected Scandinavian system

The fossil fuel/biomass demand at the point where unused electricity increases above the 5% threshold for the Connected and Disconnected Scandinavia systems is shown for each step and for the reference in Table 7.

Table 7: Fossil fuel and biomass demand at the point of unused electricity for Disconnected and Connected Scandinavia

Fossil fuel/biomass demand at point of unused electricity (TWh)	Reference	Step 1	Step 2	Step 2b
Disconnected	844	627	764	575
Connected	807	596	715	523

In the reference system for the Scandinavian Connected and Disconnected systems fuel demand consists of fossil fuel and biomass, however from step 1 onwards all fossil fuel is converted to biomass. Therefore in the steps following step 1, the biomass demand increases significantly due to the conversion to biomass dependence in all sectors in the energy systems

In the Connected Scandinavia system the biomass demand in step 1 decreases at the point of unused electricity. As explained above since Sweden can integrate more wind this decreases the overall fuel demand in Sweden, and since Sweden accounts for around 45% of the electricity demand of the countries included in the Scandinavian region (Denmark, Sweden, Norway) this influences the overall fuel demand of the Connected system significantly.

In addition in step 1 the fossil fuel and biomass demand for Norway decreases significantly due to the removal of natural gas flaring - since biomass has replaced the need for natural gas. Natural gas flaring is also reduced to 0 in Denmark.

However in step 2 when fossil fuels are converted to biofuels, the fuel demand increases which is due to the higher biomass demand for the production of biofuels.

In step 2b, for all countries and the Scandinavian systems, the biopetrol fuelled vehicles (cars and vans) are replaced with electric vehicles. This conversion reduces the biomass fuel demand significantly.

The reduction of fuels when integrating more electric vehicles is due to two reasons. Firstly and most important, the electric vehicle technology is more efficient than internal combustion engine technologies in terms of energy efficiency from engine-to-wheel (Danish Energy Agency and COWI 2013a). This results in a reduced fuel demand for meeting a similar transport demand and thereby saves some fuels.

Secondly, converting to electricity instead of fossil fuels might contribute to improving the efficiency of the entire energy system as electricity can be supplied from technologies such as condensing power plants, CHP and renewable sources instead of solely relying on solid fossil fuels. The fuels can hence be produced when required instead of stored and imported from foreign markets.

Overall the Connected Scandinavia system reduces the fuel demand more than the Disconnected Scandinavia system when integrating a higher share of wind, and this is due to the higher integration of wind in the Connected Scandinavia system, which reduces the demand for thermal power production.

5.3.1.3 Socio-economic costs

The socio-economic cost when wind is increased from 0-100% for the Disconnected Scandinavia and Connected Scandinavia systems is shown in Figure 38 and Figure 39 below.

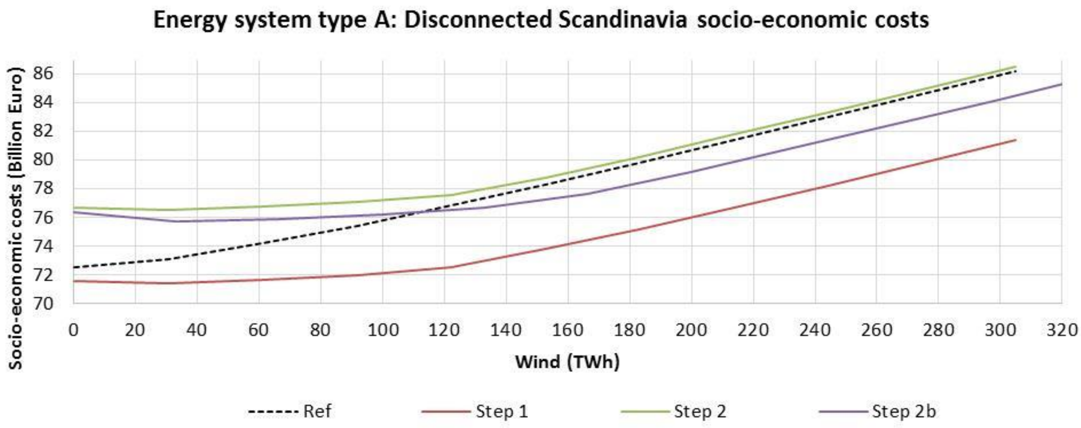

Figure 38: Socio-economic costs for steps in energy system type A in Disconnected Scandinavian system

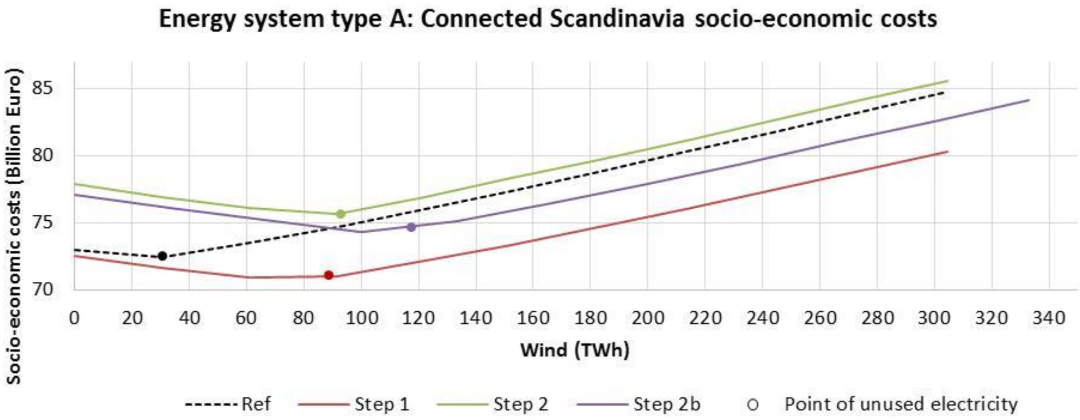

Figure 39: Socio-economic costs for steps in energy system type A in Connected Scandinavian system

The socio-economic cost at the point where unused electricity increases above the 5% threshold for the Connected and Disconnected Scandinavia system is shown for each step and for the reference in Table 8.

Table 8: Socio-economic costs at the point of unused electricity for Disconnected and Connected Scandinavia

Socio-economic cost at point of unused electricity (TWh)	Reference	Step 1	Step 2	Step 2b
Disconnected	72.6	70.1	75.3	74.5
Connected	72.5	71	75.6	74.6

For both the Connected and Disconnected Scandinavia systems the costs for step 1 are lower than the reference, with wind integration of 29% and 24%, respectively, before unused electricity is produced. The key factor that affects the costs is how much fuel can be replaced by wind and if this amount exceeds the increased costs for investment and operation for installing more wind turbines and electric vehicles. Even though step 1 does not integrate as much wind as step 2b it has lower costs which is due to the lower fixed operation and investment costs related to wind and power plants and investments in electric vehicles. Part of this reduced fuel cost is because the flaring of natural gas in the systems are removed, and that the shipping fuel oil is replaced by biofuels that has a lower cost.

Step 2 has the highest costs which is due to the lower integration of wind and higher costs for increased biomass for producing biofuels.

Step 2b can integrate the highest amount of wind but the investment costs for wind and for increasing the capacity of power plants due to higher electricity demand raises the cost above the reference system. However the fuel used in the transport sector is replaced by wind which decreases the cost below step 2.

5.3.1.4 Carbon dioxide emissions

The carbon dioxide emissions when wind is increased from 0-100% for the Disconnected Scandinavia and Connected Scandinavia systems are shown in Figure 40 and Figure 41 below. The key principle behind the steps in Energy system type A is that they should reduce the CO_2 emissions in the systems to make them 100% renewable in a relatively simple way.

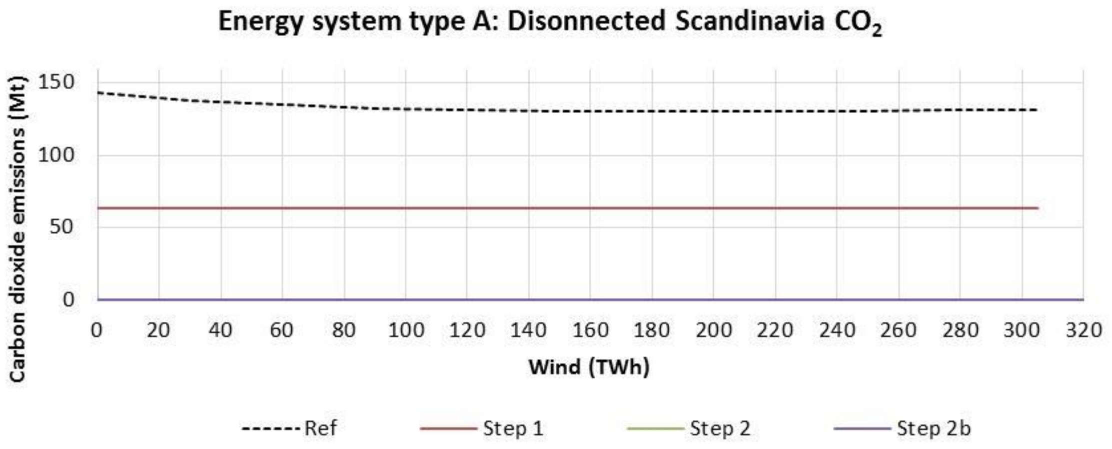

Figure 40: CO_2-emissions for steps in energy system type A in Disconnected Scandinavian system

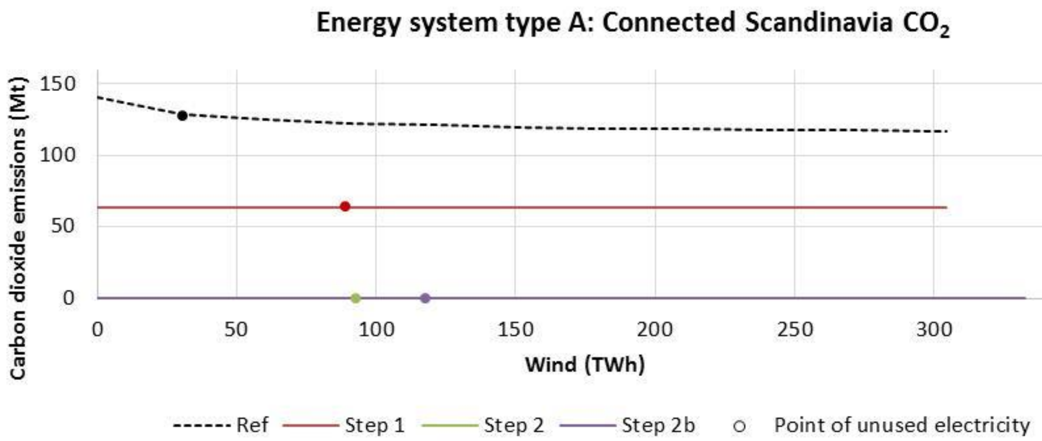

Figure 41: CO_2-emissions for steps in energy system type A in Connected Scandinavian system

The carbon dioxide emissions at the point where unused electricity increases above the 5% threshold for the Connected and Disconnected Scandinavia system is shown for each step and for the reference in Table 9.

Table 9: CO_2-emissions at the point of unused electricity for Disconnected and Connected Scandinavia

Carbon dioxide emissions at point of unused electricity (TWh)	Reference	Step 1	Step 2	Step 2b
Disconnected	133.5	63	0	0
Connected	127	64	0	0

In the Disconnected and Connected Scandinavia the CO_2 emissions are reduced to 0 from step 2 onwards. This is because all sectors have been converted to biomass. This is based on the assumption that biomass consumption is CO_2-neutral; this is discussed further in Chapter 6.

In step 1 when all fossil fuels are converted to biomass for industry, thermal electricity, and heating, the CO_2 emissions at the point of unused electricity decrease for Disconnected and Connected Scandinavia by around 54% and 49%, respectively, below the reference system.

The remaining CO_2 in step 1 is from the transport sector and is reduced to zero emissions in step 2.

5.3.2 Results for steps in Energy system type B

The results for the key factors from analysing the wind integration from 0-100% of electricity demand are explained below for the different systems in Energy system type B.

5.3.2.1 Flexibility and wind integration

The unused electricity produced when wind is increased from 0-100% for the Disconnected Scandinavia and Connected Scandinavia systems is shown in Figure 42 Figure 43 below.

For the figures below the reference and last step from energy system type A have been included. The last step from Energy system type A is step 2. As explained in the methodology Step 2b is an additional last step for energy system type A where electric vehicles are added in order to finalise the changes in the Energy system type A super grid energy system. Since the steps are sequential, step 2b is removed and step 3 continues from step 2 in Energy system type B.

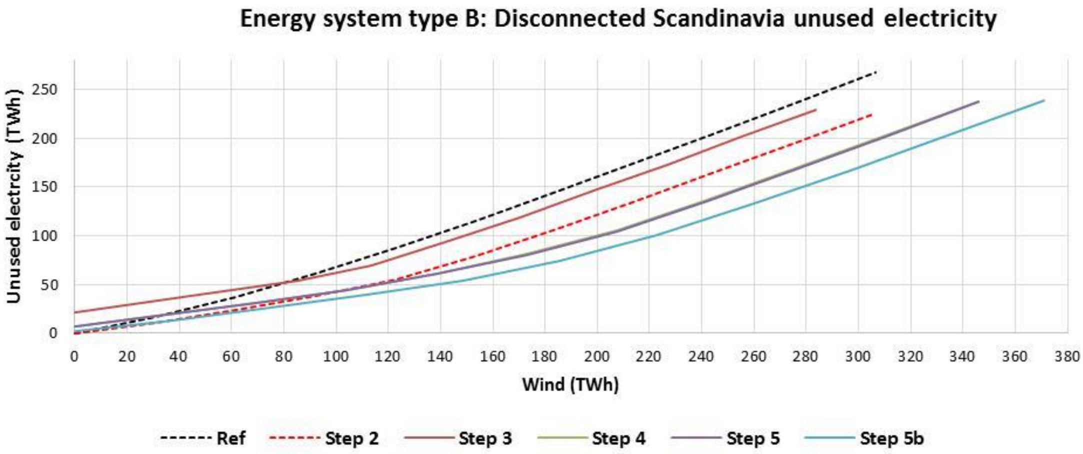

Figure 42: Wind integration for steps in energy system type B in Disconnected Scandinavian system

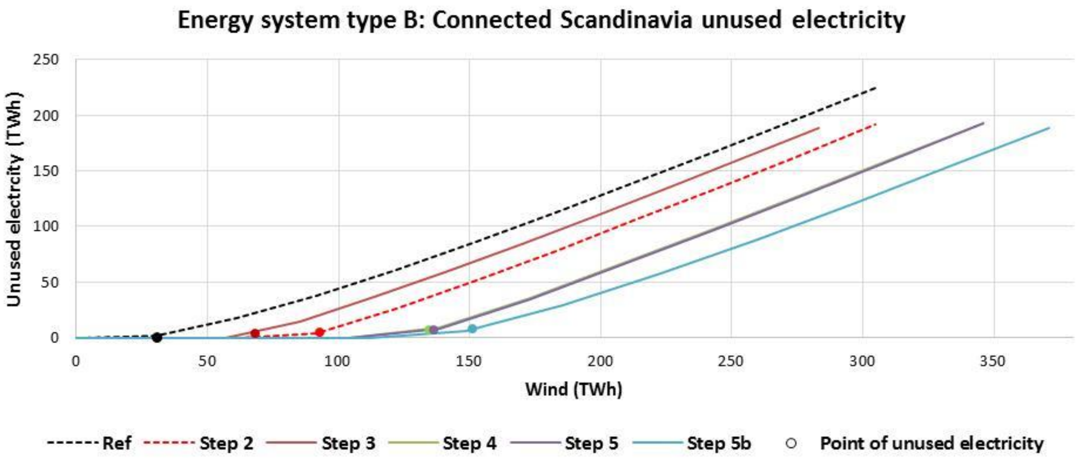

Figure 43: Wind integration for steps in energy system type B in Connected Scandinavian system

The wind electricity production at the point where unused electricity increases above the 5% threshold for the Connected and Disconnected Scandinavia system is shown for each step and for the reference in Table 10.

Table 10: Unused electricity at the point of unused electricity for Disconnected and Connected Scandinavia

Wind input at point of unused electricity (TWh)	Reference	Step 2	Step 3	Step 4	Step 5	Step 5b
Disconnected	15.9	72.3	68.2	95.4	98	117.9
Connected	30.6	93	68.2	134.5	136.4	151.2

As shown in Figure 42 in the Disconnected system the aggregate unused electricity at 0 TWh wind is above the 5% unused electricity allowance for steps 3 (individual heat pumps),4 (electrification of industry), and 5 (flexible demand). The reason for this is that in step 3 the electricity demand has been decreased for all the countries because individual heat pumps replace electric heating. This affects the Norwegian and Swedish systems significantly since they have very high electric heating demands. When the electricity demand decreases it creates a situation where surplus electricity occurs. This is apparent in step 3 with the introduction of heat pumps instead of electric heating where the Norwegian electricity demand decreases by 23.27 TWh from 132.57 to 109.03 TWh, the latter being lower than the hydropower production of 127.8 TWh.

In Norway the hydropower supplies 97% of the demand and if the demand decreases too far it is assumed there is surplus electricity from hydropower. Hence there is no room for additional wind production. Only when electric vehicles are integrated in step 5b does the ability to integrate wind increase again. It is assumed that the hydropower that cannot be used in Norway is more or less spilled in the Disconnected system while in the Connected Scandinavia it is integrated with the other countries and hence replaces some electricity that could otherwise have been produced by wind power.

Although the aggregate Disconnected system has surplus electricity at 0 TWh wind. It does not mean that wind is not being produced in Denmark and Sweden, it means that the wind produced in these countries is cancelled out due to the over-supply of electricity in Norway. In Sweden 55-96 TWh of wind can be integrated from steps 3-5b. In Denmark 13-22 TWh wind can be integrated from steps 3-5b. But when the three countries are aggregated for the purpose of the study this wind amount is cancelled out by Norway's oversupply.

In the Connected Scandinavia system the wind share that can be integrated increases to 39% in step 4 and 5 (and 41% in step 5b) since all three countries are connected and balancing power is supplied by hydropower from Sweden and Norway. In comparison, in step 5 the Disconnected Scandinavia system can integrate 28% of the electricity demand (and 32% in step 5b).

In step 4 where 40% of the industry fuel demand is converted to electricity demand more wind can be integrated in both the Connected and Disconnected system, but in particular the Connected system benefits from this as the electricity demand thereby increases in Norway and less hydropower replaces wind in the Connected Scandinavian system.

When implementing a flexible demand over 24 hours in step 5 neither the Connected or Disconnected Scandinavian systems improve their wind integration.

In step 5b when electric vehicles are integrated in the system, the wind integration improves along with the electricity demand. The electric vehicles in this step are smart charged which aims at reducing the unused electricity in the system. This smart charge makes a difference for the integration of electric vehicles as step 5b with smart charge improves the integration of wind more than step 2b that uses a dump charge strategy.

5.3.2.2 Biomass demand

The fossil fuel / biomass demand when wind is increased from 0-100% for the Disconnected Scandinavia and Connected Scandinavia systems is shown in Figure 44 and Figure 45 below. The demand consists only of biomass as all fossil fuels are replaced by biomass in Energy system type A.

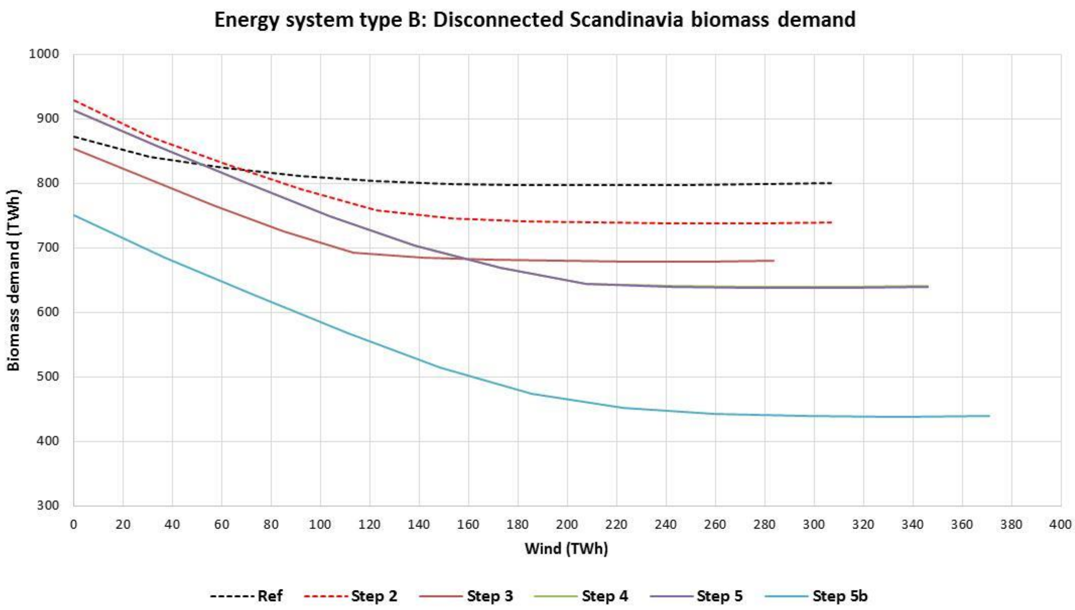

Figure 44: Biomass demand for steps in energy system type B in Disconnected Scandinavian system

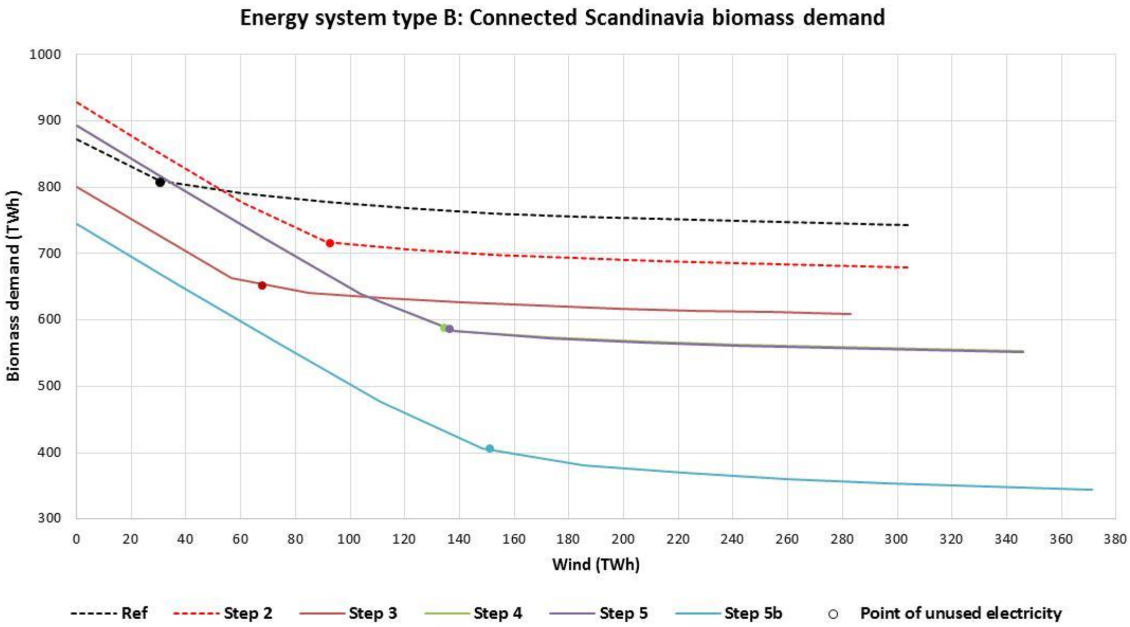

Figure 45: Biomass demand for steps in energy system type B in Disconnected Scandinavian system

The biomass demand at the point where unused electricity increases above the 5% threshold for the Connected and Disconnected Scandinavia system is shown for each step and for the reference in Table 11.

Table 11: Biomass demand at the point of unused electricity for Disconnected and Connected Scandinavia

Biomass demand at point of unused electricity (TWh)	Reference	Step 2	Step 3	Step 4	Step 5	Step 5b
Disconnected	844	764	699	692	687	477
Connected	807	715	651	588	586	406

The biomass demand for both the Connected and Disconnected Scandinavia systems decreases for all steps following step 2. However the extent that the biomass demand decreases before unused electricity occurs is different between the systems. I.e. Norway forces the Disconnected system to have unused electricity without any wind integration. The biomass demand reduces in energy system type B for Sweden and Norway while the

Danish system increases the biomass demand, but since the Swedish system impacts the Scandinavian Disconnected system more than the Danish system, this results in a reduction for all of Scandinavia.

The biomass demand increases in Denmark due to the overall growing electricity demand in this energy system type that cannot solely be supplied by wind power, and therefore thermal power is required. In Sweden the electricity demand increases by 88 TWh from step 3 to step 5b, but since the country has hydropower for balancing, it is able to integrate more wind and therefore less power is required from thermal production and thus the biomass demand decreases from step 3 onwards. In the Norwegian system the biomass demand is reduced when EVs are integrated replacing the fuel demand for biomass from biofuels.

The Connected Scandinavia system is able to integrate more wind than the Disconnected system and this leads to reduced biomass demand as the wind power replaces technologies using biomass. This can also be seen in Table 11 where the point of unused electricity occur at higher wind integration points than in the Disconnected system.

The overall biomass demand reduction from the reference to 5b in the Disconnected system at the point of unused electricity is from 844 TWh in the reference to 560 TWh in step 5b, a reduction of 35%.

The overall biomass demand reduction from the reference to 5b in the Connected Scandinavia system at the point of unused electricity reduces from 807 TWh to 406 TWh, a reduction of 50%.

5.3.2.3 Socio-economic costs

The socio-economic cost when wind is increased from 0-100% for the Disconnected Scandinavia and Connected Scandinavia systems is shown in Figure 46 and Figure 47 below.

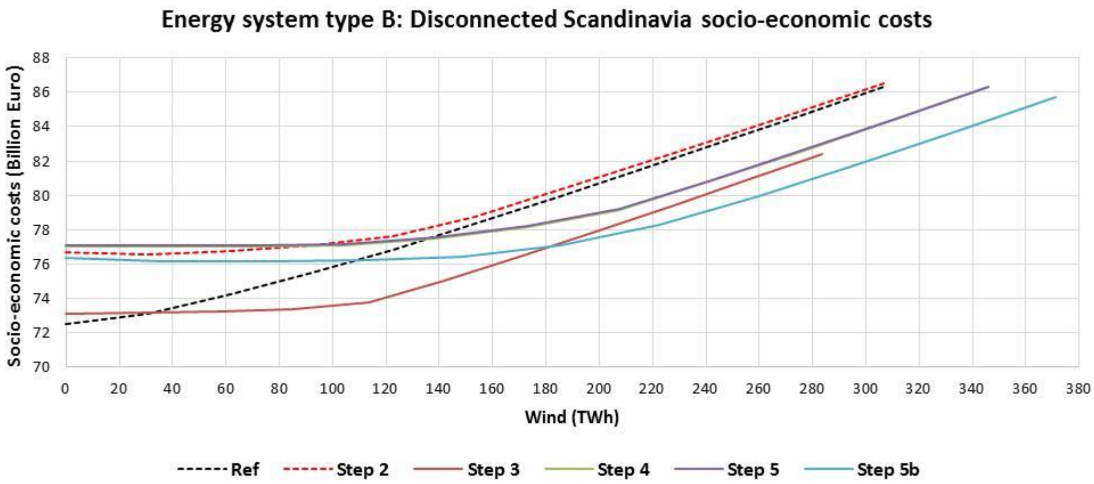

Figure 46: Socio-economic costs for steps in energy system type B in Disconnected Scandinavian system

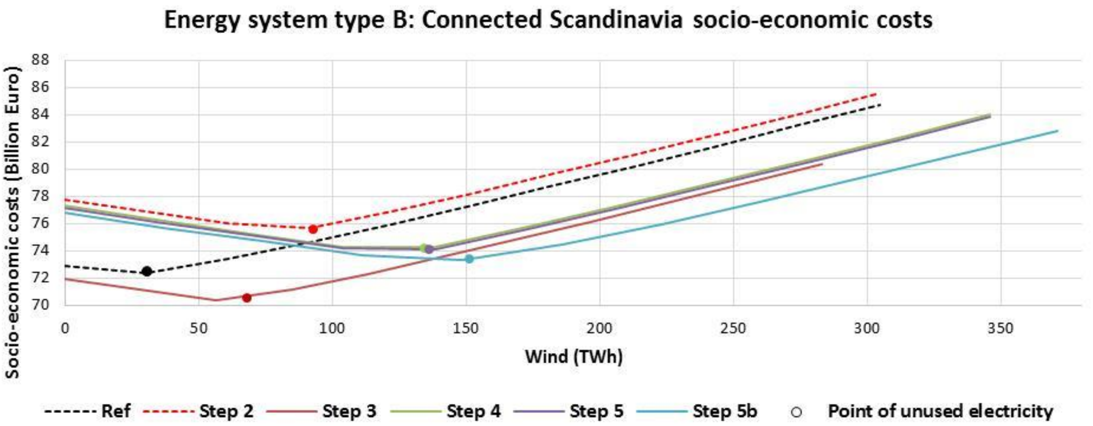

Figure 47: Socio-economic costs for steps in energy system type B in Connected Scandinavian system

The socio-economic cost at the point where unused electricity increases above the 5% threshold for the Connected and Disconnected Scandinavia system is shown for each step and for the reference in Table 12.

Table 12: Socio-economic costs at the point of unused electricity for Disconnected and Connected Scandinavia

Socio-economic cost demand at point of unused electricity (TWh)	Reference	Step 2	Step 3	Step 4	Step 5	Step 5b
Disconnected	72.6	75.3	71.5	74.7	74.7	73.6
Connected	72.5	75.6	70.5	74.2	74.1	73.4

The socio-economic costs are influenced by a number of factors such as fuels, investments and whether the technologies require infrastructural changes. In the Scandinavian Disconnected system the steps all have higher costs than the reference even though step 3 reduces the costs compared to the previous step 2. This is because individual heat pumps replace individual boilers and electric heating thereby saving fuels. The heat pumps also result in increased operation and maintenance costs, but the fuel savings make up for this. Steps 4-5b have higher costs than previous steps regardless of the amount of wind that can be integrated in the systems.

For the Connected Scandinavia system step 3 has lower costs than the reference and all previous steps. In step 4-5b the costs are higher than the reference, but lower than step 2 due to the changes in fuel costs and investments

The difference between the two Scandinavian systems are rather limited while the Connected system has slightly lower costs than the Disconnected system in most steps. In step 5b at the point of unused electricity the Disconnected system has more than 2.3 billion euro higher fuel costs than the Connected system, but it also has higher investment and operation and maintenance costs of 1.5 billion euro and 0.7 billion euro, respectively, than the Connected system which makes the difference rather small.

5.3.2.4 Carbon dioxide emissions

The carbon dioxide emissions were reduced to 0 in step 2 of Energy system type A and are therefore not elaborated in this section.

5.3.3 Results for steps in Energy system type C

The results for the key factors from analysing the wind integration from 0-100% of electricity demand is explained below for the different systems in Energy system type C.

5.3.3.1 Flexibility and wind integration

The unused electricity produced when wind is increased from 0-100% for the Disconnected Scandinavia and Connected Scandinavia systems is shown in Figure 48 and Figure 49 below.

For the figures below the reference and last step from energy system type B have been included. The last step from Energy system type B is step 5. As explained in the methodology Step 5b is an additional last step for energy system type B where electric vehicles are added in order to finalise the changes in the Energy system type B smart grid energy system. Since the steps are sequential, step 5b is removed and step 6 continues from step 5 in Energy system type C.

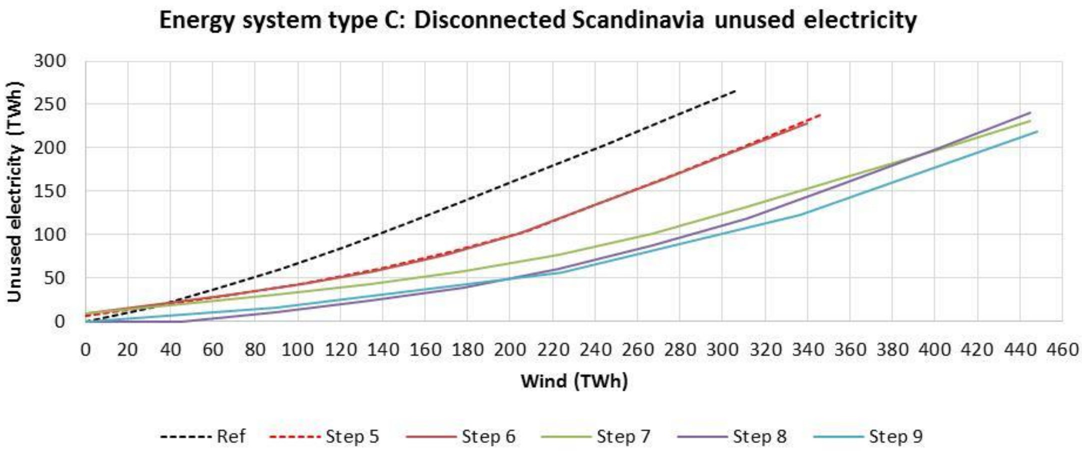

Figure 48: Wind integration for steps in energy system type C in Disconnected Scandinavian system

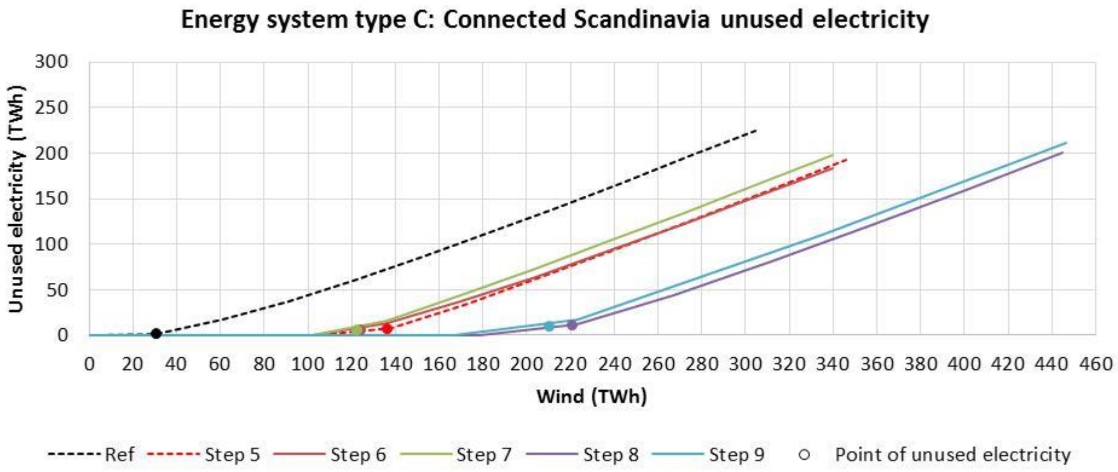

Figure 49: Wind integration for steps in energy system type C in Connected Scandinavian system

The wind electricity production at the point where unused electricity increases above the 5% threshold for the Connected and Disconnected Scandinavia system is shown for each step and for the reference in Table 13.

Table 13: Unused electricity at the point of unused electricity for Disconnected and Connected Scandinavia

Wind input at point of unused electricity (TWh)	Reference	Step 5	Step 6	Step 7	Step 8	Step 9
Disconnected	15.9	98	97.8	97.8	168.2	185
Connected	30.6	136.4	123.9	122.3	220.6	210.4

In the Disconnected Scandinavia system steps 5,6 and 7 can integrate around the same amount of wind electricity before all countries start producing unused electricity, around 98 TWh of wind. Norway can integrate more wind in step 8 since the electricity demand increases when EVs and electrolysers are integrated.

In the Disconnected Scandinavian system from step 8 to step 9 the aggregated wind integration increased to 185 TWh. Norway and Sweden did not change the wind integration much from step 8 to 9, remaining at around 17 and 118 TWh wind, respectively. However Denmark increased from 32 to 52 TWh wind from step 8 to 9. The proportion of the total electricity demand in wind for Denmark increased from 42% to 68% from step 8 to step 9.

The Scandinavian Disconnected system increases in wind integration in step 9 since Denmark is able to increase wind share significantly. However in the Scandinavian Connected system the wind share decreases which is due to the increased electricity efficiency in the CHP plants. Since the CHP plants must produce heat for district heating, they produce electricity as well, which decreases the demand for wind electricity.

In the Connected Scandinavia system, the point where unused electricity occurs is at a much higher wind integration than the Disconnected system. Steps 6 and 7 integrate around the same amount of wind at around 122 and 124 TWh, respectively. Steps 8 and 9 integrate the most wind at 221 and 210 TWh, respectively, which is 50% and 47% of the total electricity demand.

5.3.3.2 Biomass demand

The fossil fuel and biomass demand when wind is increased from 0-100% for the Disconnected Scandinavia and Connected Scandinavia systems is shown in Figure 50 and Figure 51 below. The demand consists only of biomass as all fossil fuels are replaced by biomass in Energy system type A.

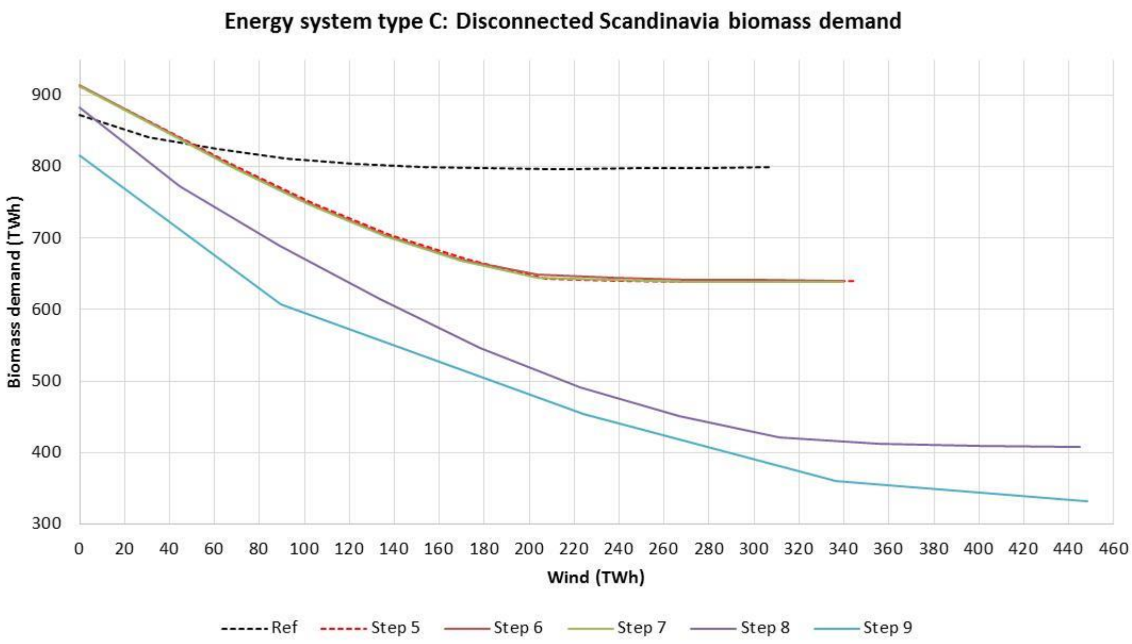

Figure 50: Biomass demand for steps in energy system type C in Disconnected Scandinavian system

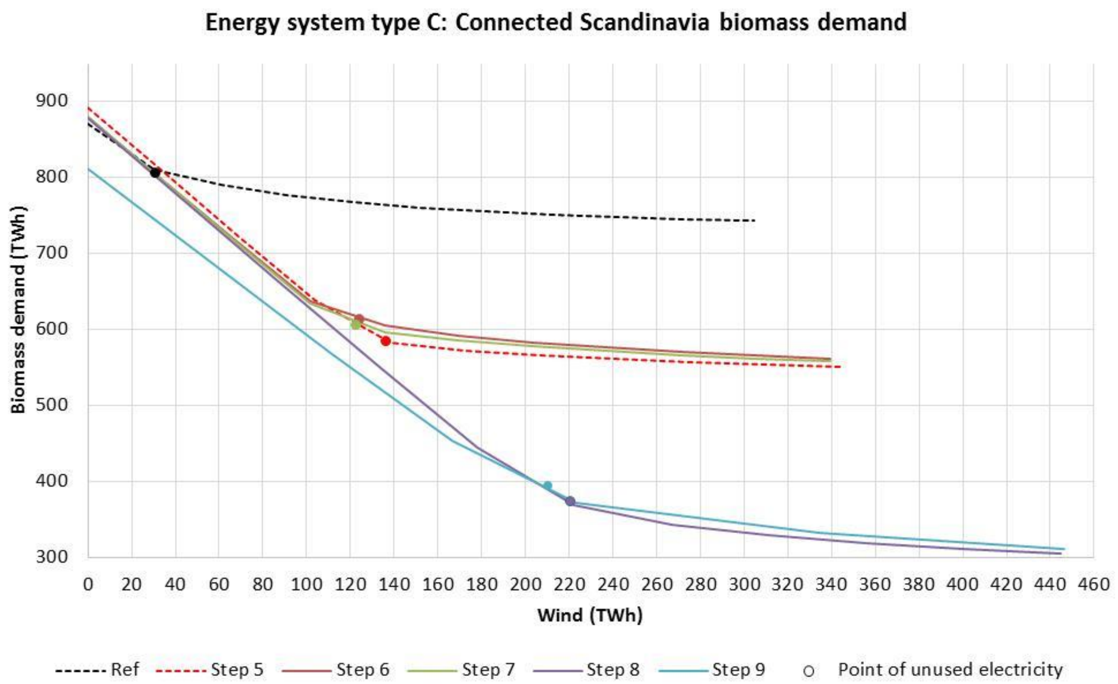

Figure 51: Biomass demand for steps in energy system type C in Disconnected Scandinavian system

The biomass demand at the point where unused electricity increases above the 5% threshold for the Connected and Disconnected Scandinavia system is shown for each step and for the reference in Table 14.

Table 14: Biomass demand at the point of unused electricity for Disconnected and Connected Scandinavia

Biomass demand at point of unused electricity (TWh)	Reference	Step 5	Step 6	Step 7	Step 8	Step 9
Disconnected	844	687	690	690	496	439
Connected	807	586	614	606	374	394

The biomass demand for all steps for both systems decrease compared with the reference. Step and 8 and 9 decrease the most where in the Disconnected system it decreases to 560 and 500 TWh, respectively. For the

Connected Scandinavia system the biomass demand decreases to 374 and 394 TWh for step 8 and 9, respectively. Step 8 decreases mostly due to the integration of EVs and the replacement of biofuels with synfuels which consume much less biomass. Step 9 does not decrease as much since gasification of biomass actually increases the biomass demand due to small losses in the gasification process, for example due to gasification efficiency and leakage of gas from conversion to final consumption. Even though step 9 can integrate the most wind for the Connected Scandinavia system the biomass demand is still higher than step 8.

Steps 6 and 7 (district heating expansion and large heat pumps) demand a slightly higher amount of biomass than step 5 (flexible demand), which is because the district heating, and large scale heat pumps do not decrease the fuel demand for heating much. By installing individual heat pumps before these steps in step 3, which increases the efficiency of the individual heating sector, the significance of adding centralised district heating and large scale heat pumps is diminished.

5.3.3.3 Socio-economic costs

The socio-economic cost from 0-100% wind for the Disconnected Scandinavia and Connected Scandinavia systems is shown in Figure 52 and Figure 53 below.

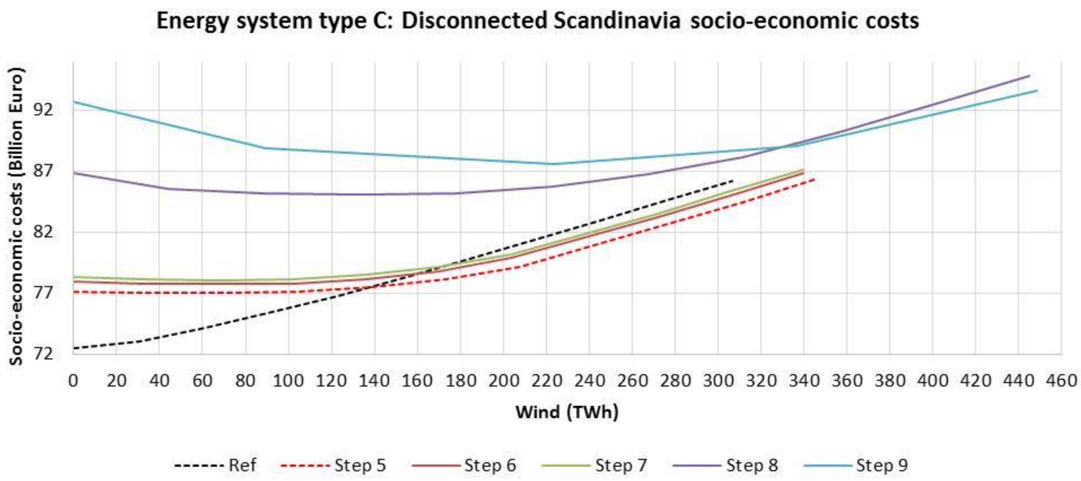

Figure 52: Socio-economic costs for steps in energy system type C in Disconnected Scandinavian system

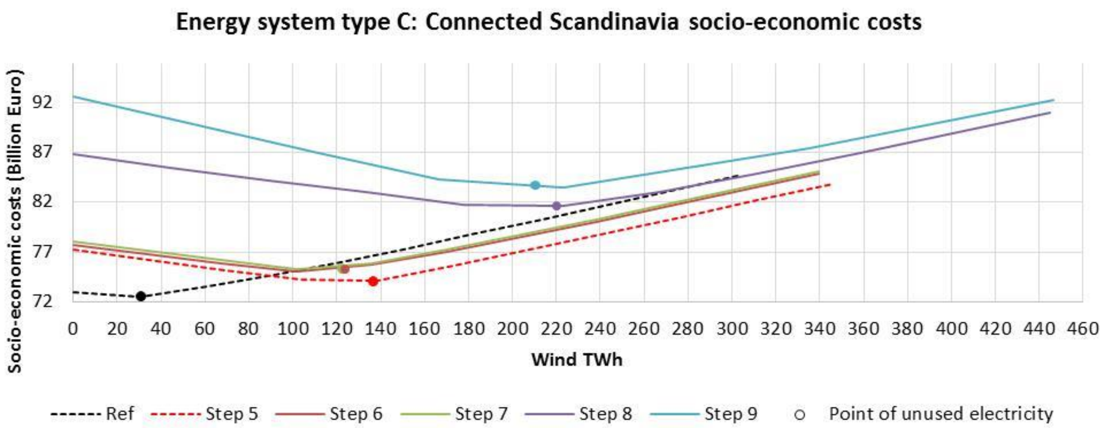

Figure 53: Socio-economic costs for steps in energy system type C in Connected Scandinavian system

The socio-economic cost at the point where unused electricity increases above the 5% threshold for the Connected and Disconnected Scandinavia system is shown for each step and for the reference in Table 15.

Table 15: Socio-economic costs at the point of unused electricity for Disconnected and Connected Scandinavia

Socio-economic cost at point of unused electricity (TWh)	Reference	Step 5	Step 6	Step 7	Step 8	Step 9
Disconnected	72.6	74.7	75.6	75.9	82.9	84.4
Connected	72.5	74.1	75.3	75.3	81.6	83.7

The socio-economic costs for all the steps are higher compared with the reference system. However for step 8 and 9 for the Connected and Disconnected Scandinavia systems the cost is the highest compared with the reference system. This is due to the introduction of EVs which have a high operation and maintenance cost; this is explored further in section Sensitivity analysis of results, methodology and delimitations.

The key factor that affects the costs is how much fuel can be replaced by wind and whether this amount exceeds the increased costs for investment and operation for installing more wind turbines and electric vehicles.

Although the socio-economic costs do not change significantly from the reference system to the final step of each energy system type, the distribution of costs changes. This is shown for the Connected Scandinavia system in Figure 54.

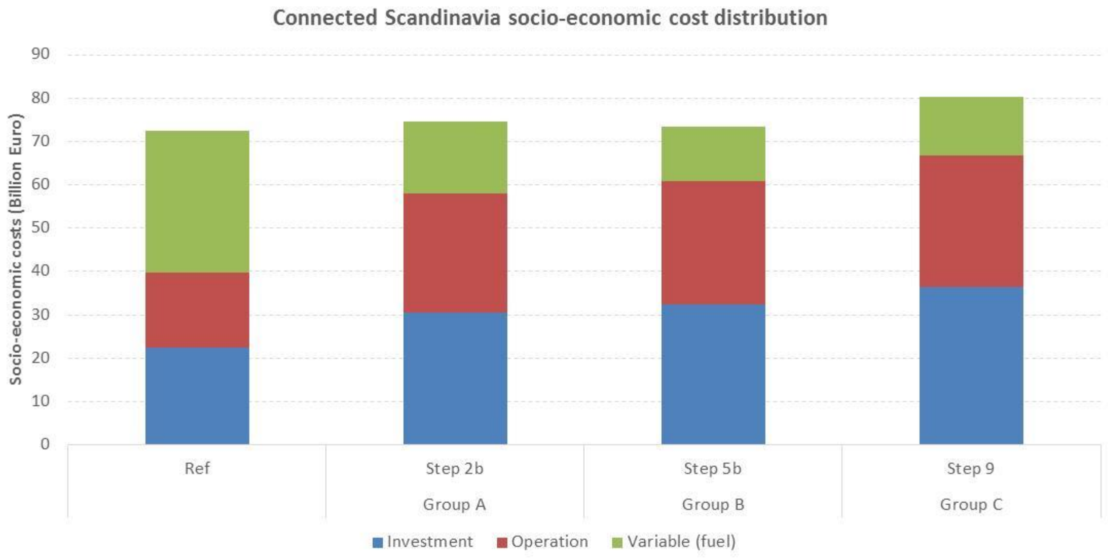

Figure 54: Cost breakdown of the Connected Scandinavian system for reference and steps 2b, 5b and 9

Originally in the reference system the costs were dominated by variable costs which mostly comprise of fuel costs. The operation and maintenance costs are lower in the reference system as well which is due to less wind integration. The operation and maintenance costs in steps 2b, 5b and 9 increase due to the EVs integration and higher wind production. The investment cost also increases due to wind integration and in step 9 the infrastructure for biomass gasification and synfuel production increase investment costs. The fuel cost for steps 2b, 5b and 9 all decrease compared to the reference which is due to savings largely related to electricity production from wind and transport via EVs.

5.3.3.4 Carbon dioxide emissions

The carbon dioxide emissions were reduced to 0 in step 2 of energy system type A and are therefore not elaborated in this section.

Some of the results across different energy system types are presented below.

The wind integration and the share of wind of the total electricity demand that can be integrated for each step and for all countries and energy systems is presented in Table 16.

Table 16: Wind integration potential and wind share of total electricity demand for each step

Wind integration at point of unused electricity (TWh) and % of total electricity demand	Denmark	Sweden	Norway	Disconnected Scandinavia	Connected Scandinavia
Reference	9.7 (27%)	3.7 (3%)	2.5 (2%)	15.9 (5%)	30.6 (10%)
Step 1	11.8 (32%)	58 (42%)	2.5 (2%)	72.3 (24%)	89 (29%)
Step 2	12 (32%)	58 (42%)	2.3 (2%)	72.3 (24%)	93 (30%)
Step 2b	13.5 (30%)	67.9 (46%)	10.5 (8%)	91.9 (28%)	117.8 (35%)
Step 3	13.2 (31%)	54.9 (42%)	0 (0%)	68.2 (24%)	68.2 (24%)
Step 4	16.5 (31%)	78.9 (47%)	0 (0%)	95.4 (28%)	134.5 (39%)
Step 5	16.7 (31%)	81.3 (48%)	0 (0%)	97.9 (28%)	136.4 (39%)
Step 5b	22.3 (36%)	95.6 (53%)	0 (0%)	117.9 (32%)	151.2 (41%)
Step 6	16.5 (32%)	81.3 (49%)	0 (0%)	97.8 (29%)	123.9 (36%)
Step 7	16.5 (32%)	81.3 (49%)	0 (0%)	97.8 (29%)	122.3 (36%)
Step 8	32.4 (42%)	118.3 (54%)	17.5 (12%)	168.2 (38%)	220.6 (50%)
Step 9	52 (68%)	116 (52%)	17 (11%)	185 (42%)	210.4 (47%)

The total costs for each country and Scandinavian system for the last step of each energy system types are presented in Table 17 below.

Table 17: Socio-economic costs for the last step in each energy system type

Socio-economic costs (billion euro)	Sweden	Denmark	Norway	Disconnected Scandinavia	Connected Scandinavia
Reference	35.1	17.7	19.9	72.6	72.5
Energy system type A	36	18.8	19.7	74.5	74.6
Energy system type B	36.3	19.4	17.9	73.6	73.4
Energy system type C	36.4	19.3	18	84.4	83.7

5.4 Sensitivity analysis of results, methodology and delimitations.

The purpose of the sensitivity analysis is not to make realistic or projected changes to the factors, but rather investigate which of the factors affects the overall results the most so it can be discussed further about what would happen if these factors are to change in the future.

The investigation is carried out either for the relevant energy system or for all of the energy systems taking the last step of each system, e.g. for the steps 2b, 5b and 8. These steps are selected as they are the last step in each energy system type and all include transport initiatives. The point of unused electricity is used as an indicator of how much the various factors influence the system.

The factors that have been investigated according to their sensitivity on the results include:

- Technical/methodology sensitivity
- The impact of minimum grid stabilisation operation in Denmark
- Using actual 2009 transmission capacities for Denmark
- Impact of removing nuclear power
- Impact from decreasing EVs operation and maintenance cost by 50%
- Cost sensitivity
- Interest rate
- Biomass prices
- Wind investment prices
- Implementation of offshore wind instead of onshore

5.4.1 The impact of grid stabilisation operation in Denmark

In this report the Danish energy system up to and including step 8 are analysed with a grid stabilisation share for condensing power plants to ensure a stable frequency, with more, in the grid. However this does not apply for the other countries in the Scandinavian region and it is therefore interesting to investigate how significant this factor is.

The grid stabilisation is investigated in the Danish system in step 2b, 5b and 8 where the alternative is that no power plants are designated to deliver grid stabilisation, and that alternatives have been created to deliver this network service instead.

The analysis shows that removing the stabilisation responsibilities for condensing power plants primarily affected the wind integration, while biomass demand and costs were only affected when wind shares much higher than the point of unused electricity were integrated. These key factors are therefore not included here.

The impact on the wind electricity integration is rather significant as can be seen in Figure 55.

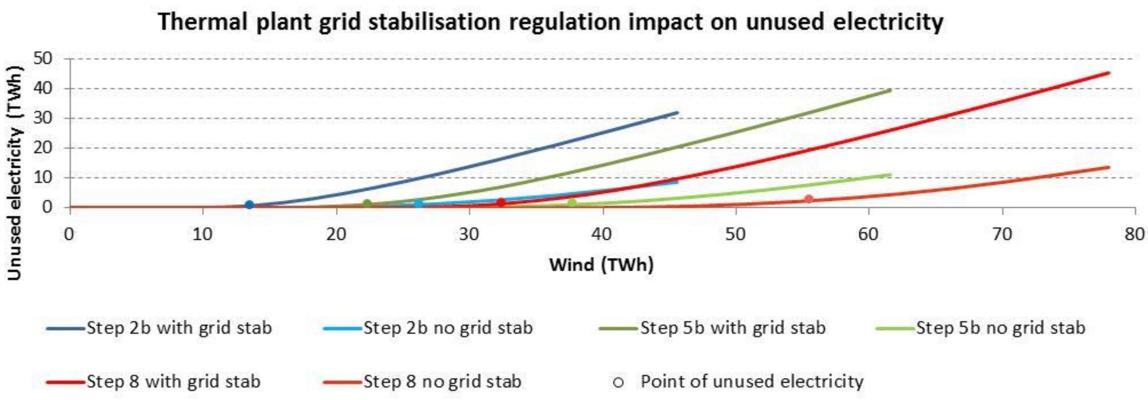

Figure 55: Sensitivity of thermal plant regulation on unused electricity in the Danish energy system

The curves without grid stabilisation are all flatter compared to the curves with grid stabilisation and the point where unused electricity is created improves significantly.

In step 2b in Denmark the point of unused electricity is improved from a wind share of 30% to 58% of the total demand and can integrated an additional wind power capacity of 6500 MW when the grid stabilisation is removed.

In step 5b the point of unused electricity increases from 36% to 61% when the grid stabilisation is removed from the power plants and instead an additional 9000 MW of wind power can be integrated.

For step 8 the removal of grid stabilisation also improves the point of unused electricity significantly from 42% to 71% and the additional wind power capacity that can be integrated is 11900 MW.

It is therefore crucial for the steps in Denmark whether the power plants are reserved for delivering grid stabilisation services, but as no other technology in the Danish system has so far been able to deliver this services the power plants in all steps, except step 9, are doing this. In step 9 this service is no longer required as the power plants can start-up much faster due to an improved technology based on gas and are therefore much more flexible in their operation.

5.4.2 Using actual 2009 transmission capacities

In the report two extreme scenarios are selected with respectively no transmission capacity at all and another system with unlimited transmission capacity. These delimitations however affect the results and is therefore investigated below for Denmark implementing the transmission capacity as of 2009 of 3440 MW in the steps 2b, 5b and 8.

It was found that increasing the transmission capacity from 0 to the aforementioned 3440 MW did not affect the fuel demand at all, the costs are only changing marginally, but only when wind shares are higher than the point of unused electricity. Below is therefore only the investigation of unused electricity when implementing the actual transmission capacity of 2009.

The impacts from implementing 3440 MW transmission cables in the Danish system can be seen in Figure 56.

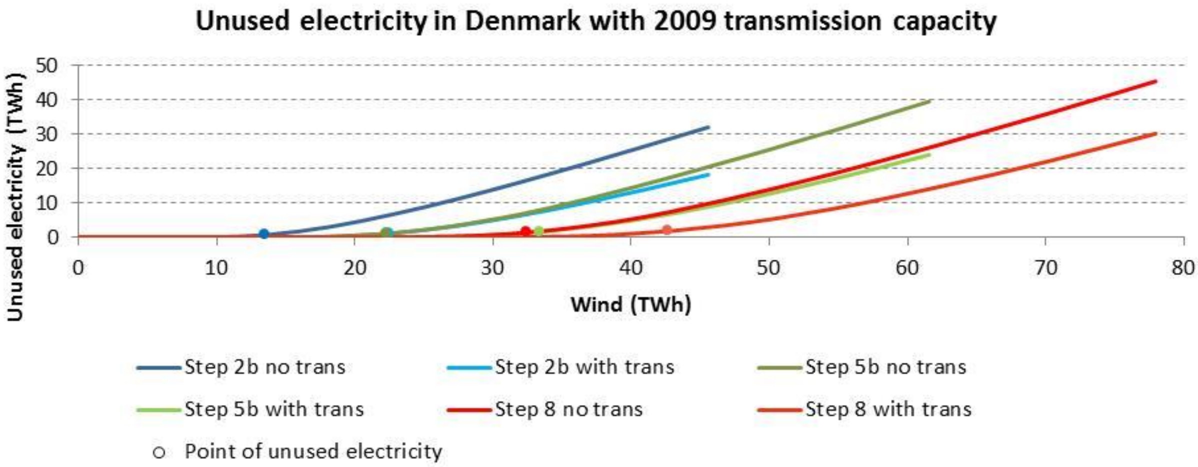

Figure 56: Sensitivity of installing transmission capacity as of 2009 in Denmark

When implementing the 2009 transmission capacity it becomes possible to integrate more wind, which is illustrated by the flatter curves with transmission capacities compared to the ones without any.

For step 2b the implementation of transmission capacity impacts the point of unused electricity to increase from 30% to 50% with 4600 MW additional wind capacity possible to be integrated into the system.

In step 5b the point of unused electricity is improved from 36% to 54% also allowing an additional 5700 MW of wind in the system.

Finally, in step 8 the point of unused electricity is improved from 42% to 55% with the additional wind in the system being 5300 MW.

The transmission capacity is therefore not only important in the extreme situations with no or unlimited transmission, but also with the installed capacities of 2009. ‘

5.4.3 Removal of nuclear power

It is tested which impact the removal of the nuclear power in step 1 meant to the Swedish energy system step 8.

The impacts in terms of wind electricity integration can be seen in Figure 57 below.

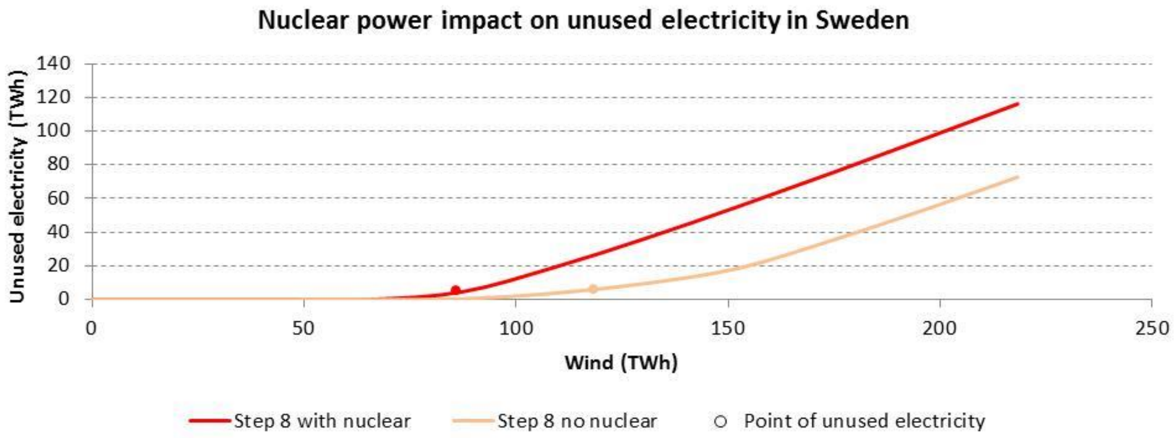

Figure 57: Sensitivity of removing nuclear power in the Swedish energy system

The nuclear power affects the unused electricity and makes the amount of wind that can be integrated lower. The share of wind in the system decreases from 54% without nuclear to 39% with nuclear. This also affects the fuel demand that increases while the total socio-economic costs in the system similarly increases by 1.2 billion euros at the point of unused electricity.

The reason for the worsened system flexibility with nuclear power is that the nuclear power operates as baseload production and hence minimises the more flexible production technologies such as power plants that can be used to balance the power when the wind power is producing.

5.4.4 Decreasing electric vehicle operation and maintenance cost by 50%

The maintenance and operation cost for electric vehicles in this study is set at 10.9% of investment per annum on an annualised basis. The operation and maintenance cost in the reference scenario for ICE vehicles is around 7% of investment. The reason the EVs has a higher cost is because the batteries are assumed to be replaced more frequently than the lifetime of the car, e.g. 7 years, which increases the annualised operation and maintenance cost.

In the future it is likely that battery technology would improve and they either will not need to be replaced as often or the cost for a new battery decreases. EV battery improvements are expected in the future (US Department of Energy 2010). Therefore in a sensitivity analysis it was tested to see how the results would change if the operation and maintenance costs were decreased by 50% to a level similar to the operation and maintenance costs for today's ICE vehicles. This reduction is consistent with other literature (US Department of Energy 2010). The results are shown below in Figure 58.

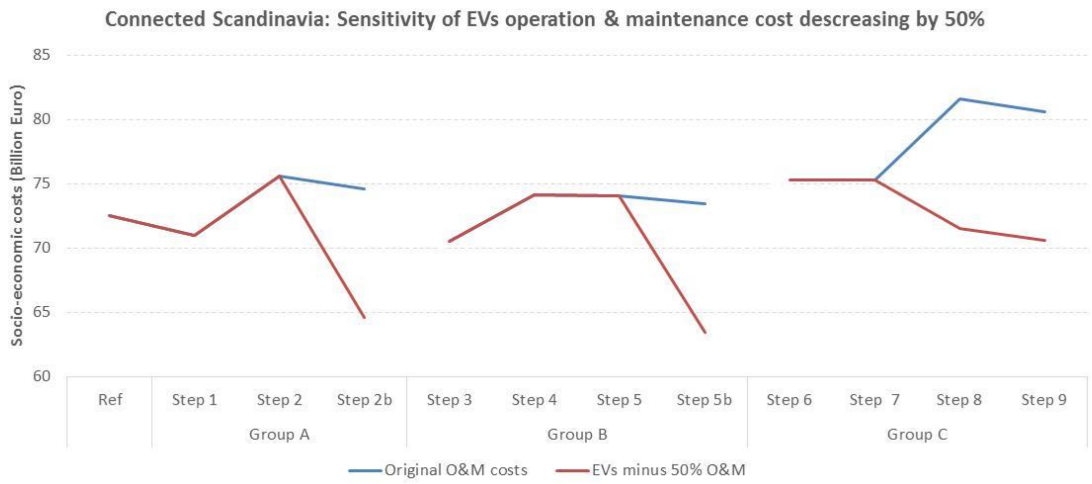

Figure 58: Sensitivity of reducing O&M costs for electric vehicles in the Connected Scandinavian energy system

As shown in Figure X the impact that the operation and maintenance costs of EVs have on the energy system types is significant. As seen in steps 2b, 5b and step 8 and 9 (integration of EV steps) when the operation and maintenance cost for EVs is lowered, the total socio-economic cost decreases by around 10 billion euro. Steps 2b and 5b decreased slightly in cost, compared with step 2 and 5 in the original assessment, but with the reduction in operation and maintenance costs for EVs the steps decrease significantly. Step 8 and 9 switch from being the most expensive steps to being close to being the lowest cost of all steps. This shows how significant the EVs battery costs will be in the future energy system.

5.4.5 Interest rate

The interest rate in this project for all energy systems across time periods has been set to 3%, see methodology chapter 4. However it is relevant to investigate the impact of this factor and how sensitive the results are to changing this rate.

The interest rate was doubled to 6% and reduced to 1% in order to investigate rather extreme changes compared to the rate applied in the report. These investigations are analysed for the Connected Scandinavia system as this system has the largest investments and therefore is most prone to experience changes. The changes were investigated in a system with wind production equal to the point where unused electricity begins.

In step 2b the total Connected Scandinavian system costs increases by around 13% when doubling the interest rate to 6% at the point of unused electricity while it is reduced by 8% if the rate is 1%.

In step 5b the costs for the Connected Scandinavian system are increasing by 15% when doubling the interest rate and is reduced by 9% when the interest rate is 1%.

In step 8 the costs increase by 18% when doubled while the reductions with a lower interest rate is 11%. The largest changes occur in step 8 as the investment costs are largest due to the increased wind power.

In addition, an analysis was conducted of the changed costs of step 8 for the Connected Scandinavian system when the interest rate is 4% similarly to the recommended rate by the Ministry of Finance. If this is the case the total costs would increase by around 6%.

In conclusion, the interest rate does affect the costs of the system with around 13-18% when doubled and decreases by 8-11% when reduced to 1%.

5.4.6 Biomass prices

The intention of this investigation is to analyse the various energy systems' sensitivity towards fuel prices, but since the only fuel in the system from step 2 and onwards is only biomass this is the only type of fuel that has been included. It is investigated what the changes in the Connected Scandinavian system is with respectively 50% higher and 50% lower costs for biomass. This means that the costs are increased to 10.95 EUR/GJ for biomass and 7.05 EUR/GJ for dry biomass while the lower costs are respectively 3.65 EUR/GJ and 2.35 EUR/GJ for dry biomass.

The analysis in steps 2b, 5b and step 8 shows that the socio-economic costs in the Connected Scandinavia system when biomass prices are 50% higher for all the steps are increased by 8-9% at the point of unused electricity and decreased by 8-9% when biomass prices are reduced by 50%. The biomass price has largest impact on energy system type A as the fuel demand is reducing in the other energy system types.

5.4.7 Wind investment prices

The key renewable technology for the steps in this report is wind power and the impact from changing the investment costs for this technology has therefore been investigated. The impact is tested in the Connected Scandinavian system with respectively a 50% higher and lower investment cost and how this influences the overall system costs. The wind investment costs are tested using higher costs of 1.88 MEUR/MW and lower costs of 0.63 MEUR/MW in comparison with the cost of 1.25 MEUR/MW that is applied for the steps in the report.

The impacts of changing the wind investment cost on the total system costs in step 2b is an increase of around 3% at the point of unused electricity and a similar decrease when changing the investment costs.

In step 5b the changed investment costs changes the total costs with an increase of 4.6% and a similar decrease at the point of unused electricity when applying the lower investment cost.

In step 8 the increase is around 6.3% with the higher cost and a similar decrease with the lower investment cost.

5.4.8 Implementation of offshore wind power instead of onshore wind power

In the report when carrying out wind integration analysis for the various steps it has solely been onshore wind that is integrated. In a technical perspective this makes no difference to integrating offshore wind as a similar wind distribution have been applied, but in terms of investment costs there is a difference. It has therefore been investigated in the Connected Scandinavian system how the socio-economic costs are influenced by the selection of onshore contra offshore.

In step 2b the impact of implementing offshore wind instead of onshore wind power is an increased total system cost of 4.6% at the point of unused electricity. This additional cost increases to 7.7% in step 5b and 10.3% in step 8 as more wind can be integrated before unused electricity is produced.

The choice of implementing offshore or onshore wind power affects energy system type C most since this is the energy system type with the highest amount of wind power.

5.4.9 Impact on findings

The sensitivity of the factors analysed resulted in different impacts on the findings. These impacts are assessed below for each factor in Table 18. A high impact means that the overall findings will change if this factor is changed. A medium impact is defined as having an impact on the results, but without changing the overall findings. A low impact means that the factor almost has no impact on the results and findings.

Table 18: Sensitivity factor impacts on results

Factors	**Factor influenced**	**Energy system influenced**	**Impact on findings (Low/Medium/High)**
Grid stabilisation in Denmark	Wind integration	Denmark	High
2009 transmission line capacities	Wind integration	All	High
Nuclear power in Sweden	Wind integration, fuel demand, costs	Sweden, Scandinavia	High
EV operation & maintenance cost	Socio-economic costs	All	High
Interest rate	Socio-economic costs	All	Medium
Biomass prices	Socio-economic costs	All	Medium
Wind investment prices	Socio-economic costs	All	Low/Medium
Onshore vs. offshore wind prices	Socio-economic costs	All	Medium

The highest impacts on the findings are for the factors related to the methodology in the report, i.e. the grid stabilisation in Denmark, transmission line capacities and nuclear power in Sweden. These factors might all change the overall findings according to when the changes are carried out in the analysis. An example could be the grid stabilisation in Denmark that could potentially be removed in an earlier stage (an earlier step) in the future if it becomes possible to operate without stabilisation services from power plants. This would improve the wind integration significantly in an earlier step.

The assessment of sensitivity of the socio-economic factors are that these can influence the findings, but in a magnitude that will not change the overall findings. The operation and maintenance costs for electric vehicles are however significant for the overall results.

6 Discussion

This chapter contains a discussion of the results and findings of the study as well as the methodology applied.

6.1 Results

6.1.1 Connected vs. Disconnected Scandinavia

It is investigated whether it is best to connect Scandinavia or not based on technical feasibility and without going into market details. In the method of this study the Connected Scandinavia system uses a near constant base load hydropower production since all the countries are connected and the system operates as one single system. This is unlikely in the future in a three country market, however the technical analysis shows that an energy system similar to this leads to the best integration of wind and lowest level of biomass consumption. Therefore the next step would be to research to which extent the countries should be connected. During an interview this importance of transmissions was also pointed out suggesting that electricity exchange will remain since different energy systems will always benefit from each other (Franck and Sørensen 2014).

In the report a socio-economic cost difference between the Disconnected and Connected Scandinavia was found and this value will here be used to discuss how much transmission capacity this could supply. The Connected Scandinavia system has in energy system type A higher costs than the Disconnected system which means that the costs in the Connected system would be even higher if the costs for transmission cables are integrated. The largest difference between the two systems is in step 8 where the Connected system is 1.4 billion euro cheaper than the Disconnected system without cable costs.

Cost data about existing transmission cables are often hard to access, but estimates have been used for this assessment. Transmission costs are based on data from the 400 kV transmission cable between Ireland and Wales that was installed in 2012 with a distance of 260 km and a capacity of 500 MW. The total costs of this project were 571 million euro (EirGrid 2012).

Another project that provides cost data is the proposed 2014 Skagerrak 4 cable between Denmark and Norway with a submarine length of 130 km, a capacity of 700 MW and project cost of around 376 million euro (Energinet.dk 2013). By assuming the same costs and length as above for the first three Skagerrak connections (1000 MW in total) the costs for these are around 1.6 billion euro. This number is higher than the available cost difference between the Disconnected and Connected Scandinavia (in step 8 the Connected system is 1.4 billion cheaper than the Disconnected system) and since the number of cables in a completely Connected Scandinavian system (or supergrid) would require multiple cables the costs for the Connected Scandinavia, including transmission cable costs, would be higher in all steps than the Disconnected system. This is based on very uncertain estimates, but gives an indication of the impact on the overall results when including transmission cable costs.

6.1.2 Energy system types

Three energy system types and their associated technologies were assessed in this study. It was found that a combination of the energy system types is the optimal situation in the future. This was also confirmed in the interviews with Franck and Sørensen (2014) and Søndergren (2014). Possibly the future energy system could in the short term develop according to supergrid characteristics to convert to a higher share of renewable energy, in the medium term smart grid technologies could be integrated, and in the longer term smart energy system technologies could be integrated.

Initially a supergrid would be required to be able to shift renewable energy between countries and to provide balance to the electricity systems of the countries. But this alone could not achieve a 100% renewable society. The supergrid should not be implemented to such a level that it precludes the development of smart grid and smart energy systems. Smart grid and smart energy system are both necessary to manage the electricity and to shift the electricity into other energy sectors. Supergrid should only be integrated to the extent that it allows these two energy systems to achieve their purpose. The three energy system types could be implemented in the same period but there is risk that supergrid and smart energy system compete with each other and this needs to be considered (Blarke and Jenkins 2013; Søndergren 2014). As explained by (Blarke and Jenkins 2013) smart energy system and supergrid are not on a level playing field. The Supergrid has big actors and radical technological change is not required whereas the Smart energy system has new actors and involves radical technological change. It is not possible to compare them in the existing regime. Hence, careful consideration is required when planning for the future energy system as supergrid might be feasible in a short-term perspective, but could hinder the achievement of long-term targets by creating lock-in situations. In an analysis conducted by Energinet.dk this fact has also been considered where no more transmission lines are installed after 2025 as other measures become more important (Franck and Sørensen 2014).

The smart energy system could be regarded as radical technological change, since not only the product is changing but the knowledge, technique and organisation may change as well. There could be a change to the current actor-networks and regimes, and this could lead to strong opposition, and strong discourse for the current regime, hiding alternative choices. These other energy systems will play an important role in the future energy system and this need to be considered when making strategic policy decisions.

It is also noteworthy that each energy system type is originally designed to deliver different functions. Super grids are actually designed to allow greater integration of renewable electricity but it will be rather impossible to achieve 100% renewable energy systems with only this energy system type.

Under the smart energy system and smart grid the security of supply can be expected to increase since this is part of the function of these systems. Compared to the system of today there would be less dependence on energy imports assuming a sustainable production of local biomass.

It is however important to notice that regardless of which energy system type will be the dominant one in the future none of them will meet the policy targets without changes in consumption patterns and user behaviour. It was found that there are no technological fixes that alone would allow a conversion towards a 100% renewable society in the future.

6.1.3 The need for a reduced biomass demand

The biomass demand in the different energy systems is relevant to compare in relation to the available residual biomass potentials in the countries. The biomass potentials are presented below along with the biomass demand in the energy systems in the report with the lowest biomass demand for each country.

Table 19: Biomass demand for the countries and Scandinavian systems compared to the domestic biomass potentials

Energy system	Domestic biomass potentials (TWh)	Biomass demand in scenarios (TWh)	Biomass import requirement (TWh)	Proportion of self-sufficiency
Denmark	40-67 (1,2,3,4)	120	53-80	33-56%
Sweden	151-162 (3)	224	62-73	67-72%
Norway	29-46 (3)	74	28-45	39-62%
Scandinavia Disconnected	220-272	439	167-219	50-62%
Scandinavia Connected	220-272	374	102-154	59-73%

(1) (Danish Energy Agency 2014a)

(2) (Danish Commission on climate change policy 2010)

(3) (Scarlat et al. 2011)

(4) (Lund et al. 2011)

The table shows the difference between the biomass demand and the domestic potentials and it is clear that in all scenarios the biomass demand is larger than the potentials. In Denmark the proportion of self-sufficiency only cover between 33-53% of the demand while the share of demand in Sweden is 62-66%. However, the conclusion is that the biomass demand is too high compared to the available resources and that either biomass has to be imported or that more measures should be taken in the energy systems to ensure a reduced biomass demand. Currently, biomass is being imported from other countries, for example Denmark imports wood pellets from the United States.

Import of biomass grown specifically with the purpose of producing energy might lead to undesirable impacts in terms of e.g. direct and indirect land-use changes. These impacts can displace food production, lead to unsustainable forest management that can affect wildlife and soil quality, etc. (Union of Concerned Scientists 2013). The land-use impacts are part of a large discussion that will not be described in detail here, but it is not desirable to import large amounts of biomass, also because the biomass demand in other regions of the world is expected to increase simultaneously.

In comparison the available wind potential in Denmark is assessed to be 340 TWh, equal to almost ten times the electricity demand in the existing Danish energy system (Danish Commission on climate change policy 2010). In terms of land-use and the following impacts wind is preferable when there is a limited amount of land available for biomass production.

6.1.4 Comparison of results with other studies

In this section the findings of this report is compared to other research studies. The findings are discussed in general terms about the types of energy systems and technologies that should be part of a future energy system.

The Coherent Energy and Environmental System Analysis (CEESA) study from 2011 conducted by a number of Danish universities and research institutions analysed the future energy system in terms of achieving a 100% renewable system with both focus on the technical aspects, lice-cycle assessments and public regulation (Lund et al. 2011).

When comparing the CEESA study to the analysis in this report it is clear that the CEESA study was more comprehensive and therefore included analysis of more technologies and scenarios, both in the short, medium and long term. This resulted in recommendations of other technologies such as solar and geothermal energy as well as low-temperature district heating. Some of the conclusions were however comparable with this study as the CEESA study found that it is essential to integrate energy sectors, for example through gasification of biomass or integration between the transport and electricity sectors, in order to reduce the biomass demand and improve the efficiency of the system. This conclusion can also be found in this report as a key recommendation.

The Danish Energy Agency recently published a study of four different scenarios towards a fossil-free 2050 Danish energy system (Danish Energy Agency 2014a). Some of the main conclusions are that the choice of a future energy system should be made shortly after 2020 as the large transitions require a certain time period. This is in line with the findings in this report about avoiding lock-ins and preparing for a transition as soon as possible. In the Danish Energy Agency study the costs for a fossil-free energy supply, excluding taxes, and applying an interest rate of 4% is 18.3 - 21.3 billion euro while the costs in this report for the Danish energy system is between 18.7 - 19.9 billion euro with an interest rate of 3%. The study finds that the fuel demand is lowest in a system based on hydrogen while a wind power system with biomass for balancing power has second lowest fuel demand. Other scenarios based on a large share of biomass in the electricity and heating sector experiences larger biomass consumption. An energy system based on hydrogen has not been investigated in this report while the wind and biomass system seems feasible in both this report and the study by the Danish Energy Agency.

In another study called *Scandinavia Energy Technology Perspectives* focus is on the five Connected Scandinavia countries of Denmark, Finland, Sweden, Iceland and Norway and it was found that it is possible to complete a near decarbonisation of the Connected Scandinavia countries (Norden and International Energy Agency 2013). The study highlights the importance of more wind power in the future energy system similarly to the conclusions in this report. On the contrary the Connected Scandinavia technology perspectives report found that it was necessary to implement CCS technologies in the industry in order to achieve sufficient CO_2 reductions. Regarding the transport sector the study finds that electric vehicles must reach a 90% share in 2050 and that freight, aviation and shipping rely on liquid fuels in the form of biofuels while the findings in this report proved that electric vehicles also form a crucial role along with liquid fuels for heavy transport. The final conclusion in the Connected Scandinavia technology perspective report was that savings in the building sector must be carried out to reduce demands.

Overall, the conclusions are close to the findings in this report in terms of the necessary technologies for a future renewable scenario with the exception of the integration of CCS technologies.

Another study focuses on the benefits of transmission capacities in a fully renewable future European system (Rodríguez et al. 2014). The methodology in the study is rather similar to the one applied in this report with a system with no interconnectors and an unconstrained system for Europe. The study focuses on the shift towards a supergrid based energy system and therefore only solar and wind supply the electricity in the study. The key conclusions relate to balancing power requirements when installing additional transmission capacity, which improves from 24% balancing energy with no interconnectors to 15% with unconstrained transmission. The capacity in the unconstrained system must however be 11.5 times stronger than the existing. A more ideal situation is identified where the transmission is twice as much as the present and reduces the balancing energy to 18%.

A comparison with the analysis in this report shows rather different conclusions. This is due to the hydropower distribution in the Scandinavian region that flattens out over the year when increasing transmission. The increased transmission capacity will allow more hydro to provide peaking demands but this means that in periods where hydro was normally utilised, in the winter period, less hydro is available and more power plants would be required. Hence, the balancing power plant capacity is actually larger for the Connected system than the Disconnected in the present study which is opposite to Rodriguez et al. 2014. This shows that the inclusion of other renewable sources over geographical boundaries via transmission in the future might impact the overall balancing energy.

Another dimension of the relevance of interconnectors is that "*all connections so far has been proven feasible because of their trade effects*" and not due to their regulating power effects (Franck and Sørensen 2014). It is therefore not enough to only focus on the regulating benefits from interconnectors in the future.

6.1.5 How might other technologies contribute to 100% renewable systems?

In this report a limited number of solutions have been investigated in order to achieve a 100% renewable energy system in the Connected Scandinavia systems and many other options could have been analysed. The scope of the report is to investigate different energy system types that defined the technologies that were implemented, but other technologies are discussed qualitatively below.

In the future energy system other renewable energy sources could have implemented such as solar power, solar thermal, wave, tidal, geothermal, possible expansion of hydropower or nuclear power and so on. These energy sources have different characteristics that would impact the energy system and a few of them are discussed below.

Solar power can contribute to producing electricity, but is characterised by a fluctuating production distribution since electricity is only produced during the daytime, and the fluctuations are in many ways similar to wind power. Solar power is in numerous studies expected to be part of a future renewable energy system, which has been shown to be beneficial (Lund 2006; Hoste, Dvorak, and Jacobson 2009; Jacobson and Delucchi

2009; Delucchi and Jacobson 2011) and could also form part of the energy systems recommended in this report by replacing some wind power. The methodology applied in the study regarding the wind test analysis however precluded solar power from the analysis of the future energy systems even though this seems realistic in the future.

Solar thermal might also contribute to a conversion towards a renewable energy future by producing heating in individual buildings, or in a larger scale by producing heating for the district heating system which has been shown to be beneficial (Delucchi and Jacobson 2011). If solar thermal technology was integrated in the energy systems in the report they might have replaced some individual heat pumps or thermal production such as CHP plants, large boilers or large heat pumps.

Wave and tidal power might potentially also contribute to producing electricity in a future energy system and thereby replace some wind power, which has been shown to be beneficial where wave power could supply 30% of electricity demand when renewable energy supply is over 80% in Denmark (Lund 2006). These technologies are however still under development and are not widespread yet, but might be feasible to implement by 2050.

Geothermal power is another option to produce renewable electricity or heating in some of the areas in the Connected Scandinavia region. Geothermal production is however operated as baseload production and will therefore counteract integration of more fluctuating renewable sources because it reduces the flexibility of the system.

Furthermore, an expansion of hydropower might be feasible since this energy source contributes to act as balancing power and thereby integrate more fluctuating sources. In addition, hydropower is relatively cheap for production of electricity compared to other technologies. However, the Norwegian National Renewable Energy Action Plan does not foresee changes in hydropower towards 2020 to meet the Norwegian 2020 targets (Ministry of Petroleum and Energy 2013). The technologies with the largest increases are onshore wind power and solid biomass. Similarly for Sweden the Governmental priorities are to implement more wind (onshore) and biomass and biogas in order to meet the European targets for 2020 meanwhile hydro remains constant (Regeringskansliet 2010).

Regarding nuclear power the sensitivity analysis proved that the integration of nuclear power is working against integrating more fluctuating sources as the nuclear power is acting as baseload production. An expansion of nuclear power would therefore only make the situation worse and the system less flexible.

6.2 Methodology

The methodology and approaches applied in the report are discussed in this section.

6.2.1 Wind distribution

The wind distribution profile used in the study is the same distribution for Sweden and Norway. It has been shown that wind distribution can vary significantly within close proximity between wind farms (a few hundred km) (Palutikof, Cook, and Davies 1990; Archer and Jacobson 2007). When the different wind profiles are combined to get a more accurate profile it is shown that the profile is less fluctuating and more consistent. This is an area in the study that could be investigated further and improved upon.

6.2.2 Denmark vs. Scandinavian focus

The point of departure in this report is the Danish society, but a large share of the analysis and results involved neighbouring countries or the Scandinavian region. This was a consequence of the findings in the diamond-E analysis as the Danish energy system is not isolated and will inevitably be affected by other energy systems and how they develop in the future.

The methodology focusing on the Scandinavian countries contributed to make it more unclear how the Danish energy system is affected by the development in the region, i.e. no precise conclusions could be drawn about how much more wind can be integrated in Denmark when connected to the Scandinavian system or how much the connection benefits Denmark in terms of costs and fuel demand. On the other hand the analysis of the Scandinavian region proved that there are benefits to be achieved from combining the Scandinavian systems by drawing on the strengths of each system. Furthermore, the Scandinavian experiences also made it possible to make conclusions for Norway and Sweden and whether these energy systems would benefit from the connections to the Scandinavian system.

6.2.3 The two extreme Scandinavian systems

In the report two extreme situations were analysed for the Scandinavian energy system in respect to the transmission capacity installed. The methodology allowed for clear comparisons between the two systems, but in reality this would never be the situation. Instead, the capacity would lie in between the two extremes with some transmission capacity installed based on the advantages that could be achieved from installing the transmission capacity and the associated costs. In this report the scope was not to investigate the optimal transmission capacity in the Scandinavian region, but it was analysed in the sensitivity analysis, how a transmission capacity as of 2009 would impact the results for Denmark. This analysis indicated that the increased transmission capacity would contribute to increasing the wind that can be integrated in Denmark and supports the conclusion that the transmission lines contributes to improving the factors analysed in the study regardless of which energy system type the developments will lead to.

6.2.4 Methodology for analysing energy system types and technological solutions

In the report the technologies and energy system types are investigated by adding technologies on top of each other, i.e. a new technology is installed in a system that already has the previous technology installed. This means that the comparisons between the steps, to some degree, will be affected by the already installed technologies in the system. An example might be step 6 that expands district heating which is affected by step 3 where all individual heating is converted to individual heat pumps. The district heating benefits are reduced significantly by replacing individual heat pumps instead of boilers.

An alternative methodology could have been to implement all the different technologies directly into the reference system and thereby only analyse the impacts of this technology in the existing system. This would have made the comparisons between the technologies more clear as they could not be influenced by other technologies. On the other hand this alternative methodology would not investigate the dynamics and system impacts when more than one technology is installed in the system. In reality more than one technology would be installed in order to convert to a 100% renewable society and these system dynamics are therefore crucial to investigate.

Similarly, an alternative approach could have been applied for investigating the different energy system types by installing all of them directly in the reference system. The comparisons between the energy system types would have been more clear using this approach. However, this would have implied that the number of steps for each energy system type would increase as for example the biomass conversion step in the electricity and heat sectors would be conducted anyhow in order to achieve a 100% renewable energy supply. Hence, a number of the steps in energy system type A and B would have been included in energy system type C anyway since parts of the smart grid is also part of the smart energy system.

Additionally, it is not realistic that the future energy system will be clearly separated into one of these three energy system types, but rather a combination of them. Hence, some of the features from one energy system type will be combined with another energy system type due to the political agenda, interests from energy companies, financial situation or other factors that might influence the development of the energy system.

6.2.5 Full life cycle thinking not considered

In this study most steps involve implementation of a new technology and the results for CO_2 emissions and fuel demand reflect the influence on the energy system in which it is being integrated. However the embodied impacts based on a life cycle thinking approach of the technology being implemented are not considered. For example when modelling the integration of electric vehicles, the embodied impacts of the millions of vehicles are not considered. When adding the environmental cost from manufacturing the vehicles the impact on the energy system would increase and the extent of this impact would need to be researched further. Not only would CO_2 and fuel demand need to be investigated but other environmental issues such as resource depletion and biodiversity loss would need to be considered.

In the report it is assumed that biomass is CO_2-neutral, but in reality this is not the full picture. Often biomass is viewed as carbon neutral "*because the carbon emissions were considered part of a natural cycle in which growing forests over time would re-capture the carbon emitted by wood-burning energy facilities*" (Walker et al. 2010, P. 6). This can also be seen in the national statistics that are published annually in Denmark as the CO_2 content for various biomass based fuels such as straw, wood pellets, biodiesel, etc. is not accounted for any CO_2-emissions (Danish Energy Agency 2010). However, recent debate and research has adopted a more sceptical approach towards the carbon neutrality of biomass. Factors such as origin of the resource, carbon debt and the delay of the mitigation potential is getting more acknowledged among researchers (Bentsen 2014; McKechnie et al. 2011; Walker et al. 2010; Franck and Sørensen 2014). The scope of this report is not to investigate the biomass neutrality further, but to highlight that this assumption is critical for the achievement of a carbon neutral society in the future as all the scenarios in this report rely on biomass as part of the fuel sources. The conclusions should therefore be viewed upon with this assumption in mind.

6.2.6 Fuel demand impact

A main assumption in this report relates to the future demands for electricity, heat and transport that remains constant compared to the existing demands. This is based on the assumption that the future lower energy demanding technologies and appliances are replaced by additional demand (the rebound-effect) and thereby keeping a constant demand.

However, if the demands were changed it would influence the results of the study. With a higher demand the need for electricity and heat capacity would increase thereby requiring more biomass for example for transport and power plants. Hence, the self-sufficiency shares in the energy systems would be reduced while socio-economic costs would increase at the same time. On the opposite, a reduced electricity and heat demand would mean a lower electricity and heat capacity and thereby reduced investments and fuel demands. Also the fuel demand would be lower getting closer to or potentially below the amount of biomass that can be produced within the countries. The amount of wind would similarly be decreased, but as the electricity demand also decreases the share of electricity production of the total electricity demand would remain largely unchanged.

The demands are therefore essential for reducing the biomass demand to meet the biomass production that can be produced within the countries and conservation measures should be carried out in accordance with the development of the future energy system to improve both biomass demand and socio-economic costs.

6.2.7 Transferability of the study results and methodology

The results of this study are highly specific to the countries assessed since the energy system of each country is very different; Denmark's electricity is based largely on wind and CHP, Sweden's electricity is based on nuclear and hydropower and Norway's electricity is based on hydropower. These specific characteristics make it difficult to make any generalizations from this study that can be used for other country groups. This conclusion was also drawn during an interview with Dansk Energi where it was highlighted that the transmission capacity should be scaled according to a certain country's electricity production structure and the countries it is connected to (Søndergren 2014). However the findings about the influence of specific technologies on the overall energy systems could be used for other energy systems (for example by implementing EVs the fuel demand decreases). But the understanding of the extent in which different energy systems of different countries should be interconnected with each other is less certain, and would require further investigation.

It is likely that smart energy system and smart grid would be better at integrating renewable energy and reducing fuel demand. However the costs could be higher for smart energy system. The costs for supergrid depend on the length of cables and are therefore different from one country to another.

In saying this, the concepts tested in this study and the methodology that was developed could be utilised in other studies for other country combinations. Many researchers are discussing future energy systems being based on high levels of renewable energy and the proposed option for this is a more interconnected grid, or a supergrid. It is recommended that the concepts tested in this study, for example reducing fuel demand in the heating and transport sector should be researched in context of the supergrid for other countries. It is not recommended to only focus on the supergrid and hence the electricity sector and avoid the problem that heating and transport sectors face in the transition to a renewable future. If the ultimate target is to achieve a 100% renewable system it is therefore not sufficient to analyse a supergrid only.

6.3 Choice Awareness Theory

This study takes point of departure from Choice Awareness Theory which has the thesis that all the choices available are often not well understood or known when making technology transitions. Choices are often hidden from view by the current regime, so that the current regimes can maintain their position. The research question in this study focused on the future energy systems of Denmark, Sweden and Norway and what the best options are for reducing CO_2 emissions, fuel demand and integrating more renewable energy. This was investigated by integrating different technologies within a completely Connected Scandinavian system and a Disconnected system. This analysis could have taken departure from the dominant discourse in literature around energy system types and how they should develop into the future, which would likely further progress certain agendas and beliefs which control dominant discourse. This would be the easier option.

But this theory provides a useful justification for making new analyses which begin from a different perspective from the current discourse and ideology. The theory is based on analysing the energy systems from a problem based perspective, rather than ideological perspective, where the analysis attempts to find a solution to this problem, this allows a more free and comprehensive analysis of choices which could be made.

Due to the nature of the choice awareness theory, which is about creating choices from new analysis, the outcomes from these analyses could potentially be vulnerable to scrutiny due to the limited understanding and knowledge of the choices being investigated and promoted from the research. By creating new choices based on pure problem analysis rather than based on dominant discourse and ideology means that the choices need to gain support and become popularised quickly before the dominant regime strengthens its position. The way to strengthen and solidify the new choices is through public policy making which assumes that government is able to make this happen. Since the theory has often been tested in Denmark, which has a history of relatively progressive government, it is more appropriate that public policy can be used to help solidify the choices analysed in Denmark. However if this theory was applied in other countries with less progressive governments, then the recommendation to promote choices through policy making may not be very productive.

An alternative to this dilemma is to provide a strategy for empowering the public to demand these choices. This part of the Choice Awareness Theory is not fully developed at the moment.

6.4 Data collection

The majority of the data collection was carried out in connection with the technical data that was gathered from various sources in order to firstly create reference energy systems and to carry out analysis of the future energy systems.

The technical data was collected from a limited number of sources with the primary sources being the International Energy Agency (IEA) and the national energy agencies and TSO's in the Scandinavian countries. The reason for selecting these references were that the data should be collected and presented in a similar manner across countries to ensure that for example demands and fuels were presented similarly.

However, it was necessary to supplement IEA data with more data as these were not detailed enough regarding for example CHP production and efficiencies as well as distributions for hydropower and wind power production. During the analyses it was clear that the IEA data were useful when collecting data regarding demands and to some degree fuel distributions while other data was not possible to extract from here and should be collected elsewhere.

Another data collection method included in the report was interviews that did not play a crucial part of the report, but rather provided information about the context in which the energy system in Denmark may develop. The interviews were useful in terms of getting a deeper understanding of the non-technical part of the energy system such as the political dimensions, interplay between various actors and what seems realistic in terms of future developments.

7 Recommendations and short-term outlook

This chapter presents the recommendations and short-term outlook based on the results and the discussion in the report. The chapter is structured as follows:

A. Recommendations for a 2050 Danish energy system, including electricity, heating and transport sectors as well as interconnections.

B. Recommendations for short-term investments for a 2020 Danish energy system.

The recommendations focus on the Danish energy system, but include the Scandinavian system when it affects the Danish system.

The recommendations can be used to prioritise between investments for technologies and energy system types for a future energy system. However, they cannot be used for constructing a complete future energy system as this was out of the scope of the report, for example the analysis did not include energy conservation measures.

The recommendations are not ranked according to importance.

7.1 Recommendations for a renewable 2050 Danish energy system

The general conclusion is that technological fixes on their own will not be sufficient to convert the energy system in 2050 into a 100% renewable energy system. Instead measures should relate to all three approaches for transforming the energy system, i.e. energy conservation technologies, renewable energy sources and improved efficiency of supply systems. It was found in the study that even when improved efficiency of supply systems and renewable energy sources were integrated, the domestic biomass potential would not meet the demand without carrying out conservation measures.

7.1.1 Biomass demand

- The biomass demand exceeds available biomass potentials and therefore it is necessary to carry out conservation measures, for example in the electricity, heating or transport sector.

7.1.2 Electricity sector

The recommendations for the electricity sector are:

- Promote technologies (e.g. highly flexible thermal power plants or potentially wind power) that will allow grid stabilisation to be delivered in other ways than in the existing system so that more wind can be integrated to reduce biomass demand.

- Replace electricity technologies based on biomass with technologies depending on other energy carriers, for example wind.

- Shift towards electricity production from sustainable biomass in the short to medium term in order to lower CO_2 emissions.

7.1.3 Heating sector

The recommendations for the heating sector are:

- Convert individual boilers to individual heat pumps or district heating to improve the efficiency of the energy system.

- Convert electric heating to more efficient technologies in Norway and Sweden, e.g. heat pumps or district heating.

7.1.4 Transport sector

The recommendations for the transport sector are:

- Convert transport to more direct electrification (e.g. electric cars and light vans).
- Promote production of less biomass demanding transport fuels (e.g. synfuels for heavy transport).
- Avoid biopetrol and biodiesel production due to high biomass demand.

7.1.5 Interconnections

The recommendations regarding interconnections are:

- The Scandinavian countries should be connected, to a certain degree, in order to improve wind integration and reduce biomass demand.
- Future energy strategies must take into account that nuclear power in Sweden impacts the Scandinavian wind integration potential.
- Future energy strategies must take into account that if the Norwegian electricity demand decreases below its hydropower production, hydropower will be exported decreasing the wind integration potential in the entire region.

7.1.6 Energy system types

The recommendations for future energy system types are:

- In the long term, progression towards a smart energy system should be promoted while ensuring that other types of energy systems do not preclude this.
- A supergrid system should be a stepping stone towards more complex energy systems such as smart grid and smart energy system.

7.1.7 Further research activities towards a renewable 2050 energy system

Recommendations for further research activities are:

- Further research should be focused on inter-country electricity exchange and to which extent the Scandinavian countries should be connected.
- Research should be focused on developing and lowering costs for less developed technologies that might be required in a 2050 renewable energy system (e.g. EVs, synfuels, gasification of biomass, etc.).
- Further research should be focused on ensuring a level playing field between the different energy system types.

7.2 Recommendations for short-term outlook in 2020

In order to achieve the recommendations for 2050, short-term investments focusing on 2020 are presented below. These recommendations focus on avoiding undesirable lock-in situations that later will be difficult or impossible to change.

- Reduce biomass dependency by investing in energy systems that do not only rely on biomass consuming technologies

- Promote conservation in the electricity, heat and transport sectors to keep demands within sustainable limits.

- Accelerate the energy system conversion towards 100% renewable energy sources (e.g. biomass, wind, solar).

- Replace fossil fuels with sustainable biomass in the electricity and heating sector in the short to medium term.

- Accelerate the conversion of the transport sector away from fossil fuels towards more electrification, to reduce fuel demand (e.g. promote uptake of electric vehicles or synfuels).

- Individual heating should be supplied by less energy demanding technologies than boilers, such as individual heat pumps or district heating.

- Before large energy system investments are taken studies should be carried out in terms of their long-term impacts on a future energy system. This is to avoid infeasible technologies or systems being implemented that prevent the renewable energy targets to be met (areas of particular interest with long lifetimes could be for example nuclear power in Scandinavia, transport infrastructure, district heating systems, building stock).

8 Conclusion

In this study some conclusions about the future development of the energy systems of the Scandinavian countries in their ambition to achieve a 100% renewable energy future have been made. The main conclusions from this study are presented below.

Research question

- How is a 2050 100% renewable Danish energy system in the context of an interconnected and disconnected Scandinavian energy system affected when applying super grid, smart grid and smart energy system technologies, in terms of energy system flexibility, energy efficiency, socio-economic costs and CO_2 emissions?

Connected vs. Disconnected Scandinavian energy system

- A connected Scandinavian system has lower fuel demand, and improved wind integration ability compared to the disconnected Scandinavian system in all steps. In the smart grid and smart energy system the Connected system has lower socio-economic costs than the Disconnected system and the optimum interconnection capacity is at a level in between these two extreme situations. Transmission line costs were not considered in this study, and the Connected system may be more expensive when including transmissions costs.

- Hydropower in Norway and Sweden is good for balancing power in the Connected Scandinavian system and can contribute to integrate more wind. However, if the electricity demand is lower than the hydropower production in Norway, through energy conservation or new technologies, then no wind can be integrated and hydro power may be exported which might also impact neighbouring countries.

- The Danish electricity demand in the Scandinavian context is low and has a small influence on the future renewable energy production profiles in a Scandinavian system. However, Denmark is able to integrate a high share of wind of the total electricity demand compared with the other countries.

Integration of wind

- In general, as the demand for electricity gets higher for the three independent countries and the Scandinavian systems the ability to integrate wind increases.

- The integration of wind improves in smart energy systems and smart grids compared to a supergrid, with the smart energy system integrating the largest share of wind.

Socio-economic costs

- The socio-economic costs for converting to 100% renewable energy increase for Denmark and the Scandinavian systems compared with the reference system in each energy system type. The largest increase in costs is for the smart energy system, which is largely caused by EV integration, which has high operation and maintenance costs, and the synfuel production costs.

- The EV operation and maintenance cost sensitivity is significant for the socio-economic costs. When operation and maintenance costs are decreased by 50% to a cost level similar to today's vehicle fleet, the energy system type costs decrease, especially the smart energy system.

- The sensitivity of the interest rate, wind investment cost and biomass costs do not change the main findings.

Super grid, smart grid and smart energy systems

- Supergrid on its own, without integration of smart grid and smart energy system technologies, does not lead to much fuel reductions, improved wind integration or socio-economic cost savings. A combination of the three energy systems is the ideal situation. The smart energy system allows the greatest integration of wind and fuel savings but with a slightly higher cost than the smart grid.

- Supergrid should only be integrated to the extent that it allows the smart grid and smart energy systems to achieve their purpose. However, it might be possible to implement the three energy system types following each other over a period of time.

100% renewable target

- All energy system types will be able to meet the future renewable energy policy targets, but with large differences in terms of fuel demand, especially for biomass. It was found that there are no technological fixes that alone would allow a conversion towards a 100% renewable society in the future. Carbon dioxide emissions are reduced to 0 but only if the biomass is sustainable. Life cycle emissions were not assessed and this needs to be investigated further.

- In all energy systems analysed in this study the biomass demand is higher than available biomass potentials in the region. Energy conservation is therefore necessary for biomass demand to stay within sustainable limits.

Technological solutions

- Electric vehicles increase the demand for electricity and improve the ability for integrating wind for all energy systems, as well as leading to fuel reductions. When the electric vehicles are charged with a smart charge strategy the improvements are larger than with a dump charge strategy. The socio-economic costs related to electric vehicles are closely linked to the operation and maintenance costs (i.e. battery costs).

- Biofuels do not improve wind integration and they increase fuel demand significantly.

- Synfuels improve fuel demand and wind integration compared to biofuels and for these key factors synfuels are more feasible for heavy transportation.

- Introducing individual heat pumps lowers the electricity demand in Sweden and Norway since they depend heavily on electric heating, which causes wind integration to fall, however the overall fuel demand and socio-economic costs decrease.

- Replacing individual boilers with heat pumps decreases the fuel demand and socio-economic costs, but forces Norway to export hydropower due a lower electricity demand.

- Large scale heat pumps do not influence the systems in this assessment when it is replacing individual heat pumps.

- Gasification of biomass allows more efficient gas power plants to be installed leading to lower fuel demands. This is especially important for Denmark where fuel demands from power plants are high. Due to the improved electricity efficiency for CHP plants the electricity produced in cogeneration operation reduces the wind integration ability.

Key factors for different countries

- Part of the benefits for wind integration and fuel savings from having a Connected Scandinavian system might be allocated to Denmark, but the size of the benefits is incalculable in this assessment.

- In Denmark the socio-economic cost for 100% renewable energy systems using supergrid, smart grid and smart energy system is higher than the reference from 2009. The increase ranges from 7% to 21%, with the smart energy system having the highest costs.

- The minimum grid stabilisation regulation of thermal plants in Denmark prohibits integration of more wind. When the grid stabilisation responsibility is removed from the existing power plants or grid stability is delivered by other technologies in Denmark the wind integration increases significantly whilst maintaining grid stability.

- Nuclear power in Sweden reduces integration of more wind and may increase costs, fuel demand and reduce the flexibility of the energy system in both Sweden and the Scandinavian energy systems.

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10 Appendices

10.1 Appendix A – Diamond-E

Table 20: The Diamond-E analysis results for prioritising key factors in the analysis

Diamond-E analysis	Consequences for the content of study
Natural and socioeconomic environment • High GHG emission • Energy security is at risk in the future (less self-sufficient in the future) • Global warming and climate change • High unemployment in europe • Renewable energy is creating new job opportunities in Europe • Liberalisation of energy systems within Europe and Scandinavia • Possible switch between the left and right every four years • UN Kyoto / EU directives guide renewable energy and carbon reduction measures • Denmark rely on import and export of electricity	Analyses of the natural and socioeconomic environment conditions suggest that: • A future energy system should reduce GHGs • The future system should reinforce national energy security • Mitigation of global warming and climate change impacts • The energy system should contribute to job creation (possibly from RE) • Changes to the energy system structure should be analysed in terms of their robustness/resilience within the liberalisation process that is ongoing • Policies/analyses should be considered as a balance between long-term goals and short-term optimisation • The future energy system should be in accordance with international guidelines • The Danish energy system should be open and interconnected to larger markets/energy systems
Organisational goals • That the Danish CO_2 emission is reduced by 40% in 2020 compared with 1990 • That the energy and transport sector is 100% renewable by 2050 • That by 2020 50% of the electricity consumption is sourced from wind • That a transition towards a renewable energy system should create more jobs than is lost • in 2030 no more coal in power plants • in 2035 electricity and heat is covered by RE • Improve competitiveness for Danish companies	The organisational goals tell that: • CO_2 emission should be reduced in a future energy system • The future energy system should accommodate an integration of more RE • Development of the energy system should contribute to job creation • The flexibility should be increased to accommodate more wind power • Competitiveness for Danish companies is essential for the energy system development
Organisational resources • A population which can participate actively in political processes • A population which can participate actively in the energy system • Changing demographic structure (more old) • Around 150,000 without employment • Many SMEs	Analyses of the organisational resources tells that: • The energy system development should allow for public participation (Intelligent technology is being developed to allow the population to participate more easily) • Old people consequence? • The energy system should contribute to job creation • Focus on decentralised systems in the analysis as they fit with the industrial structure
Financial resources • high level of foreign and private debt • there is potential that taxes could pay subsidies and projects within energy development • Stable economy where consumers can pay their bills • Subsidies (feed-in tariffs) for energy production (in particular wind)	Analyses of the financial resources tell that: • The energy system should contribute to reduce foreign and private debt • The Government can contribute to finance for energy system projects. (Public/private projects.) • Attractive to investors for the energy system • Good, stable economic conditions for integrating renewable energy production

<table>
<tr>
<td>Priorities</td>
<td>Key factors for analysis:

Socio-economy (costs)
Climate - CO_2
Flexibility and integration with other energy systems (unused electricity/import), integration of RE
Energy efficiency (fuel and energy consumption (biomass))
long term vs. short term
international guidelines (review and follow them in scenarios)
Open to international markets and energy systems (Connected Scandinavia approach)
Allow for public participation (or private dominance)
Economic conditions (taxes for RE)

Other factors:

competitiveness for dk companies
Job creation (one-pager about literature review)
National energy security
Mitigation of global warming and climate change
Demographic changes
Decentralised system compared to industrial structure
Private and foreign debt discussion
Government financing option (PPP)
Attractive for investors
</td>
</tr>
</table>

10.2 Appendix B – Methodology

10.2.1 Methodology procedure

The text below describes the study approach presented in Figure 17 in chapter 4 Methodology.

The first phase is to define the research area and narrow it down to a research question. In the report this is conducted through the literature review and Diamond-E analysis that highlighted certain challenges and visions and these were following prioritised and formulated as a question, which guides the work carried out in the remaining phases in the report.

After defining the research question the phase of data collection is initiated to collect the relevant data for investigating the research question. In this report three types of data collection was gathered, i.e. technical data for modelling, data from literature reviews and knowledge about the Danish energy system through interviews. These data can easily become immeasurable and hence the third phase was about organising and systematising the data into various country and technology categories. After organising the data they were prepared for modelling as input data into the modelling tool in phase 4.

The data was input as demand and production data for respectively the electricity, heating, cooling and transport system to form a full energy system. These input data were then modelled to create output in phase 5. The output data were organised for analysing the individual countries, the Disconnected and the Connected Scandinavian energy systems. The output data was in phase 6 analysed in terms of impacts on the key factors for each step in each energy system and presented by drafting graphs, tables and other relevant documentation of the output.

This presentation and analysis were following used to interpret the results and compare the different energy systems in phase 7. The comparisons then formed the basis for drafting recommendations about the feasibility of each technological solution, energy system type and the different types of interconnections in the Scandinavian energy system.

It is important to notice that the phases are illustrated as a linear process, but the process of making energy system analysis is never carried out like that. During the process many iterations, adjustments and new methods were integrated as the knowledge about the methodology and results grew. This means that there ought to be many more links between the phases of the report, which are not included in Figure 17. A typical example could be during the output phase where it was realised that the output data were not complete because of missing input data. This links back to the data collection process as new data had to be collected, organised and input to the model in order to create new and updated versions of the output.

10.2.2 EnergyPLAN

The EnergyPLAN tool is a deterministic computer based model using an input/output format to perform energy system analysis. The tool uses hourly simulation during one year to create outputs and has been continuously developed since its creation in 1999 (Lund, 2010). The tool can be used on a normal computer and performs calculations and outputs in a short period of time, often around a few seconds. The tool is programmed in Delphi Pascal where the user is responsible for inserting inputs in various input tab sheets linked to e.g. electricity demand, transport or renewable energy, see Figure 59. The model encompasses all energy system sectors such as electricity, heating, cooling and transports in terms of both demand and production distributions.

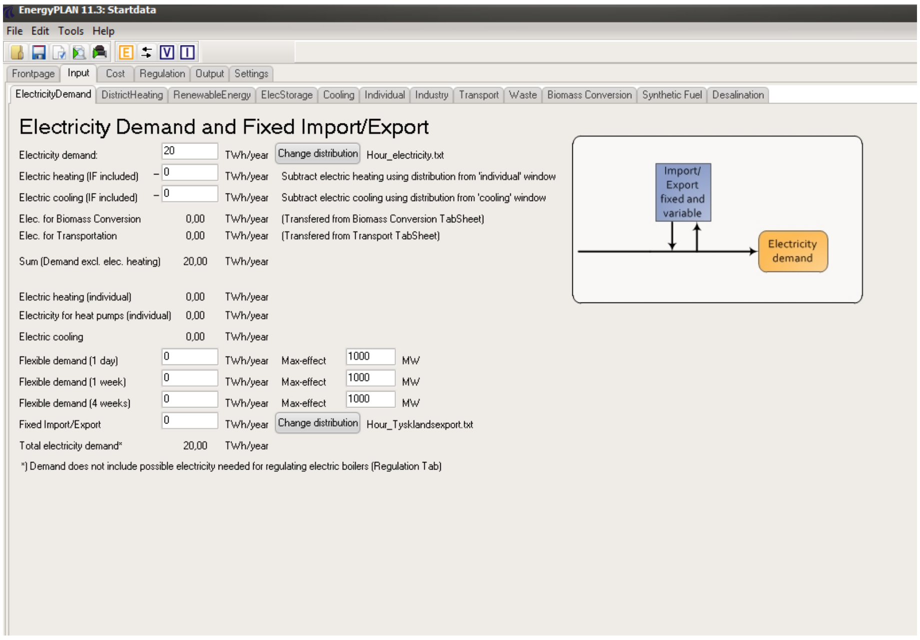


Figure 59: The outlay of the EnergyPLAN tool

The inputs for the model vary from demands and fuel sources to capacities and efficiencies as well as costs. Some of the outputs from the model includes energy balances in the form of fuel balance, production, import/export and total energy system costs. For costs the input data are investment costs for various technologies along with their accompanied operation and maintenance costs and lifetimes. Furthermore, fuel and CO_2 costs are included as well as potential electricity exchange costs.

A complete overview of the input-output structure for the tool can be seen in Figure 60.

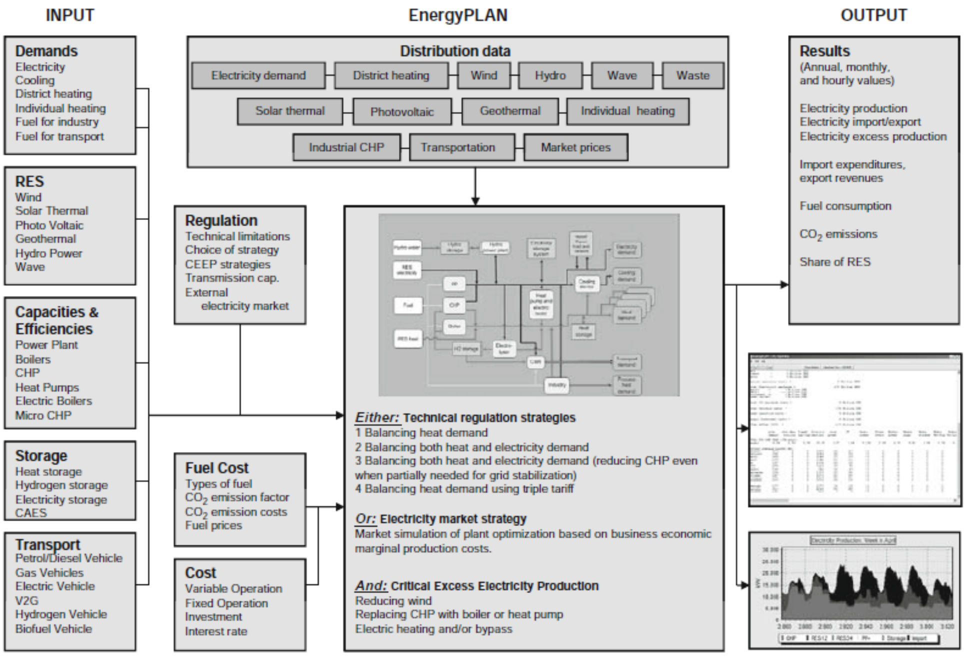


Figure 60: Input output structure of the EnergyPLAN model

The tool is publicly available online free of charge and has been used in a continuously increasing number of analysis projects and articles (Lund and Mathiesen 2009; Connolly et al. 2011; Lund and Mathiesen 2008)[1].

The EnergyPLAN tool differs from other energy system analysis models with respect to the temporal scale as it models the energy system hour-by-hour in opposition to aggregated monthly or annual models. Furthermore, other differences relate to the energy system scale as some models are designed to model regions, projects or individual plants while the EnergyPLAN tool can model both international, national, or regional energy systems.

10.2.3 The concept behind EnergyPLAN

The overall aim of EnergyPLAN is to aid in the design and analysis of alternative energy systems based on renewable energy system technologies in terms of technical or economic analysis.

The following quote from (Lund 2010) describes the principal objective of the tool:

"*The model should be able to make a consistent and comparative analysis of all alternatives in question as well as a reference*." (Henrik Lund 2010, P. 51).

The tool is designed so all alternatives are calculated and analysed equally in order to create the basis for comparisons. It is possible within the tool to explore an almost infinite range of future options in order to compare the various alternatives.

Additionally, the objective of the tool is to be able to model both the existing system as well as systems with radical technological changes and hence the model has been designed so it is not too affected by the design of the existing energy system. Furthermore, the objective is that the tool should be transparent and consistent in order to make replicable analyses of energy systems.

For more information on how the tool works see (Department of Development and Planning 2014).

[1] **Note**: A version of EnergyPLAN was used in this report that is not yet publicly available with improvements of hydropower modelling

10.3 Appendix C – Technology catalogue

In this technology catalogue is a description of some of the technologies applied in the different steps in the report. This serves as background information and for creating a better understanding of the various technologies.

The technologies that are presented are related to biofuels, individual and large heat pumps, flexible demand, synfuels and gasification.

10.3.1 Step 2 - Biofuels

In this report biofuels are replacing fossil fuel consumption to reduce CO_2-emissions. The types of biofuels are biodiesel, biopetrol (bioethanol) and bio jetfuel. The biofuels can be categorised as either 1st or 2nd generation biofuels depending on the source for the biomass, but this has not been taken into consideration in the report. The assumption in this report is that the biomass demand for the entire energy system should stay within the domestic limits for sustainable biomass resources.

The production of biopetrol is often based on wheat, straw or sugar cane and create different bi-products such as lignin and molasses (Danish Energy Agency and COWI 2013a).

The biodiesel is typically based on rapeseed, but all types of vegetable and animal fat or oils can be used for the production. The fuel is produced through a chemical process that changes the chemical structure of the product so that it achieves characteristics similar to diesel. It is done in practice by creating a reaction between the oils or fat and methanol thereby creating Fatty Acid Methyl Ester (FAME). This type of technology is the most widespread type in Europe for biofuels.

When biodiesel is consumed in a clean version with no additional fossil fuels smaller engine technology conversions are required, hence the additional transport infrastructure costs in the report (Danish Energy Agency and COWI 2013b).

10.3.2 Individual and large heat pumps

Individual heat pumps are implemented in step 3 while large heat pumps are implemented in step 7. They are both explained below.

The individual heat pumps are used for space heating in households and other buildings and can potentially deliver all of the heating demand depending on the type of heat pump.

An individual heat pump is a technology that moves heat from one location to another by drawing heat from the ambience and converting it to higher temperatures. There are different types based on air-to-air, air-to-water, brine-to-water, etc. that takes advantage of different ambient heating sources. The heat pumps have different efficiencies in terms of heat delivery compared to the electricity consumption. This ratio is defined as the COP (Coefficient of performance) and is in this report assumed to be 3.2, but might change according to the type of heat pump. If the COP is three, one third will come from electricity while the remaining two-thirds will be collected through the heat exchanger (Danish Energy Agency and Energinet.dk 2012a).

The large heat pumps that are implemented in step 7 are all compressor heat pumps using electricity unlike absorption heat pumps that are based on heating from sources such as steam, flue gas, etc. The heat pumps in this report are used for district heating purposes with a COP of 3.5. The heat pumps are delivering heat for the district heating network along with other sources to ensure the appropriate temperatures. This technology can contribute to creating a more flexible energy system by converting electricity to heating at high efficiencies when there is surplus electricity production. The heat pumps can regulate continuously going from cold to full load production, often in less than five minutes (Danish Energy Agency and Energinet.dk 2012b).

10.3.3 Flexible demand

The flexible electricity demand may consist of a range of technologies that changes consumption patterns, but has not been fully implemented in reality yet and is therefore still rather unproven. Its effect is however often highlighted in literature and consists as one of the key components of a future smart grid system.

Examples of the flexible demand can be heating pumps that stops because of congestion in the electricity grid or electric vehicles that charges in a smart fashion according to the fluctuating electricity production. The flexible demand can hence contribute to integrating more renewable energy, but also reduce and delay investments for distribution companies in grid expansions and ensure stability in the electricity grid. The flexible demand can be divided into two types based on pricing mechanisms that creates an economic incentive for consumers or based on flexibility products that delivers a certain service to e.g. reduce the peak demand in return for a reduced price. Products such as smart meters and intelligent appliances are part of a future flexible demand (Dansk Energi and Energinet.dk 2013).

10.3.4 Synfuels

Synfuels in the way it has been carried out in this report is similar to bio-methanol. The chemical reactions are as below:

C6(H2O)5 + 5.75 H2 --> ½C12H23 + 5H2O

The creation of synfuels contains four steps that are each briefly described below.

Table 21: Steps involved in synfuel production

1. Electrolysis of water	2. Gasification of biomass
3. Hydrogenation of gasification gas	4. Chemical synthesis of liquid fuels

1. Electrolysis of water

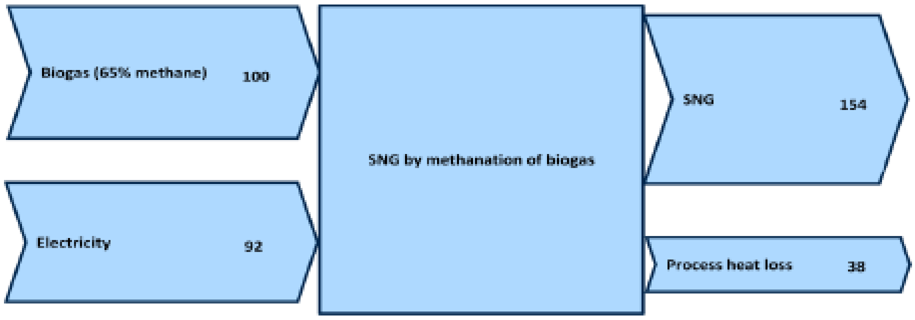
"Electrolysis is a process, where electricity is used to electrochemically reduce or oxidise a reactant into fuel. The water decomposition via electrolysis takes place in two partial reactions at both electrodes, which are separated by an ion-conducting electrolyte. At the negative electrode (cathode) hydrogen is produced and on the positive electrode (anode) oxygen is produced. To keep the product gases separated the two reaction compartments are separated. Depending on the type of electrolyser, separation is either achieved by means of a solid electrolyte (SOEC, PEMEC) or a micro-porous diaphragm (alkaline) (Danish Energy Agency and Energinet.dk 2012b, P. 179).

2. Gasification of biomass

"A gasifier produces a combustible synthetic gas (syngas) from a fuel. In a low-temperature gasifier, it is easy to use high alkaline containing fuels, as the gasifier operates below the melting point of those. This encompasses low grade biomass, such as agricultural residues, energy crops and certain waste fractions." (Danish Energy Agency and Energinet.dk 2012b, P. 198).

3. Hydrogenation of biogas

"SNG (synthetic natural gas) can be produced through methanation of biogas. The main components in biogas are methane and CO_2. The content of CO_2 may vary between about 35-50 vol. % depending on the actual biogas production technology. Through methanation of the CO_2 contained in biogas, it is possible to upgrade the biogas to natural gas quality." (Evald et al. 2013, P. 74).



(Evald et al. 2013, P. 75)

4. Chemical synthesis of liquid fuels

"Methanol can be synthesized by using biomass as start material such as straw, wood, corn stover or other lignocellulosic materials. Biomass is first pre-treated (drying, grinding, etc.) and gasified in a gasifier which is usually specially designed for the specific biomass type. The gas from the gasification step is subsequently converted to syngas through a thermal reforming process. The produced syngas is then cleaned and converted to methanol through a catalytic synthesis process. The final methanol product is produced after a final purification step. An integrated unit for power and heat generation supplies the whole production process for power and steam or heat. (Evald et al. 2013, P. 23).

10.3.5 Gasification

Gasification technology is implemented as the final step in the analysis in the report. It contains three steps that are explained below.

The first step in the gasification technology is the actual gasification that converts solid biomass into gas that can be used in gas engines or boilers. The gasification itself contains a number of processes that will not be further elaborated upon here. The gas that leaves the gasifier is called producer gas until it has been cleaned in the next step. The cleaning is carried out when the biogas is upgraded in order to inject it into the natural gas grid. Alternatively, the upgraded biogas can be used in vehicles that are driven by gasses. After the cleaning the gas is called a synthetic gas, or in short syngas. The syngas is then used in CHP plants or power plants using combined cycle gas turbine technology that compared to traditional technologies based on internal combustion technology have lower overall efficiencies, but much higher electricity efficiencies. Combined with other technologies such as heat pumps for heating production the gasification technologies should be able to increase the efficiency of the system (Danish Energy Agency and Energinet.dk 2012c).

10.4 Appendix D – Technical background information

Comparison of input data for reference energy systems

Table 22: Comparison of EnergyPLAN data with national statistics and IEA for the reference systems

		Sweden					Norway					Denmark				
		Nat. Stat.	IEA	Energy PLAN	Difference nat. Stat.	Difference IEA	Nat. Stat.	IEA	Energy PLAN	Difference nat stat	Difference IEA	Nat. Stat.	IEA	Energy PLAN	Difference nat stat	Difference IEA
Fuel total, incl. Electr. export	TWh	551,5	548,3	538,73	-2,37%	-1,78%	299,3	298,85	293,19	-2,08%	-1,93%	225,55	221	220,78	-2,16%	-0,10%
- coal	TWh	18	22,4	18,36	1,96%	-22,00%	5,8	6,55	5,31	-9,23%	-23,35%	46,02	46,6	45,94	-0,17%	-1,44%
- oil	TWh	174	165,8	166,77	-4,34%	0,58%	78	84,7	84,72	7,93%	0,02%	87,44	86,9	88,93	1,68%	2,28%
- natural gas	TWh	12,7	12,8	12,04	-5,48%	-6,31%	71,7	63,8	58,47	-22,63%	-9,12%	45,89	45,4	43,29	-6,01%	-4,87%
- biomass	TWh	125	120,7	118,55	-5,44%	-1,81%	16,8	16,6	15,86	-5,93%	-4,67%	36,41	35,1	35,79	-1,73%	1,93%
- renewables	TWh	68,5	68,5	68,59	0,13%	0,13%	127	127,2	128,83	1,42%	1,27%	7,04	7	6,83	-3,07%	-2,49%
- nuclear	TWh	149	158,1	154,42	3,51%	-2,38%	0	0	0			0	0	0		
CO_2	Mton	55,895		54,01	-3,49%		N/A		36,32			48,965		48,24	-1,50%	
Adjusted CO_2	Mton	-		54,01			N/A		36,32			49,416		48,23	-2,46%	
Net export	TWh	4,7		0			N/A		0			0		0		
Electricity demand	TWh	138,4	136,6	138,46	0,04%	1,34%	N/A	131,9	131,95		0,04%	34,78	36,36	36,49		-0,36%
District heating demand	TWh	55,6		59,26	6,18%		3,64		2,18	-67,07%		36,00		37,22	3,29%	
Individual heating	TWh	N/A		38,3			N/A		50,31							
Industry	TWh	131,5		94,6	-39,01%		N/A		82,98			25,48		27,07	5,88%	
Transport	TWh	123		118,9	-3,45%		N/A		62,64			58,1		65,45	11,23%	

Table 23: Comparison of EnergyPLAN data with national statistics and IEA for the reference systems

		Disconnected Scandinavia	Connected Scandinavia	Difference (%)
Fuel total, incl. Electricity export	**TWh**	**1052,7**	**1052,2**	**-0,05%**
- coal	TWh	69,61	61,06	-14,00%
- oil	TWh	340,42	341,5	0,32%
- natural gas	TWh	113,8	117,73	3,34%
- biomass	TWh	170,2	171,87	0,97%
- renewables	TWh	204,25	205,62	0,67%
- nuclear	TWh	154,42	154,42	0,00%
CO_2	Mton	138,57	135,89	-1,97%
Adjusted CO_2	Mton	138,56	135,89	-1,96%
Electricity demand	TWh	306,9	306,82	-0,03%
District heating demand	TWh	98,66	98,68	0,02%
Individual heating	TWh			
Industry	TWh	204,65	212,92	3,88%
Transport	TWh	246,99	241,63	-2,22%

Table 24: Technology data for energy system analysis for the Danish, Swedish, Norwegian and Scandinavian energy systems

Technology		**Denmark**	**Sweden**	**Norway**	**Connected Scandinavian**	**Disconnected Scandinavian**
Power plants	Capacity (MW-e)	7000	6903	740	14643	14643
	Efficiency (%)	40				
CHP plants - Decentral - Centralised	Capacity (MW-e)	- 1625 - 5836	- 500 - 3000	- 0 - 100	- 2125 - 8936	- 2125 - 8936
	Efficiency (heat/electricity) (%)	- 37/46	- 31/53			
DHP	Capacity (MW-th)	608	6039	94	6741	6729
Large heat pumps - Decentral - Centralised	Capacity (MW-e)	- 50 - 0	- 150 - 380	- 0 - 50	- 200 - 430	- 200 - 430
	Efficiency (%)	3.5				
Boilers - Decentral - Centralised	Capacity (MW-th)	- 3667 - 7978	- 1500 - 2000	- 0 - 50	- 5167 - 10028	- 5167 - 10028
	Efficiency (%)	93				
Ind. boilers - oil - natural gas - biomass	Capacity (MW-th)	6822	7171	3105	17098	17098
	Efficiency (%)	- 85 - 90 - 80				
Elec. heat	Capacity (MW-e)	379	5800	11758	17937	17938
	Efficiency (%)	100				
Hydropower	Capacity (MW-e)	-	16544	28188	44732	44732
	Efficiency (%)	-	100	90	0,93	0,93
	Storage (GWh)	-	33700	84300	118000	118000
Pump	capacity (MW-e)	-	0	1351	1351	1351
	efficiency (%)	-	-	90	90	90
Nuclear power	Capacity (MW-e)	-	9036	-	9036	9036
	Efficiency (%)	-	33	-	33	33
Waste incineration	Capacity	N/A				
	Efficiency (heat/electricity) (%)	-75/19				

Cost database for energy systems analysis

Table 25: Fuel prices (Danish Energy Agency 2011)

2009 €/GJ	
Raw oil (USD/bbl)	107,4
Coal	3,1
Fuel oil	11,9
Gas oil	15,0
Diesel	15,0
Petrol	15,2
JP1	16,1
Natural gas	9,1
LPG	17,0
Biomass	7,3
Energy willow (Dry Biomass)	4,7
Nuclear	1,50

Table 26: Fuel handling costs (Danish Energy Agency 2011)

2009 - €/GJ	Centralised Power Plants	Decentralised Power Plants & Industry	Consumer
Fuel			
Natural Gas	0,412	2,050	3,146
Coal	-	-	-
Fuel Oil	0,262	-	-
Diesel/Petrol	0,262	1,905	2,084
Jet Fuel	-	-	0,482
Straw	1,754	1,216	2,713
Wood Chips	1,493	1,493	
Wood Pellets	-	0,543	3,256
Energy Crops	1,493	1,493	
Average Biomass	1,580	1,186	2,985

Table 27: CO_2 price (Danish Energy Agency 2011)

2009-€/Ton	CO_2 Price
	15,2

Table 28: CO_2 emission factors (Danish Energy Agency 2011)

Fuel	Coal/Peat	Oil	Natural Gas	Waste	LPG
Emission Factor (kg/GJ)	95	74	56,7	0	59,64

Table 29: Vehicle prices (Danish Energy Agency and COWI 2013b)

Vehicle	Investment (euro/vehicle)	Annual O&M (% of Invest)
Cars		
ICE Diesel	12,822	7.21
ICE Petrol	11,480	8.19
Battery electric vehicles	12,971	11.16
ICE Bio-methanol	14,104	6.55
Busses		
ICE Diesel	161,074	1.23
ICE Bio-methanol	163,960	1.20
Trucks		
ICE Diesel	161,074	1.23
ICE Bio-methanol	163,960	1.2

Table 30: Energy technology investment prices

Production Type	Unit	Invest-ment (M€/unit)	Life-time (Years)	Fixed O&M (% of Investment)	Source for Costs
Solar Thermal	TWh/year	440	20	0.1	(Danish Energy Agency and Energinet.dk 2012c)
Small CHP - Single cycle gas turbine medium	MWe	1.35	25	1.12	(Danish Energy Agency and Energinet.dk 2012c)
Small CHP - Medium steam turbine woodchips	MWe	2.6	30	1.12	(Danish Energy Agency and Energinet.dk 2012c)
Heat Pump Group 2	MWe	2.7	20	0.2	(B. V. Mathiesen et al. 2011)
Heat Storage CHP	GWh	3	20	0.70	(Danish Energy Agency and Energinet.dk 2012c)
Large CHP - Gas turbine single cycle large	MWe	0.65	25	1.12	(Danish Energy Agency and Energinet.dk 2012c)
Large CHP - Medium steam turbine woodchips	MWe	2.6	30	1.12	(Danish Energy Agency and Energinet.dk 2012c)
Large CHP - Steam turbine, pulverised coal fired	MWe	2.04	40	1.12	(Danish Energy Agency and Energinet.dk 2012c)
Heat Pump Group 3	MWe	2.7	20	0.2	(B. V. Mathiesen et al. 2011)
Heat Storage Solar	GWh	3	20	0.70	(Danish Energy Agency and Energinet.dk 2012c)
Boilers Group 2 & 3	MWth	0.32	30	1.86	(Danish Energy Agency and Energinet.dk 2012c)
Large Power Plants - coal (400-700 MW)	MWe	2.03	40	3.03	(Danish Energy Agency and Energinet.dk 2012c)
Large Power plants - biomass (pellets) (250-400 MW)	MWe	2.03	40	3.03	(Danish Energy Agency and Energinet.dk 2012c)
Large power plants - Combined Cycle Gas Turbines	MWe	0.82	25	3.66	(Danish Energy Agency and Energinet.dk 2012c)
Wind Onshore	MWe	1.25	20	3	(Danish Energy Agency and Energinet.dk 2012c)
Wind Offshore	MWe	2.3	20	2.9	(Danish Energy Agency

					and Energinet.dk 2012c)
Hydro Power	MWe	1.9	50	2.7	(European Commission 2011b)
Hydro Pump	MWe	0.6	50	1.50	Assuming the same as PHES Pump
Nuclear	MWe	3	25	3.74	(European Commission 2011b)
Alkaline Electrolyser	MWe	2,54	27,5	4	(B. V. Mathiesen, Ridjan, and Connolly 2013)
SOEC Electrolyser	MWe	0,57	20	2.46	(B. V. Mathiesen, Ridjan, and Connolly 2013)
Hydrogen Storage	GWh	10	30	0.5	(Danish Energy Agency and Energinet.dk 2012c)
Pump	MWe	0.6	50	1.5	(Danish Energy Agency and Energinet.dk 2012c)
Turbine	MWe	0.6	50	1.5	Assuming the same as PHES Pump
Individual Boilers - biomass	MWth	0.58	20	1.35	(Danish Energy Agency and Energinet.dk 2012c)
Individual Boilers - natural gas	MWth	0.58	23	3.7	(Danish Energy Agency and Energinet.dk 2012c)
Individual Boilers - oil	MWth	0.48	20	3.7	(Danish Energy Agency and Energinet.dk 2012c)
Individual Heat Pump	MWe	1.188	15	0.6	(Lund et al. 2010)
Individual Electric Heat	MWe	0.303	20	0.9	(Lund et al. 2010)
Biogas Upgrade	MW Gas Out	0.278	15	1.94	(Evald, Hu, and Hansen 2013)
Gasification Gas Upgrade	MW Gas Out	0.278	15	1.94	(Evald, Hu, and Hansen 2013)
DHP Boiler Group 1	MWth	0.32	30	1.86	(Danish Energy Agency and Energinet.dk 2012c)
Waste CHP	TWh/ year	250.45	20	1.82	(Danish Energy Agency and Energinet.dk 2012c)
Biogas Plant	TWh/ year	376.5	20	11.25	(Danish Energy Agency and Energinet.dk

					2012c)
Gasification Plant	MW Syngas	0.649	20	9.77	(Danish Energy Agency and Energinet.dk 2012c)
Biodiesel Plant	MW-bio	0.74	20	2.95	(Evald, Hu, and Hansen 2013)
Biopetrol Plant	MW-Bio	1.92	20	3.32	(Evald, Hu, and Hansen 2013)
Biojetpetrol Plant	MW-Bio	1.92	20	3.32	(Evald, Hu, and Hansen 2013)
Chemical Synthesis MeOH	MW-Fuel	0.49	20	3.96	(Danish Energy Agency and COWI 2013b)

10.5 Appendix E – Supplementary results

10.5.1 Reference system input data

This section describes the input data used in the study for each reference energy system which includes the electricity sector, the heat sector as well as the cooling and transport demand.

Table 31 presents a breakdown of the electricity demands for each energy sector in each country. All data in this table is the data used in EnergyPLAN; some is directly added based on external data sources and some is calculated by the EnergyPLAN tool. The electricity production data for power plants and CHP plants is calculated for example. For a comparison of the accuracy of the calculated data with the actual data from national statistics and IEA refer to Appendix D – Technical background information.

Table 31: Electricity demand and production for the reference energy systems

Category - Energy		**Denmark**	**Norway**	**Sweden**	**Disconnected Scandinavia**	**Connected Scandinavia**
Electricity demand (TWh)		**36.4**	**132**	**136.6**	**304.9**	**304.9**
	Fixed demand	34.6	91.6	114.6	240.9	240.9
	Heating	1.26	38.8	20.3	60.3	60.3
	Transport	0.4	0.7	2.4	3.5	3.5
	Cooling	0.5	1.5	1.7	3.7	3.7
	Biomass conversion	**0.35**	**0.4**	**0.19**	**0.91**	**0.91**
Electricity production (TWh)		**36.4**	**132**	**136.6**	**304.9**	**304.9**
	Combined heat & power	15.8	0.2	11.5	27.5	28.5
	Power plant	10	0.9	0.5	11.4	10.4
	Wind electricity	6.7	1	2.5	10.2	10.2
	Hydropower	0	127.8	66.1	193.9	193.5
	Waste and industry	4	2.1	7.5	13.6	13.6
	Nuclear	0	0	50.9	50.9	50.9

The electricity generation capacities of the different technologies in each country are described in The electricity production capacities of the different countries and Scandinavian systems are shown below.

Table 32 below. These capacities are all taken from literature.

10.5.1.1 Electricity production capacities

The electricity production capacities of the different countries and Scandinavian systems are shown below.

Table 32: Electricity production capacities for the different energy systems in Denmark, Sweden, Norway and Scandinavia (Swedish Energy Agency 2012; Svensk Energi 2009; Norwegian Water Resources and Energy Directorate 2011; Lund et al. 2011)

Electric capacity (MW-e)	Denmark	Norway	Sweden	Disconnected Scandinavia	Connected Scandinavia
Power plants	1,164	640	3,903	5,707	5,707
Combined heat and power	7,461	100	3,500	11,061	11,061
Wind	3,241	431	1,437	4,448	4,448
Hydropower	-	28,188	16,544	44,732	44,732
Nuclear	-	-	9,036	9,036	9,036
Industry*	unknown	unknown	1,199	unknown	unknown
Total	11,205	29,359	34,420	74,984	74,984

* Industry capacity is not included for some countries due to data gaps

The unique characteristics about each country's energy systems are described below. As explained above the data presented below is the data entered into EnergyPLAN and some data calculated by EnergyPLAN.

Denmark

The electricity demand in Denmark is the lowest of the three countries (36 TWh), with the primary part being fixed demand. The fixed demand is defined as demand from households, services and industry, and which is not for heating, cooling or transport. Transport, electric heating and cooling demand are reported separately and are much smaller amounts.

In 2009 the electricity production is mostly from thermal production, including Combined Heat and Power (CHP) plants (15.8 TWh from 7461 MW) and central power plants (10 TWh from 1164 MW), and some production from waste incineration plants and industries (4 TWh from an unknown capacity). The large power production plants use a large share of coal (47 TWh) followed by natural gas (17 TWh).

Beyond the thermal production wind turbines produce a smaller amount of electricity (6.7 TWh in 2009 from 3241 MW), which is a 24% capacity factor.

Sweden

The electricity demand for the Swedish 2009 reference system is the highest of the three countries (138.4 TWh). This includes a net import of 4.7 TWh. Excluding this imported electricity, the national production is 133.7 TWh. Transmission losses account for around 10 TWh. In this study the total demand is used including the imported amount.

The electricity in Sweden is primarily produced from hydro and nuclear power, supplemented with condensing power and CHP, and wind. In 2009 the hydro and nuclear power plants produced the largest amount of electricity (65.3 TWh and 50.9 TWh from 16544 and 9036 MW, respectively). The nuclear power has an efficiency of 33% meaning that the 50.9TWh of electricity consumes 154.4 TWh of primary energy. In this study the hydropower is assumed to be produced 100% by reservoir hydro. Wind power produces a small amount of electricity (2.5 TWh from 1560 MW of capacity), which is a capacity factor of 18%.

In 2009 district heating CHP plants accounted for a small amount of electricity production (10.2 TWh). Cold condensing plants and gas turbines account avery small amount (0.7 TWh). And some electricity was produced from industrial CHP (back-pressure) (5.6 TWh from 1199 MW).

Norway

The total electricity demand for the Norwegian reference system for 2009 is slightly lower than Sweden (132 TWh). In 2009 Norway exported 9 TWh of electricity.

The electricity in Norway is primarily produced from hydropower (127.8 TWh from 28,188 MW)) supplemented by small amounts of power plants (3.2 TWh from 740 MW). Wind power produced a small amount (1 TWh from 431 MW).

An hourly wind production profile for Norway was unavailable therefore the Swedish wind profile was used for Norway.

Disconnected Scandinavia system

In the Disconnected Scandinavia reference system the electricity demand and production of the system is based on combining the demand from the individual countries by adding them as if they are separate and have no interconnection. Consequently, the majority of the demand is from fixed demand while the electric heating is around 20% of the total demand. The transport and cooling electricity demand are relatively small.

The electricity produced in the Disconnected Scandinavia system is primarily hydropower from Norway and Sweden, producing around 63% of the total demand while nuclear is producing 17% and CHP 9 %. Only small shares of wind, condensing power plants and waste and industrial production are part of the Disconnected Scandinavian system. The thermal production is relatively limited while baseload production is produced from nuclear power, waste and industry as well as hydropower.

Connected Scandinavia system

The electricity demand for the Connected Scandinavia reference system is based on modelling the three countries as one single country. This means that the production of electricity changes slightly since the system is one whole system so Norwegian hydro can supplement Danish CHP electricity production for example. While all production capacities remain the same the production amounts change slightly. In general the whole system remains largely the same as the Disconnected system when all countries are combined together. Only power plant and Combined heat and power change by 1-2 TWh.

10.5.1.2 Heating

The heating demands and production for each country and the Scandinavian systems are presented in Table 33.

Table 33: Heating demand and production for the energy systems in Denmark, Sweden, Norway and Scandinavia

Category - Energy		Denmark	Norway	Sweden	Disconnected Scandinavia	Connected Scandinavia
Heat demand		**60.9**	**513**	**104.4**	**216.6**	**216.6**
	District heat	37.2	2.2	59.4	98.8	98.8
	Individual heat	23.7	491	45	117.8	117.8
Heat produc-tion		**61.7**	**51.6**	**104.2**	**217.5**	**218.51**
District heating	DHP	2.2	0.36	26.91	29.47	29.1
	CHP	26.5	0.3	19	45.8	47.1
	Waste and industry	9.3	1.9	13.3	24.5	24.5
Ind. Heating	Ind. boilers	22.48	10.2	23.61	56.29	56.31
	Ind. Heat pump	0	0.1	2.3	2.4	2.4
	Electric heating	1.2	38.7	19.1	59	59.1
	Difference	0.8	0.3	0.2	1.3	1.9

The heating capacity is presented for each country and Scandinavian systems in Table 34 below.

Table 34: Heating capacity for Denmark, Norway, Sweden and Scandinavia

Heating capacity (MW-th)	Denmark	Norway	Sweden	Disconnected Scandinavia	Connected Scandinavia
Total	31.493	15.241	29.018	75.752	73.286
CHP	11.989	171	5.748	17.908	17.907
DHP	608	94	6.039	6741	4272
Boilers, large	11.645	50	3.500	15.195	15.195

Boilers, ind.	6.822	3.105	7.171	17.098	17.098
HP	50	50	530	630	630
Ind. Electric heat	379	11.758	5.800	17.937	17.938
Ind. HP	-	13	230	243	246

* Industry and waste capacity is not included due to data gaps

Denmark

Denmark is characterised by a large share of district heating with more than 60% of the Danish population connected to the district heating system (Danish District Heating Association 2014). Having CHP allows for a high conversion efficiency of the fuels as both heat and electricity is generated from the fuels thereby improving the efficiencies compared to solely producing electricity.

The district heating demand in 2009 is 37.2 TWh. The district heating is produced from large CHP plants (26.5 TWh), waste incineration and industrial excess heat (9.3 TWh) and district heating only technologies such as large heat pumps, boilers and district heating plants (2.2 TWh).

The demand for individual heating is 23.7 TWh in areas where it is not possible or not economically feasible to connect to the district heating network, and this is mostly supplied by individual boilers (22.5 TWh). A small share is provided by electric heating (1.2 TWh).

Sweden

Sweden has a relatively high proportion of electrical heating, of more than 19 TWh in total. Electric heating accounts for around 30% of all heating energy used in the residential sector, primarily in single-family homes (Svensk Energi 2009). Individual boilers also account for a high proportion of heating (24 TWh).

The heating system in Sweden also consists of district heating. The total national district heating demand is 59.4 TWh.

Not all buildings are connected to the district heating for various reasons such as distance to closest district heating system or high installation costs, etc., and these buildings rely on individual heating solutions in the forms of individual boilers, electric heating, heat pumps or solar thermal.

Norway

Norway is also characterised by a large share of electric heating in the individual buildings in 2009 (39 TWh). This was supplemented by a minor district heating supply (2.2 TWh). Electric heating equals around 64% of the total electricity demand in residential houses in Norway (SINTEF 2012).

For district heating, the private and public services have the highest demands (68%) followed by households (22%) and industry (9%).

The district heating is produced from few CHP plants using primarily biomass and from waste incineration plants.

Individual boilers supply a small amount of heating (10 TWh) from biomass and oil boilers. Only a small amount of heat pumps were installed as of 2009.

Disconnected Scandinavia

The heating demand and production for the Disconnected Scandinavia reference system is based on combining the demand from the individual countries by adding them. Consequently, the majority of the demand is from individual heating demand which is met by electric heaters and individual boilers.

Connected Scandinavia

The heating demand for the Connected Scandinavia reference system is based on modelling the three countries as one single country. All production capacities remain the same and the production amounts remain the same. Consequently, the majority of the demand is from individual heating demand which is met by electric heaters and individual boilers.

10.5.1.3 Cooling

The cooling demand for each country and Scandinavian systems are presented in Table 35 below.

Table 35: Cooling demands for Denmark, Sweden, Norway and Scandinavia

	Denmark	Norway	Sweden	Disconnected Scandinavia	Connected Scandinavia
Cooling demand (TWh)	0.5	1.5	17	3.7	3.7

Denmark, Sweden Norway

The cooling demand in all three countries is low. In Denmark the cooling demand is 0.5 TWh and is supplied solely from electricity. The largest demand is from services that require cooling for their facilities. In Sweden in 2009 the cooling demand is 0.83 TWh and the main consumers of cooling are services. In Norway the cooling demand is 1.5 TWh and the majority is supplied for services and industries.

Connected & Disconnected Scandinavia

The cooling demand and production in the Connected and Disconnected Scandinavia systems are exactly the same as each other since they are the combined total for the three countries.

10.5.1.4 Transport

The total transport fuel demand for the three countries and the Scandinavian systems in 2009 are presented in Table 36.

Table 36: Transport duel demand for Denmark, Sweden, Norway and Scandinavia references

Transport fuel demand (TWh)	Category - Energy	Denmark	Norway	Sweden	Disconnected Scandinavia	Connected Scandinavia
	Diesel	29.8	31.4	38.9	100.1	100.1
	Petrol	19.7	15.2	40.6	75.5	75.6
	Jet fuel	9.4	8.2	10	27.6	27.6
	Fuel oil	6.4	6.8	25.2	38.4	38.4
	Biofuels	0.11	1.1	4.2	5.4	5.4
	Electricity	0.4	0.7	2.4	3.5	3.5
	LPG/NG	-	0.6	-	0.6	0.6
	TOTAL	65.8	64	121.3	251.1	251.1

Denmark

The transport sector in Denmark in 2009 consumes a high amount of energy (66 TWh) of which petrol and diesel is account for the majority of this (50 TWh), followed by jet fuel and fuel oil (9.4 and 6.4 TWh, respectively) and electricity and biofuels are low (0.4 TWh and 0.1 TWh, respectively).

The transport sector is dominated by individual transport modes such as cars for passenger transport and trucks and vans for freight transport. These modes are all road transport, which consume more than 75% of the total fuel consumption for transportation. The second largest fuel consumer is aviation that consumes around 16% of the total fuel consumption followed by a minor amount of fuel for rail and sea transport.

Sweden

The transport sector in Sweden consumed a high amount of energy in 2009 (121 TWh). The majority of fuels are petrol and diesel followed by a relatively high fuel oil amount (41, 39 and 25 TWh, respectively). The transport sector is dominated by individual transport modes such as cars for passenger transport and trucks and vans for freight transport. In 2009 there were 4,300,752 passenger cars in use in Sweden in 2009 out of population of around 9.5 million (Statistics Sweden 2014).

Sweden has the highest amount of biofuels and electric vehicles than the other countries (4.2 and 2.4 TWh, respectively).

Norway

The total energy demand for transportation in Norway is also high (64 TWh). There are almost three million cars in Norway (incl. vans) (Institute of Transport economics 2013). The population in Norway is around 5.1 million people and the car ownership per citizen is higher than in most other countries in Europe (Statistics Norway).

The majority of transport fuels are diesel and petrol (31 and 15 TWh, respectively) followed by jet petrol (8.2 TWh).

The road transport is responsible for more than 87% of the Norwegian passenger transport work with air transport the second largest group followed by rail and sea.

Connected & Disconnected Scandinavia

The transport demand in the Connected and Disconnected Scandinavia systems are exactly the same since they consist of the three countries combined. Consequently the Scandinavian systems have high diesel, petrol, jet fuel and fuel oil consumption.

The fuel consumed in industry in each country and the Scandinavian systems is presented in Table 37 below. The waste utilised for energy recovery is also shown in the table.

Table 37: Industrial and waste sector fuel consumption in Denmark, Sweden, Norway and Scandinavia

	Fuel mix (TWh)	Denmark	Norway	Sweden	Disconnected Scandinavia	Connected Scandinavia
Industry	Coal	1.5	5,2	3.7	10.4	10.4
	Oil	15.3	18.4	34	67.7	67.7
	Natural gas (flared natural gas)	8.3 (6.9)	7.5 (48)	6.4	22.2 (77.1)	22.2 (77.1)
	Biomass	2	3.8	50.5	56.3	56.3
Waste		10.3	2.4	12.7	25.4	25.4

10.5.1.5 Total fuel consumption for entire energy system

Overall the energy system in each country and the Scandinavian systems consume fuels in the electricity, heating, transport, industry and waste sectors. The total amount of fuel according to fuel type is shown below in Table 38.

Table 38: Energy system fuel mixes for Denmark, Sweden, Norway and Scandinavia

Fuel mix (TWh)	Denmark	Norway	Sweden	Disconnected Scandinavia	Connected Scandinavia
Coal	45.9	5.3	18.4	69.6	69.6
Oil	88.9	84.7	166.8	340.4	340.4
Natural gas	43.2	58.5	12	113.7	113.7
Biomass	35.8	15.9	118.6	170.3	170.3
Nuclear	-	-	154.4	154.4	154.4
Renewable energy	6.8	128.8	68.6	204.4	204.4
TOTAL	220.6	293.2	538,8	1052.6	1052.6

Denmark

The total fuel demand in the Danish reference system is around 220 TWh. The fuel mix in the reference system is dominated by a large share of fossil fuels. More than 80% of the fuel demand is fossil fuels with a large share of oil for transport and coal and natural gas for heat and electricity production. The biomass demand is around 36 TWh and is used primarily in CHP plants, individual boilers and waste incineration.

Norway

The fuel mix for Norway is dominated by hydro which generates electricity for the electricity and heating sector. The transport sector is supplied with oil which is the second highest fuel, which has an amount similar to Denmark. Natural gas fuel is high due to a high natural gas flaring from extraction in Norway (48 TWh). Norway has the lowest biomass demand of the three countries.

Sweden

Sweden has the highest biomass demand of the countries (119 TWh). This is due to high use in industries such as pulp and paper. Sweden has a high nuclear fuel use (154 TWh) which is due to the nuclear power production with efficiency of 33%. Sweden has the highest oil consumption of 167 TWh due to its population size that impacts the transport sector consumption and because of large consumption in shipping. Sweden has the lowest natural gas consumption of the three countries since it does not extract natural gas.

Connected & Disconnected Scandinavia

The two Scandinavian systems have a slightly different distribution of fuels compared with the individual countries since they are the combined totals from the countries. Oil is the highest fuel consumed (340 TWh) but this is followed by hydro power (204 TWh) and biomass (170 TWh). Nuclear power also has high energy consumption (154 TWh). The lowest fuel consumption is for coal (70 TWh).

10.5.2 Inputs for future energy system steps

In this section the input data for all the steps for the different energy system types are described. Following this the results when wind is increased from 0-100% is presented for each energy system type for the Connected and Disconnected Scandinavian systems.

In each step in the energy system types, the total electricity demand, power plant capacities and socio-economic costs change due to the technological change. For each step in each energy system type the data are shown in Table 53, Table 54 and Table 55.

10.5.3 Energy system type A

Energy system type A includes steps 1, 2, and 2b, which are called the “Biomass conversion” steps and are inspired by a supergrid system. The first two steps involve conversion of all non-renewable to renewable energy such as biomass in order to reduce CO_2 emissions to zero. This also includes the conversion of nuclear to power plants based on biomass in Sweden. The third step, 2b, involves converting all light vehicles to electric vehicles. Each step is described in more detail below.

Table 39: The steps included in energy system type A

Step	Tagline	Description
Step 1	Biomass conversion	All fossil fuel energy consumed in power plants, CHP plants, industry, and individual heating is converted to biomass
Step 2	Biofuel conversion	All transport is converted to biofuels
Step 2b	Dump charge EVs	All light vehicles including cars and light vans are converted to EVs

10.5.3.1 Step 1 - Biomass conversion

In step 1 all fossil fuels, excluding the transport sector, is replaced by biomass resources. The purpose of this is to convert into a 100% renewable energy system in a short term perspective. No new technologies are hence required for this step as the only factor affecting the system is the fuel conversion.

In addition to the biomass conversion two other changes are conducted in the various reference systems. Firstly, the natural gas flaring is removed from the energy systems as it is assumed that there is no need for natural gas in this step as the energy systems are converted to 100% renewable energy. Hence, the fuel consumption is reduced for natural gas for all the reference systems. In the Danish system the natural gas flaring is reduced by 6.9 TWh, in the Norwegian system it is reduced by 48 TWh as Norway is a large producer of natural gas. In the Swedish system there is no natural gas reduction as Sweden is not a producer of natural gas. The total reduction of natural gas in the Scandinavian system is 54.9 TWh.

Secondly, the nuclear power production is out phased from the Swedish energy system in this step as it is assumed to be a prerequisite to become 100% renewable. If nuclear is included, the energy system would only become carbon neutral, but not renewable in the definition of this study. Hence, the nuclear power is replaced by other production technologies and this also affects the Scandinavian system.

Finally, the waste sector was also affected by the conversion as it is assumed that only the organic fraction of the waste is used for incineration to make it 100% renewable. It was assumed that 60% of the original waste is organic (CTR, Københavns Energi, and VEKS 2009).

All the biomass conversions were made on a 1:1 energy basis, for example 1 TWh coal was converted into 1 TWh biomass. The biomass demand following the conversion for each country and energy sector is shown in Table 40.

Table 40: Biomass demand for step 1 after conversion

Biomass demand after Step 1 (TWh/year)	CHP	DH only	PP	Biomass for biofuels	Residential biomass demand	Industry	Waste	Total
Denmark	55,1	2,2	27,0	1,6	26,3	27,1	6,2	145,4
Sweden	59,6	16,7	78,1	8,7	28,0	94,6	7,6	293,4
Norway	1,0	0,3	2,6	1,5	12,5	35,0	1,5	54,3
Disconnected Scandinavia	115,7	19,3	107,7	11,8	66,8	156,6	15,3	493,1
Connected Scandinavia	116,8	18,6	100,2	11,8	67,0	156,6	15,3	486,2

In Sweden the nuclear power is removed in step 1 since it is assumed that this is non-renewable. The amount of electricity generated by nuclear in 2009 was 50.95 TWh. The nuclear capacity is replaced with thermal power plant capacity.

There are no additional technology costs in this step but the fuel costs of the energy systems change due to the biomass transition. For more details on the costs for fuels see Appendix D – Technical background information.

The change in electricity demand and modified power plant capacities from this step are presented at the end of this section in Table 53 and Table 54.

10.5.3.2 Step 2 - Biofuel conversion

This section describes the input data for step 2 which converts fossil fuels in the transport sector to biofuels based on biodiesel, biopetrol and bio-jetfuel.

The assumption for fuel conversion for various transport modes is that fuels for ships (fuel oil) is converted directly to biodiesel. Jetfuel consumption in the reference scenario is converted to bio-jetfuel while petrol in the reference scenario is converted to biopetrol.

The biomass source for these fuels is not relevant in this study since land use is not considered but the conversion efficiencies are relevant. The conversion efficiencies are generic efficiencies from EnergyPLAN.

The conversion efficiencies are:

- Biodiesel production: 1.04 TWh biomass per 1 TWh biodiesel
- Biopetrol production: 2.77 TWh biomass per 1 TWh biopetrol
- Biojetfuel production: 2.77 TWh biomass per 1 TWh biojefuel

All the fuels have been converted by using a 1:1 relationship, which means that 1 TWh of fossil fuel is replaced by 1 TWh of biofuel.

After this step is carried out there are no more fossil fuels used in the energy system and the transport system is therefore 100% renewable, but relying on very large biomass demands.

The demand for biofuel and biomass for each country and the Scandinavian systems after the conversion are presented in Table 41. There are additional costs in this step, assuming that the new vehicles that consume biofuels have slightly higher investment costs. There are additional costs for the biofuel production as well. These additional costs are also shown in Table 41. For more details on the costs for biofuels see Appendix D – Technical background information.

Table 41: Biofuel demand in step 2 after conversion

Biofuel demand (TWh)	Denmark	Sweden	Norway	Disconnected Scandinavia	Connected Scandinavia
Biopetrol	19.8	42.5	15.8	78.1	78.1
Biodiesel	36.2	66.4	39.2	141.8	141.8
Bio-jetfuel	9.4	10	8.2	27.6	27.6
Total biofuel demand	65.5	118.9	63.2	247.5	247.5
Total biomass demand from transport (TWh)	108	191.7	98.9	398.6	398.6
New biofuel production annual cost(Billion EURO)	1.8	2.2	2.7	6.7	6.7
Original vehicle fleet annual costs (Billion EURO)	6.1	11.7	7.3	25.1	25.1
New vehicle fleet annual investment (Billion EURO)	6.4	12,2	7.6	26.2	26.2

Other considerations such as land requirement for producing feedstock for the biomass for the biofuels are not considered in this study.

10.5.3.3 Step 2b

Step 2b is the last step in the biomass conversion energy system type for the supergrid energy system type of technologies. Step 2b involves the conversion of all light vehicles, including cars and light vans, from internal combustion engine (ICE) vehicles to electric vehicles in each country. This is based on a dump charge system. Heavy transport remains using biofuels similar to the previous step. These changes are reversed in step 3 in the smart grid energy system type of technologies since this energy system type integrates EVs in its last step 5b.

The electricity demand for the EVs was calculated based on calculating the number of charges required per annum for all the vehicles and the total battery capacity being charged. The number of charges was calculated by using the total distance travelled by cars and light vans and an average range of 160 km for electric cars and 120 km for electric vans. The total electricity demand was calculated using a battery capacity of 24 kWh for cars and 34 kWh for vans. The electricity demand includes 10% efficiency loss. The technologies are mostly based on today's technological status rather than what is expected for 2050, but this was to keep the assumptions rather conservative and to focus more on the impact from implementing electric vehicles rather than on which exact technology should be used in 2050.

Some of the key data used in this step is shown in Table 42. The socio-economic cost from having a fleet of EVs for light vehicles increases the annual investment and this is shown for each country and Scandinavian system in Table 42.

Table 42: Electricity demand and hanged investment costs after conversion to electric vehicles

	Denmark	Sweden	Norway	Disconnected Scandinavia	Connected Scandinavia
Total EVs (cars and vans)	2,580,977	4,924,259	2,628,280	10,133,516	10,133,516
Total distance travelled (Billion km)	42.9	61.8	39.6	144.3	144.3
Electricity demand (TWh)	8.3	11.2	7.5	27	27
New biofuel production annual investment (Billion EURO)	0.7	1.0	0.7	2.4	2.4
Original vehicle fleet annual investment (Billion EURO)	6.4	12,2	7.6	26.2	26.2
New vehicle fleet annual investment (Billion EURO)	8.4	16.1	9.9	34.5	34.5

10.5.4 Energy system type B - Electrification

Energy system type B includes steps 3, 4, 5 and 5b, which are called the "electricity transfer" steps and are inspired by a smart grid system. The steps are described in Table 18 below.

Table 43: The steps included in energy system type B

Step	Tagline	Description
Step 3	Individual heat pumps	Conversion from individual boilers and electric heating into individual heat pumps with a similar heat demand before and after this conversion.
Step 4	Electrification of industry	In this step 40% of the industrial fuel demand is converted into electricity
Step 5	Flexible demand	Flexible demand means that 20% of the electricity demand is made flexible within 24 hours.
Step 5b	Electric vehicles - smart charge	All light vehicles, including cars and vans, are converted into electric vehicles.

10.5.4.1 Step 3 - Individual heat pumps

In step 3 all electric heating and individual boilers are converted to heat pumps in individual houses and services. The purpose of this step is to convert less efficient, or fuel intensive heating into more efficient heating such as heat pumps. The conversion was carried out by taking the heat demands from individual boilers and electric heating and converting the heat demand to be supplied by heat pumps. The heat pumps have an electric efficiency from electricity to heat of 3.2 (Danish Energy Agency and Energinet.dk 2012b).

The heat pump demand for each country and the Scandinavian energy systems after the conversion are presented in Table 44. The additional investment costs for the heat pumps for each country and the Scandinavian systems are also shown in Table 44.

Table 44: Changing heat pump demands after conversion in step 3

(TWh)	Denmark	Sweden	Norway	Disconnected Scandinavia	Connected Scandinavia
Original boiler heat demand (fuel demand)	21.2 (26.5)	22.4 (28)	9.9 (12.5)	53.5 (67)	53.5 (67)
Original electric heating demand	1.2	19.1	38.7	59.1	59.1
Original heat pump demand (electricity demand)	0.01 (0.005)	2.3 (1.1)	0.1 (0.07)	2.4 (1.2)	2.4 (1.2)
New heat pump heat demand (electricity demand)	22.4 (7)	43.8 (13.7)	48.8 (15.3)	115 (36)	115 (36)
Original heat pump annual cost (Billion Euro)	0,000	0,007	0,000	0,008	0.008
New heat pump annual cost (Billion Euro)	0,1	0.3	0.3	0.8	0.8

As shown in Table 44 by replacing these technologies with heat pumps, the fuel demand decreases and is replaced with electricity.

10.5.4.2 Step 4 - Electrification of industry

This section describes the input data for step 4 which converts 40% of the industrial fuel demand to electricity.

It is assumed that 40% of the energy in industry can be directly replaced with electricity since the energy is not being used for industrial processes but only for the heat content in the form of steam (Energinet.dk and Dansk

Energi 2011). The remaining 60% of the fuel is assumed to serve other purposes, other than heat, such as for chemical reactions in steel production for example.

The demand for biomass for each country and the Disconnected Scandinavia and Connected Scandinavia energy systems after the conversion are presented in Table 45.

Table 45: Biomass demand after electrification of industry

Energy (TWh)	Denmark	Sweden	Norway	Disconnected Scandinavia	Connected Scandinavia
Original industrial fuel demand (biomass)	27.1	95	35	157	157
New industrial fuel demand (biomass)	16.2	57	21	94	94
New industrial electricity demand	11	38	14	63	63

There are no additional industry investments included in the socio-economic analysis for converting to electricity from biofuels. The cost may be internalised by industry and may lead to higher costs for the products but this is not included.

10.5.4.3 Step 5 - Flexible demand

Step 5 involves shifting 20% of the electricity demand from being inflexible to flexible within a 24 hour period. This could be achieved in real-life by installing smart meters in homes and businesses and smart appliances for example. The amount that could be shifted is assumed to be 20% which is based on the Danish Smart Grid Strategy calculations for Denmark (Danish Ministry of Climate 2013).

The changes in this step only relate to the amount of fixed electricity and the share that is converted into flexible demand and this is shown in Table 46. The cost for creating flexible demand is also shown in Table 46 and this cost includes smart meters and other communication technologies.

Table 46: Flexible and fixed electricity demand for step 5

Electricity demand (TWh)	Denmark	Sweden	Norway	Disconnected Scandinavia	Connected Scandinavia
Flexible demand	11.1	34.2	24.8	70.1	70
Fixed demand	42.6	134.9	98.2	275.7	275.4
Total	**53.7**	**169.1**	**123**	**345.8**	**345.4**
New flexible demand annual costs (Billion EURO)	**0,1**	**0.3**	**0.2**	**0.6**	**0.7**

10.5.4.4 Step 5b - Electric vehicles (smart charge)

Step 5b is the last step in the electricity transfer steps designed for the smart grid system technologies. Step 5b involves the conversion of all light vehicles, including cars and light vans, from ICE vehicles to electric vehicles in each country. These changes are reversed in step 6 in the smart energy system type of technologies since this energy system type integrates EVs in step 8.

The electricity demand was calculated based on the same method as for step 2b. The costs for EVs and the biofuel production are also the same as for step 2b.

The conversion to electric vehicles increases the electricity demand of each country and Connected Scandinavia system and the increase in electricity is the same as in step 2b in Table 42. In this step the EVs are operated using smart charge rather than receiving electricity from a dump charge. The smart EVs depend on an intelligent grid that charges EVs with the aim of decreasing unused electricity production and the overall amount of condensing power in the energy system (Lund 2013).

10.5.5 Energy system type C - Integration of energy sectors

Energy system type C includes steps 6, 7, 8, and 9, which are called the "integration of sectors" steps and are inspired by a smart energy system. The steps are described in the table below.

Table 47: The steps included in energy system type C

Step	Tagline	Description
Step 6	District heating expansion	Expansion of district heating in each country
Step 7	Large-scale heat pumps	Increasing large-scale heat pump capacity to utilise more electricity in the district heating production
Step 8	EVs and synfuels	All light vehicles, including cars and vans, are converted into electric vehicles. All non-electric vehicles run on synfuels
Step 9	Biomass gasification	All biomass used for electricity and heat production is converted into gas

10.5.5.1 Step 6 - District heating expansion

In step 6 a proportion of individual heat pumps are converted into district heating, in order to test whether district heat expansion is able to create a more flexible system and thereby integrate more wind electricity.

The district heating conversion is carried out according to estimates for the individual countries about the feasibility of district heat expansion from relevant sources.

The conversion was made by taking the heat demands from individual heat pumps and converting the heat demand to be supplied by district heating. As shown in Table 48 by replacing these technologies with district heating, the electricity demand decreases (compared with step 5).

In Denmark district heating increases from 62% of the total heat demand to 70% based on (Dyrelund et al. 2010; Wittrup 2014). In Norway the district heat demand increases the most of all countries from 4% to 22% based on (Havskjold and Lislebø 2010). In Sweden the district heating increases from 54% to 64% of the total heat demand, which is an estimate.

The district heating demand increases for each country whereas the individual heat pump demand decreases for each country and the Disconnected Scandinavia and Connected Scandinavia energy systems. The demands after conversion are presented in Table 48 as well as the additional socio-economic costs.

Table 48: District heating and heat pump after expansion of district heating in step 6

(TWh)	Denmark	Sweden	Norway	Disconnected Scandinavia	Connected Scandinavia
Original individual heat pump demand	22.4	44	49	115.4	115.4
New individual heat pump demand	17.8	37.1	40	94.9	95
Original district heat demand	36.9	59	2.2	98.1	98.1
New district heat demand	41.5	65.9	11	118.4	118.4
New additional district heating annual costs (Billion Euro)	0.3	0.4	0.3	1.0	1.0

10.5.5.2 Step 7 - Large-scale heat pumps

This section describes the input data for step 7 which increases the capacity of large-scale heat pumps for district heating production. Large-scale heat pumps function the same way as individual heat pumps but are larger, see more information in Appendix B – Methodology.

The electricity demand does not change when large-scale heat pumps are utilised since they are used in the system to consume electricity that is in excess and that would otherwise be unused. This occurs when more wind is added and unused electricity is created for example. When they are utilised they replace other forms of heat producers such as boilers and can potentially contribute to fuel savings.

The heat pump capacity for Norway increased the most in decentralised district heating areas rather than centralised areas while it is opposite for Denmark and Sweden. This is because the structure of the district heating networks is different between the countries.

The increases in large-scale heat pump capacity for each country and the Disconnected Scandinavia and Connected Scandinavia energy systems are presented in Table 49. The additional socio-economic costs are also presented in Table 49.

Table 49: Large heat pump capacity after conversion in step 7

MW-e	Denmark	Sweden	Norway	Disconnected Scandinavia	Connected Scandinavia
Original large-scale heat pump capacity decentralised/centralised	50/0	150/380	0/50	200/430	200/430
New large-scale heat pump capacity decentralised/centralised	300/600	500/600	500/50	1300/1250	1300/1250
New additional large scale heat pump annual investment (Billion EURO)	0.2	0.2	0.1	0.5	0.5

10.5.5.3 Step 8 - EVs and synfuels

Step 8 involves the conversion of all light vehicles from ICE vehicles to smart charging electric vehicles in each country. This includes all cars and small vans. The heavy transport is also converted from biofuels to synfuels in the form of biomethanol. Further information about the production of biomethanol is presented in Appendix B – Methodology.

The efficiency for electrolysers is set at 73% for every country (B. V. Mathiesen, Ridjan, and Connolly 2013). The production efficiency for the chemical synthesis of synfuels was set 80% from syngas.

The electricity demand for EVs was calculated based on the same method as in step 2b and 5b and the electricity demand is the same as in step 2b in Table 42. The socio-economic costs are also the same as for step 2b.

In this step the EVs are operated on a smart charge system similar to EVs in step 5b.

The production of synfuels and biomass and electricity demand for electrolysers for the synfuels is presented in Table 50 below for each country and Disconnected Scandinavia and Connected Scandinavia. The additional socio-economic costs are also presented in Table 50.

Table 50: Synfuel production and changing costs after conversion in step 8

Energy (TWh)		Denmark	Norway	Sweden	Disconnected Scandinavia	Connected Scandinavia
Synfuel demand	Syndiesel	17.4	28	54.1	99.5	99.5
	Synpetrol	0	0	0	0	0
	Synjetfuel	9.4	8.2	10	27.6	27.6
Total biomass demand for synfuels		26,36	36.47	65.56	128.4	128.4
Electricity demand by electrolysers for hydrogen		16.4	22.7	40.7	79.8	79.8
Electrolyser capacity (MW)		4000	3200	5000	12000	11000
Electrolyser hydrogen storage		500	400	600	1500	1300
New additional electrolyser and hydrogen storage annual costs (Billion EURO)		0.5	0.6	0.4	1.5	1.4
New additional synthetic fuel production annual costs (Billion EURO)		0.6	1.5	0.9	3	3

10.5.5.4 Step 9 - Gasification of biomass

In step 9 all the biomass used in CHP and power plants is converted into gas via a gasification process. This gas is then upgraded to the appropriate quality to be able to be stored in the natural gas grid. When the gas is required it is combusted in a combined cycle power station based on steam extraction and combined cycle back-pressure CHP plants. The new technologies that combust the gas have higher efficiencies than for solid biomass technologies. Further details about the technologies are provided in Appendix B – Methodology.

The biomass to biogas conversion is different for different amounts of wind integration. This is because when wind increases, the amount of electricity produced by power plants and CHP decreases therefore the amount of biomass required for biogas decreases as well.

The biomass and biogas data for the wind input from 0-100% is presented in Table 51 below. The socio-economic costs are also presented in Table 51.

Table 51: Biomass demand and changing costs after gasification in step 9

(TWh)	Denmark	Norway	Sweden	Disconnected Scandinavia	Connected Scandinavia
New total biomass for biogas 0-100% wind	219-105	85-61	312-177	617-343	639-314
New total biogas for CHP and PP	135-42	20-1	131-21	286-64	307-44
Biogas storage capacity (GWh)	11000-14000	1000-3000	6000-14000	21000-30000	19000-29000
New additional biomass gasification & gas upgrade annual costs (Billion EURO)	0.8 - 2.3	0.4 - 1.0	0.9- 4.8	2.1 - 8.1	1.9.- 6.7

The efficiencies of the power plants change in this step since they are powered by gas rather than combustion, and the new efficiencies are shown in Table 52 below.

The efficiencies for the power plants and CHP plants are presented below.

Table 52: Changing efficiencies after gasification and new thermal plants in step 9

(TWh)		Denmark	Norway	Sweden	Disconnected Scandinavia	Connected Scandinavia
Original thermal efficiencies with solid biomass	Power plant	40%	40%	40%	40%	40%
	CHP decentralised elec./heat	37%/46%	37%/46%	37%/46%	37%/46%	37%/46%
	CHP centralised elec./heat	31.5/53%	31.5/53%	31.5/53%	31.5/53%	31.5/53%
New thermal efficiencies with biogas	PP	56.5%	56.5%	56.5%	56.5%	56.5%
	CHP decentralised elec./heat	48/37,5%	48/37,5%	48/37,5%	48/37,5%	48/37,5%
	CHP centralised elec./heat	48/37,5%	48/37,5%	48/37,5%	48/37,5%	48/37,5%

10.5.6 Total electricity demands

The electricity demands for each energy system in each step are presented below.

Table 53: Electricity demand for each step in Denmark, Sweden, Norway and Scandinavia

Electricity demand (TWh)	Denmark	Sweden	Norway	Disconnected Scandinavia	Connected Scandinavia
Reference	36.4	137	132	304.9	304.9
Step 1	36.4	137	132	304.9	304.9
Step 2	37.1	137.9	132.6	307.5	307.5
Step 2b	45	148	139.7	332.7	332.7
Step 3	42.9	131	109	283	283
Step 4	53.7	169	123	345.9	345.9
Step 5	53.7	169	123	345.9	345.9
Step 5b	61.5	179.3	130.2	371	371
Step 6	52.2	167	120.3	339.5	339.5
Step 7	52.2	167	120.3	339.5	339.5
Step 8	52.2	167	120.3	339.5	339.5
Step 9	76.5	218	150	445	445

It can be seen that the electricity demand in all countries and Scandinavian systems continue to increase with energy system type C having the highest electricity demands.

10.5.7 Change in power plant capacity for each step

The power plant capacities are adjusted according to the maximum electricity demand in one hour of the year and therefore increase when the electricity demand is increasing.

Table 54: Power plant capacity for each step in Denmark, Sweden, Norway and Scandinavia

Power plant capacity (MW-e)	Denmark	Sweden	Norway	Disonnected Scandinavia	Connected Scandinavia
Reference	7000	6903	740	13,833	14,643
Step 1	7000	17,750	740	25,490	34,000
Step 2	7000	17,750	740	25,490	35,000
Step 2b	7000	19,200	6500	32,700	37,600
Step 3	7000	16,400	740	24,140	29,000
Step 4	11,750	24,100	740	36,590	43,200
Step 5	10,500	21,500	740	32,740	38,000
Step 5b	12,500	24,000	2000	38,500	43,200
Step 6	7000	20,500	740	28,240	34,000
Step 7	7000	20,600	740	28,340	34,000
Step 8	13,500	28,000	6900	48,400	50,000
Step 9	13,000	29,000	7000	49,000	49,000

10.5.8 Total socio-economic cost for each step

The socio-economic costs for each step are presented Table 55 below.

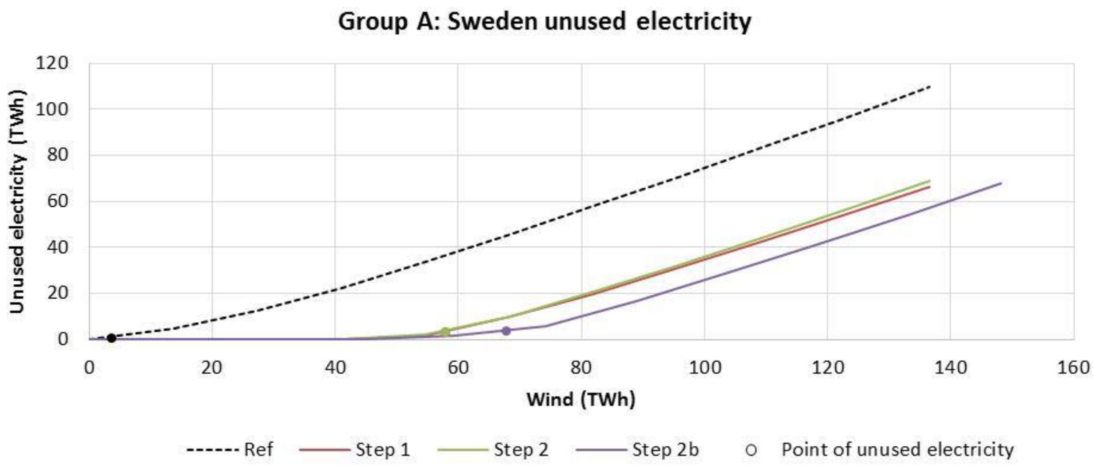
Table 55: Socio-economic costs for each step in Denmark, Sweden, Norway and Scandinavia

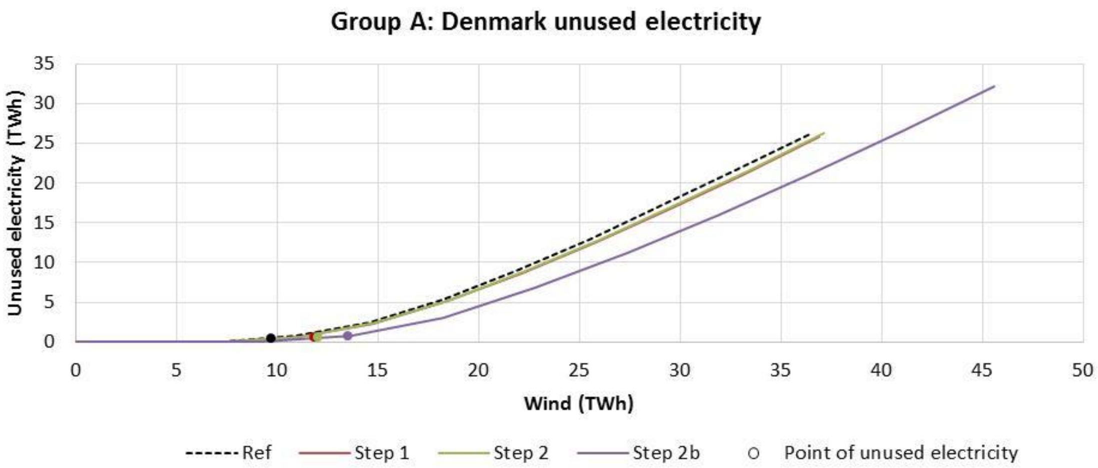
Socioeconomic cost (Billion Euro)	Denmark	Sweden	Norway	Disconnected Scandinavia	Connected Scandinavia
Reference	17,7	35,1	19,9	72,6	72,5
Step 1	18	34,5	17,6	70,1	71
Step 2	19,5	37,1	18,8	75,3	76.0
Step 2b	18,8	35,9	19,7	74,5	74,9
Step 3	18,7	35,1	17,8	71,5	70,5
Step 4	19,9	37,5	17,3	74,7	74,2
Step 5	19,8	37,4	17,6	74,7	74,1
Step 5b	19,4	36,3	17,9	73,6	69,2
Step 6	19,7	37,6	18,3	75,6	75,3
Step 7	19,9	37,7	18,4	75,9	75,3
Step 8	21.4	40.9	20.6	82.9	81.6
Step 9	21.3	40.2	20.3	81.8	80.6

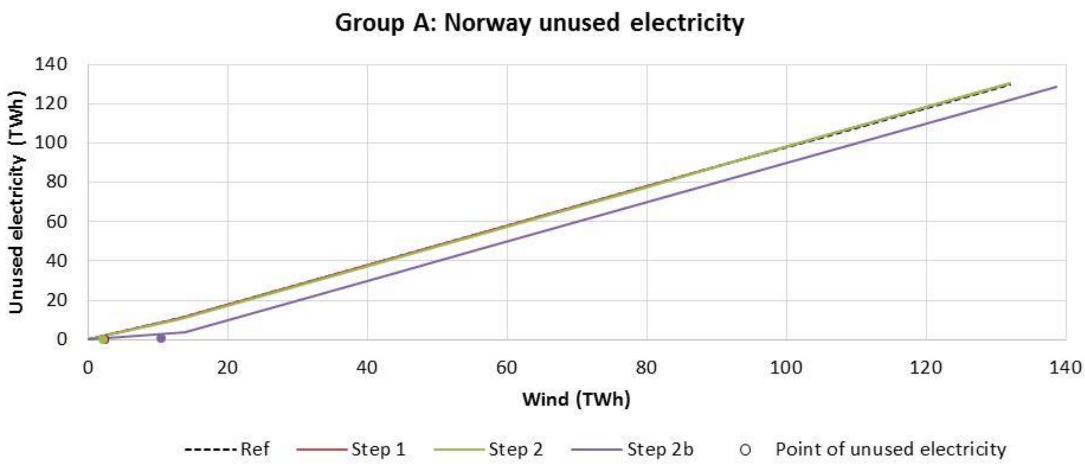
10.6 Appendix F – Individual country graphs

10.6.1 Energy system type A

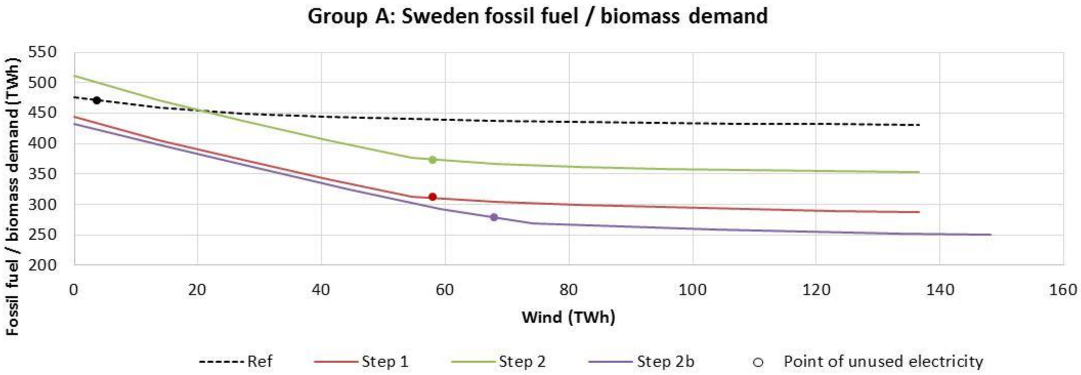
10.6.1.1 Wind integration

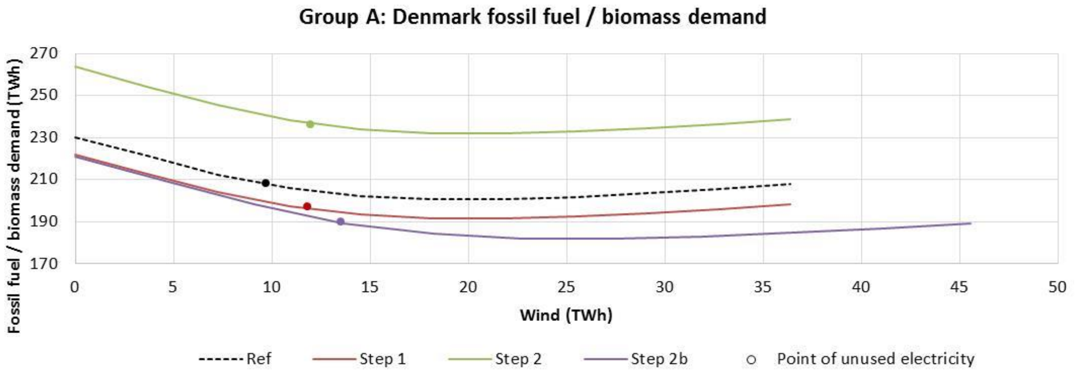


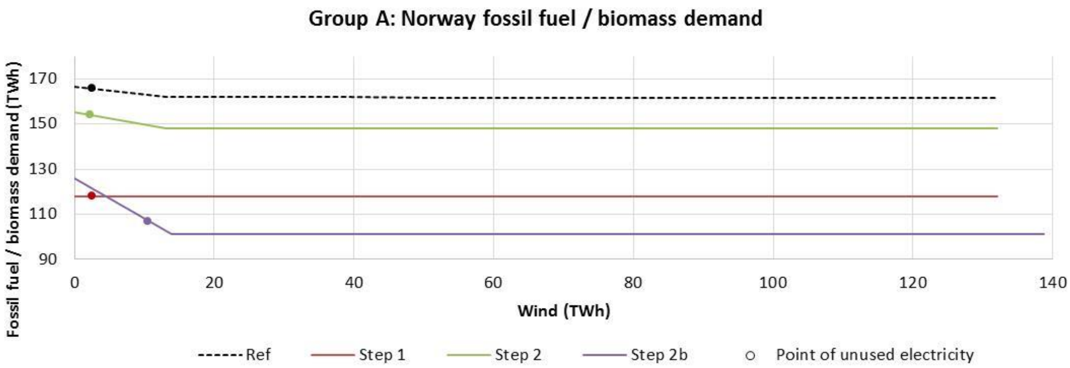




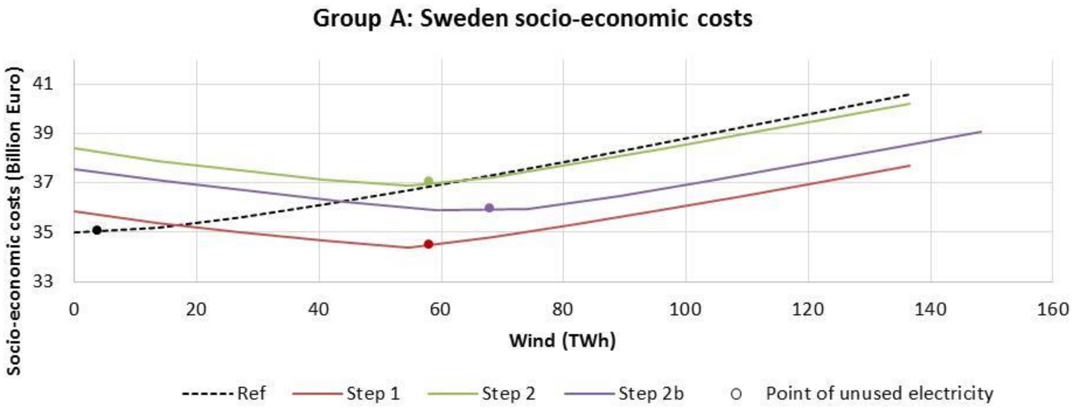
10.6.1.2 Fossil fuel and biomass demand

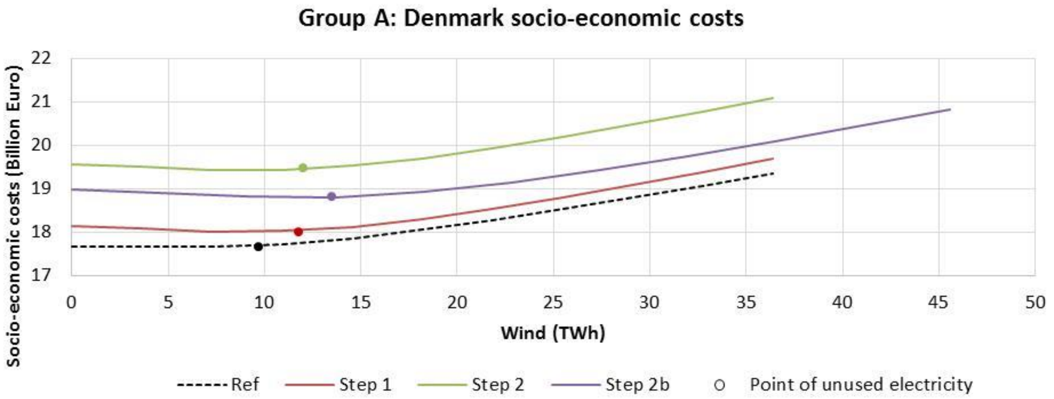


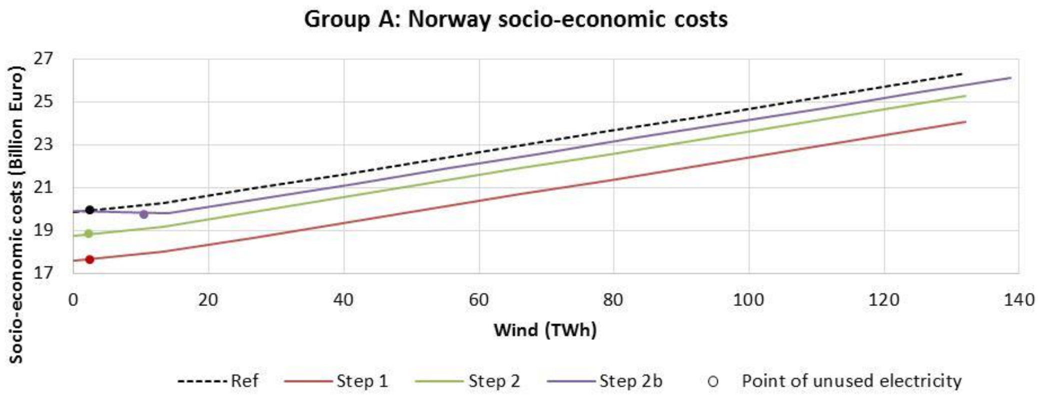




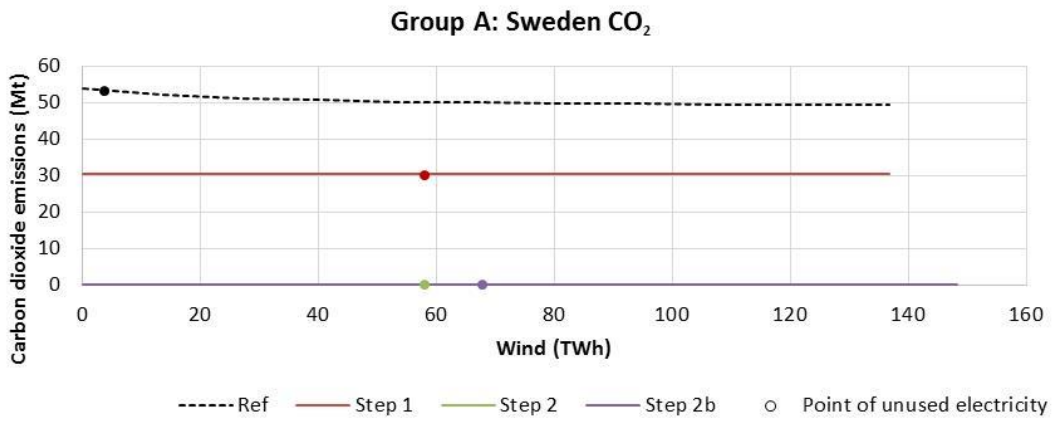
10.6.1.3 Socio-economic costs

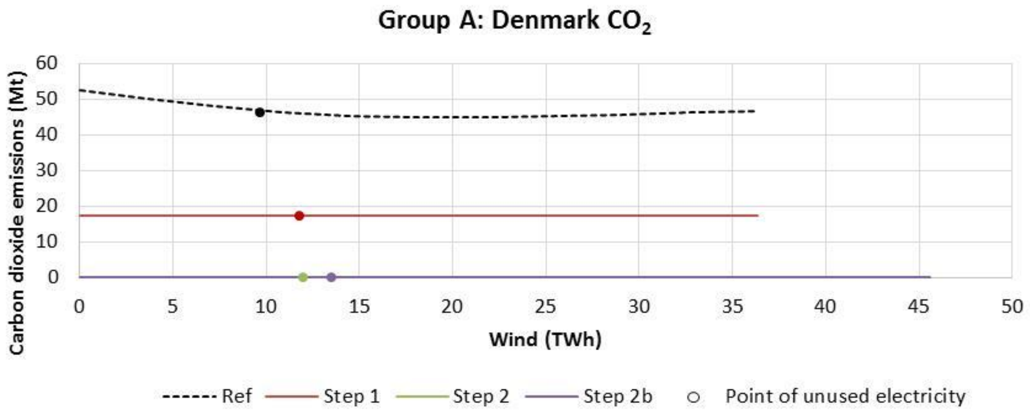


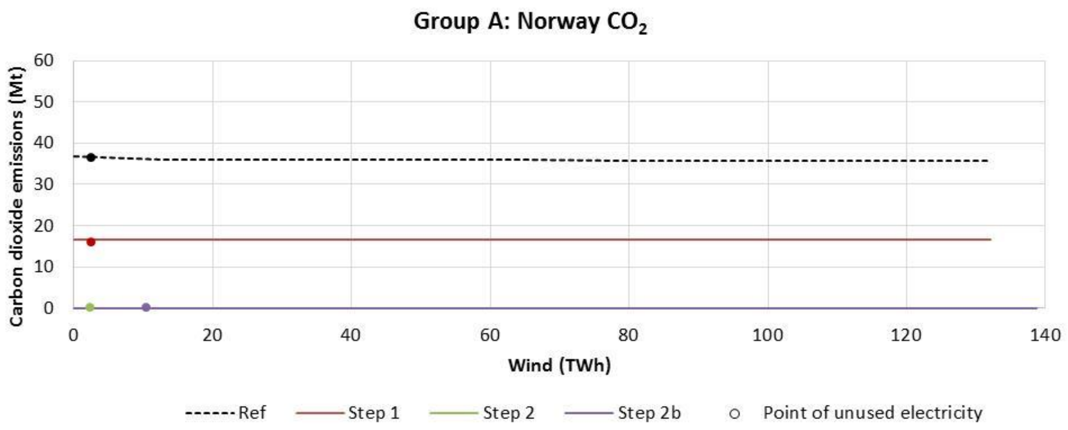




10.6.1.4 CO_2-emissions

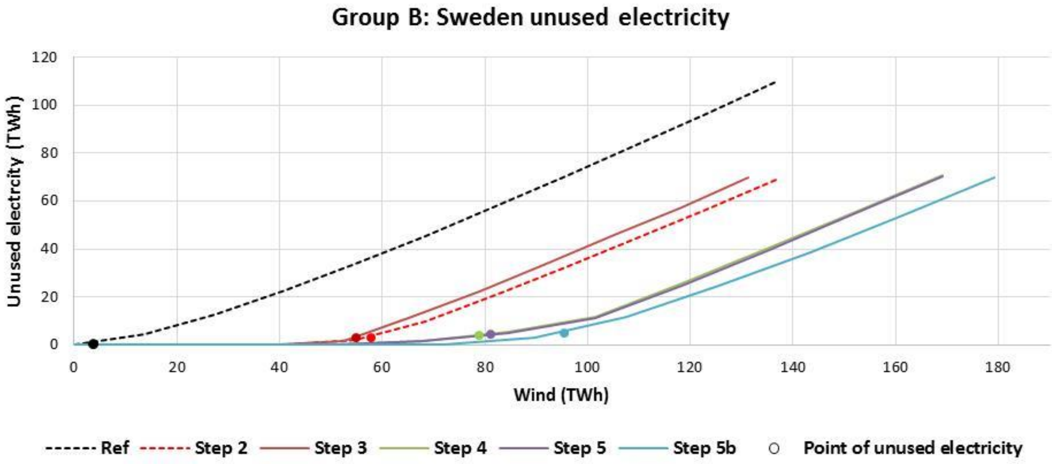


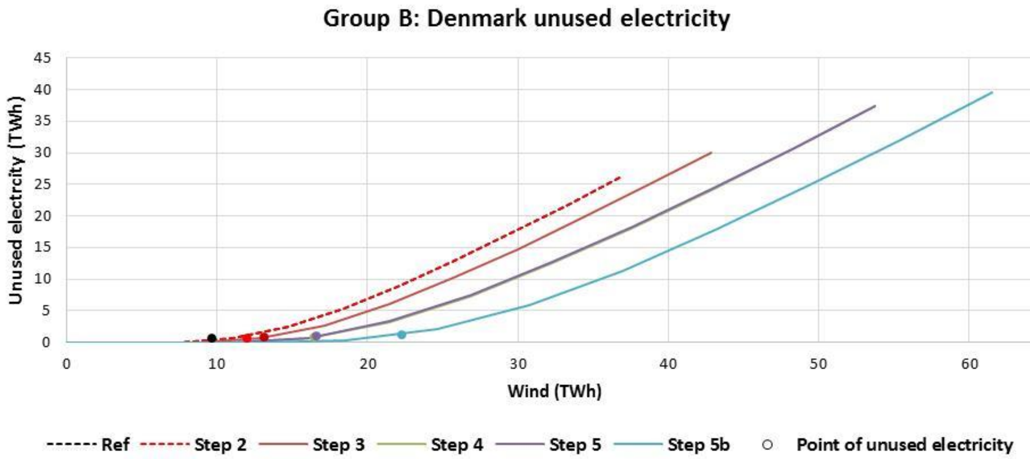


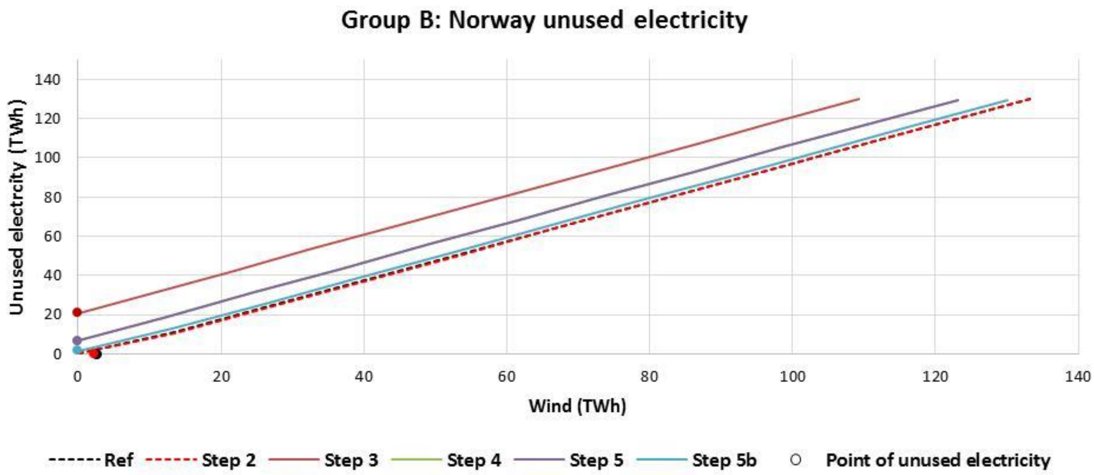


10.6.2 Energy system type B

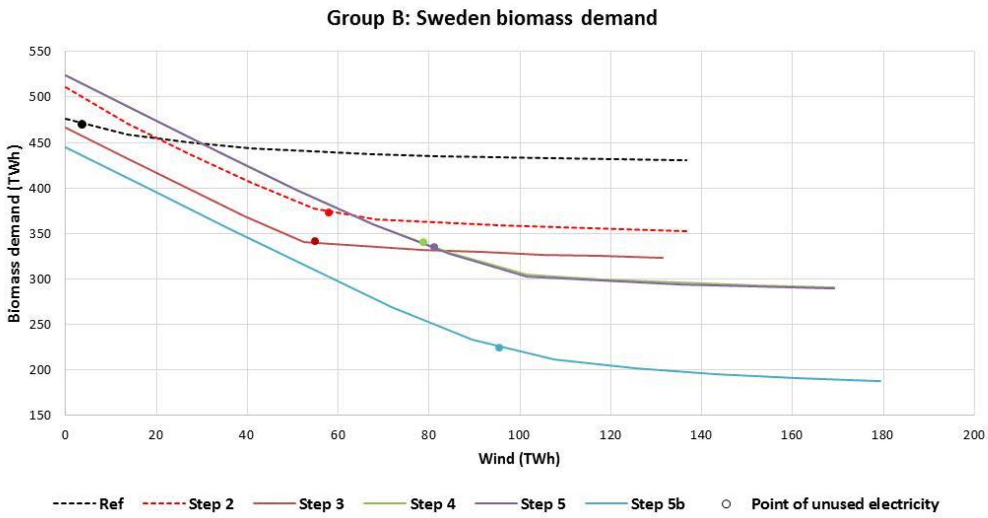
10.6.2.1 Wind integration

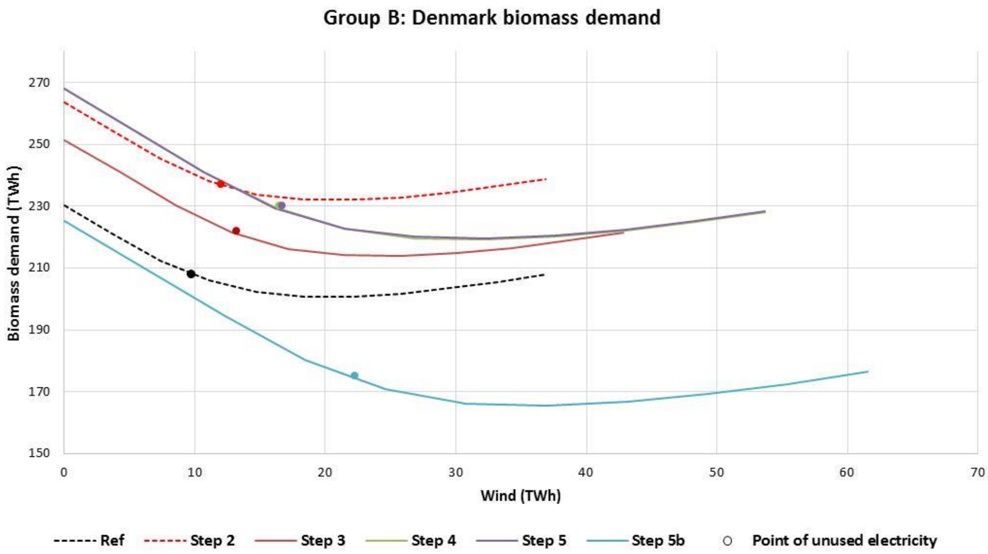


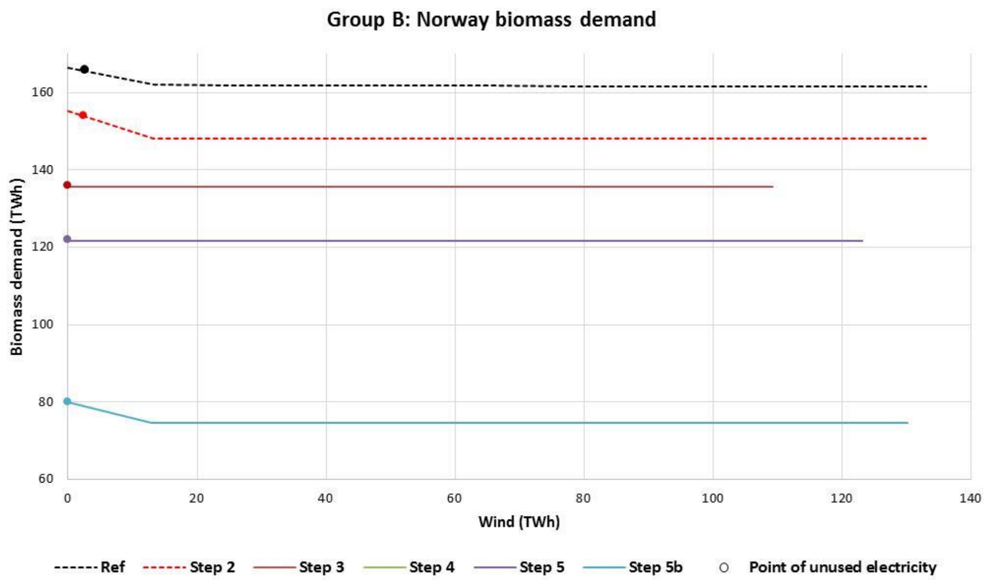




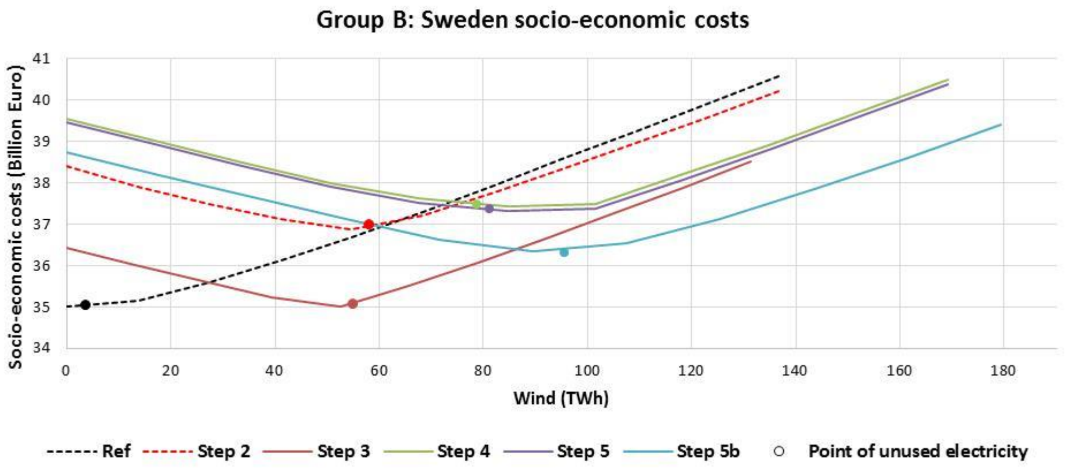
10.6.2.2 Biomass demand

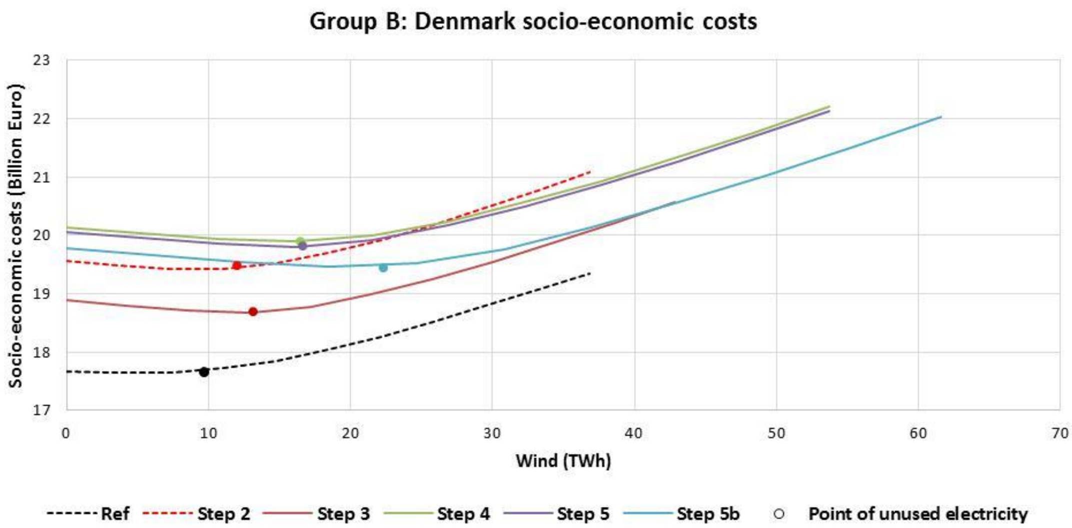


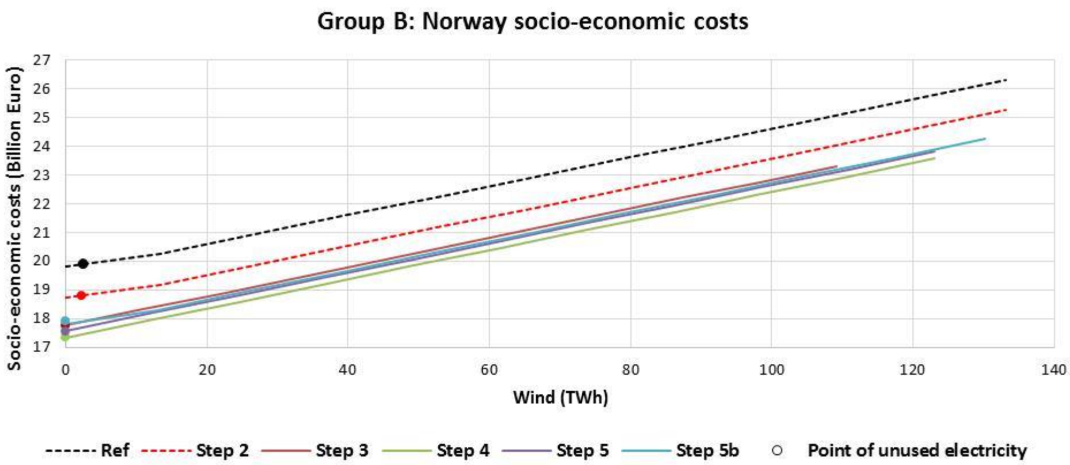




10.6.2.3 Socio-economic costs

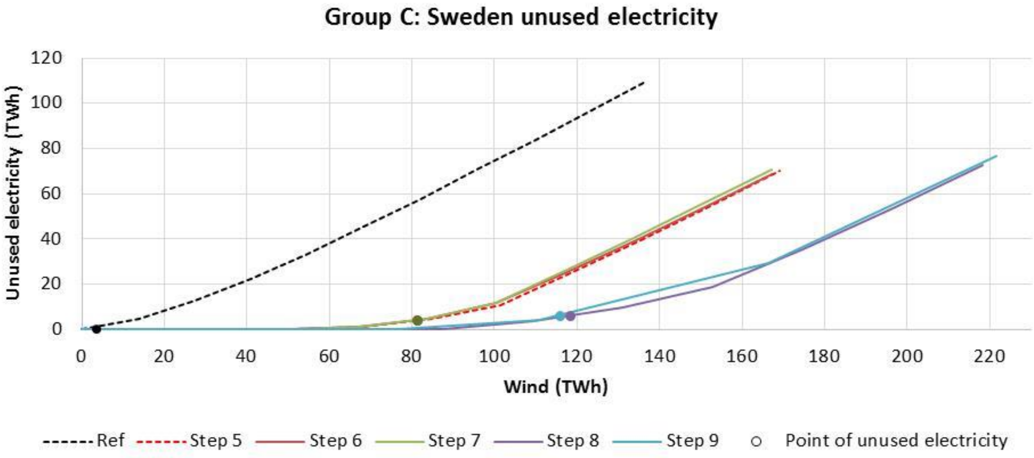


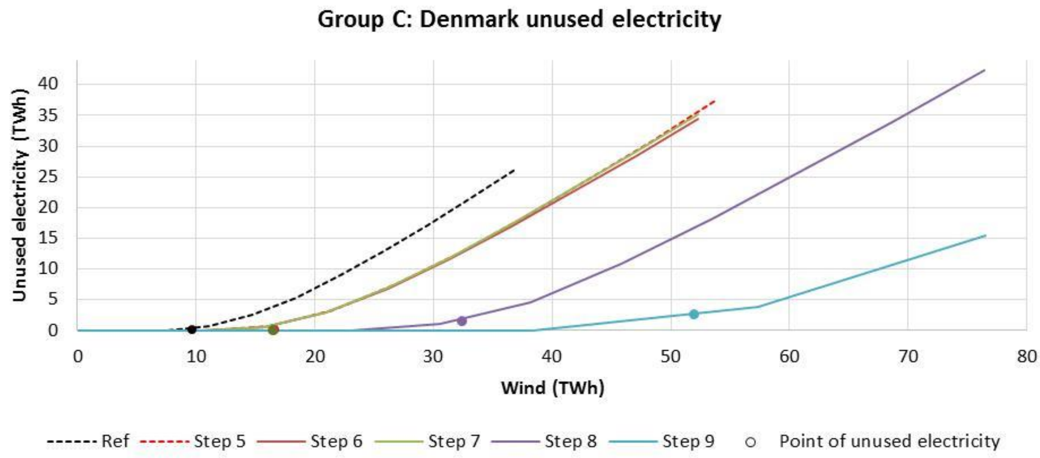


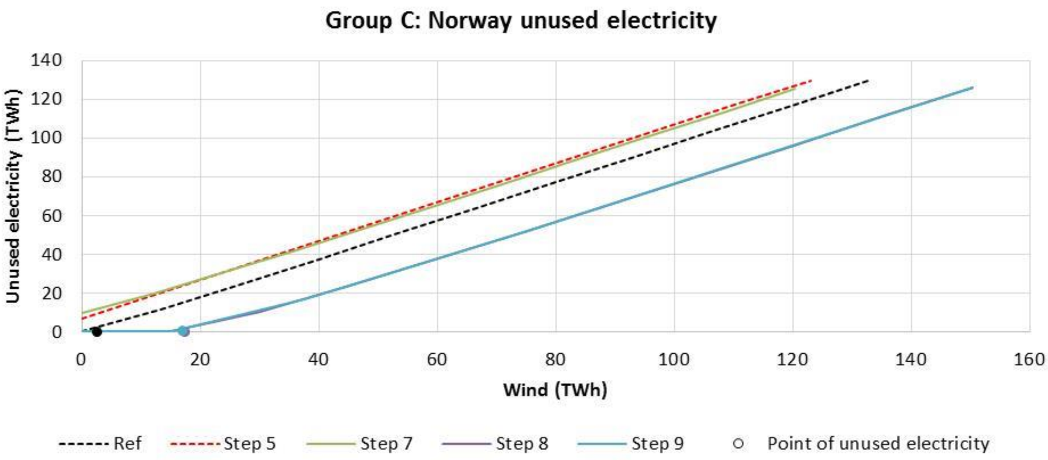


10.6.3 Energy system type C

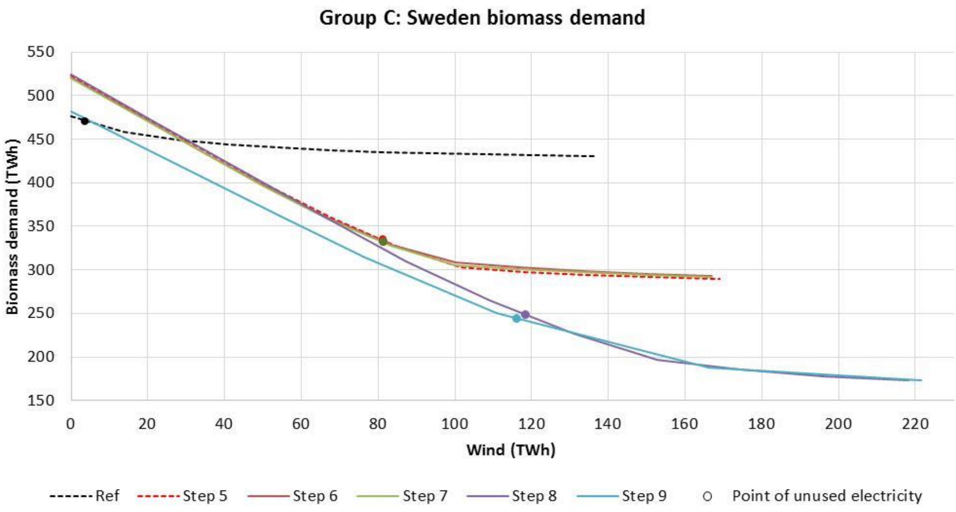
10.6.3.1 Wind integration

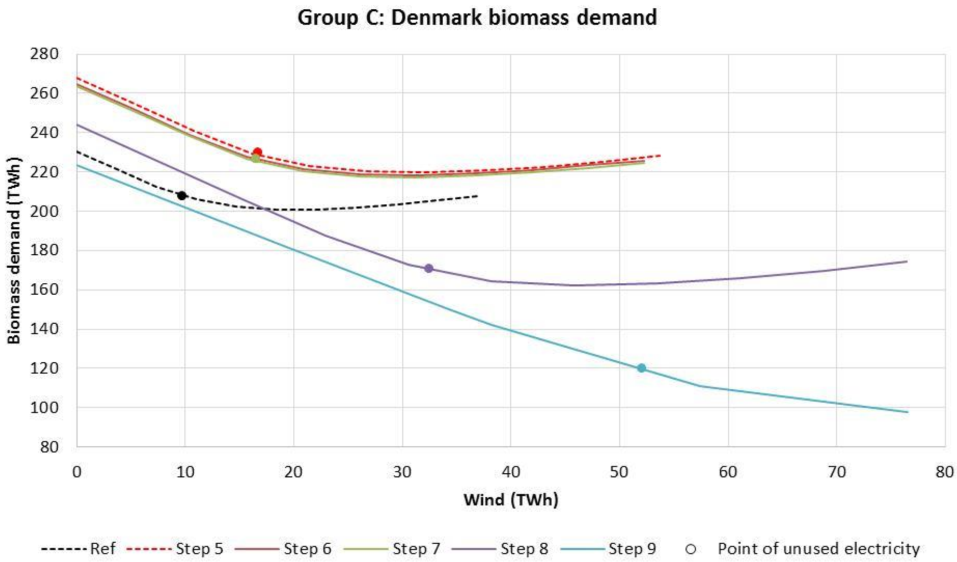


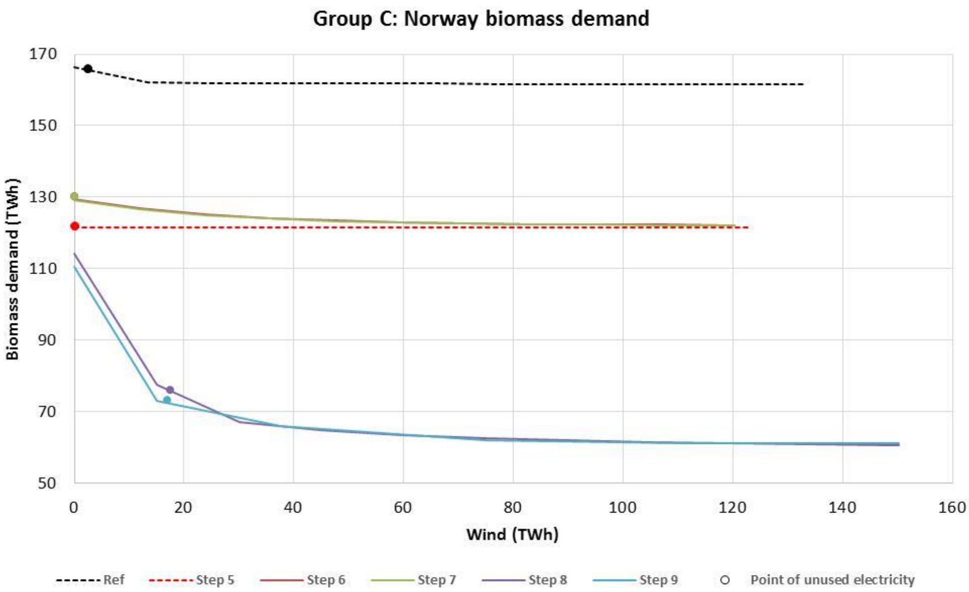




10.6.3.2 Biomass demand







10.6.3.3 Socio-economic costs